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RESEARCH ARTICLE

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Quartile risk dependence between clean energy markets and the U.S. travel and leisure index

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ABSTRACT

We employed the Cross-quantilogram method for the first time to assess the cross-quantile risk relationship among the clean energy market and the Dow Jones U.S. Travel & Leisure Index during the period from 2014 to 2023. This investigation aimed to explore the asymmetric nature of the risk-dependence structure. Our findings reveal that, under market stability conditions, the U.S. Travel & Leisure index exhibited the highest correlation with all clean energy stocks. However, the risk correlation with the NASDAQ OMX Geothermal, NASDAQ OMX Solar, and NASDAQ OMX Wind Indices significantly decreased during longer investment horizons and extreme quantiles. Notably, in the extreme tail, the correlation between specific clean energy markets and the U.S. Travel & Leisure index displayed heterogeneity. Our results have new practical implications for policymakers and investors who need to capture the risk connection among clean energy indices and the U.S. Travel and Leisure sector.

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Clean energy markets; U.S. Travel and leisure index; cross-quantilogram; risk dependence; granger-causality in quantiles

1. Introduction

Mainly driven by human-induced greenhouse gas emissions, with a notable emphasis on carbon dioxide (CO^2) emissions, there occurred a notable global temperature rise. This elevation set in motion a succession of profound climate change repercussions, encompassing escalating sea levels and a surge in occurrences of extreme weather events (Zhao et al., 2024). The release of the United Nations reports in 2020 concerning the Sustainable Development Goals for 2030 prompted governments worldwide to reevaluate climate-related risks and the challenges of global warming (Yu et al., 2020). In fact, governments across the world have progressively undertaken measures to shift from primarily utilising fossil fuels to increasing investments in and utilisation of clean energy sources. Clean energy refers to energy forms that reduce greenhouse gas emissions and environmental pollution during production and utilisation, in contrast to traditional fossil fuels like coal, oil, and natural gas, which release substantial greenhouse gases and significant amounts of CO^2 during combustion (X. Wang et al., 2024; Zeng, Abedin, Zhou, et al., 2024). Thus, research and development of clean energy are imperative as a crucial alternative to fossil fuels.

Amidst heightened market uncertainty, the stability of the clean energy industry and its expansion remain essential challenges (Bouteska et al., 2024). Given that the clean energy index is a key funding source for clean energy development (Ji & Zhang, 2019), the inter-connectedness of risks

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among the clean energy stock and other financial markets has drawn considerable attention from various sectors.

The United States stands as one of the most appealing destinations for Travel & Leisure. As the largest global economy, its diverse natural landscapes, rich cultural heritage, high-quality service facilities, and varied entertainment activities have made it a popular choice for global travellers (Kim et al., 2007). Ranging from metropolitan areas to natural scenery, and from theme parks to cultural events, the U.S. possesses extensive allure within the Travel & Leisure sector. With advancements in transportation and communication, the U.S. Travel & Leisure industry has evolved into a vast economic chain. This industry has increasingly contributed to the U.S. economy, generating significant employment opportunities while fostering the development of related sectors such as hospitality, dining, and aviation. The U.S. Travel & Leisure sector has long been a cornerstone of the national economy and is gradually rebounding from the pandemic that began in 2020. In 2022, the outbound U.S. tourism market reached a value of $101.697 billion, with projected revenue of $190.4 billion for the travel and tourism market in 2023, and an estimated $198.0 billion in international travel expenditure by 2025.[1] This market size reflected the importance of the U.S. travel & leisure industry and the high level of attention investors paid to this field. According to the efficient market hypothesis (Fama, 1970), stock prices reflected all publicly available information, including the market size and growth prospects of the industry. The vast market size of the U.S. travel & leisure industry indicated the economic strength and development potential of the industry, which was of significant informational value to investors. Furthermore, based on the theory of behavioural finance (Shefrin, 2002), investors' sentiments and psychological biases could also influence their investment decisions. The thriving development of the U.S. travel & leisure industry might lead to optimistic sentiments among investors, thereby driving active trading in related stocks. The active trading and considerable investment size of US travel & leisure stocks reflected market participants' confidence in the industry's prospects. This phenomenon could be explained by the herd effect (Banerjee, 1992), which suggests that investors tend to follow the decisions of other investors, forming collective behaviour. When most investors were optimistic about the development prospects of the U.S. travel & leisure industry, other investors might also be influenced and join the ranks of investing. In summary, the market size of the US tourism industry had a significant impact on investor attention, which could be explained by theories such as the efficient market hypothesis, behavioural finance theory, and the herd effect. The tourism industry significantly contributes to the national economy, offering consistent economic surplus and standing as one of the primary drivers of job creation within the economy (Ghosh et al., 2023; Li et al., 2018). Thus, investigating the U.S. Travel & Leisure industry holds relevance not only for industry practitioners and investors but also for influencing government welfare and economic development policies.

This study selected U.S. data as the research focus not only because of the country's leading position in clean energy and tourism but also due to the significant indicative value of U.S. market trends and investment behaviours for the global economy and financial markets. As the world's biggest economy, the economic policies and market trends of the United States often have profound impacts on other countries (Zeng, Ahmed, et al., 2024). Therefore, a detailed evaluate of the relationship between the U.S. clean energy index and the travel & leisure index can provide decision-making references for American investors and valuable insights for investors and policymakers in other countries. For instance, if the study finds a significant positive connection between the U.S. clean energy index and the tourism and leisure index, it might indicate that, in the context of global economic integration, other countries' clean energy and tourism sectors could face similar market environments and risk factors. Consequently, investors in other countries could use the U.S. market experience to adjust their investment strategies and control investment risks. Likewise, policymakers in other countries could learn from the U.S. experience to formulate policies that coordinate the development of clean energy and tourism, addressing the impacts of economic cycles and extreme events. In summary, the connection between clean energy and tourism revealed by U.S. data holds significant reference value for global investors and policymakers.

Close interrelations exist among the clean energy indices and the U.S. Travel & Leisure market, particularly concerning alternative energy demand, shared emphasis on sustainable development, and environmental impact. Initially, the operation and growth of the tourism industry are reliant on stable and economically viable energy supplies. Fuelled by concerns about deteriorating global climate conditions and uncertainty in the oil market, tourism practitioners and investors are considering shifts towards renewable or clean energy sources, potentially contributing to sustainability. Subsequently, within the context of ongoing environmental transformation, sustainability and ESG principles constitute common goals for participants in the clean energy and travel & leisure markets (Zeng, Abedin, & Lucey, 2024). The development of the clean energy industry aims to minimise adverse environmental effects through the substitution of conventional high-carbon energy sources, reducing carbon emissions, air pollution, and resource consumption. Correspondingly, sustainable development within the Travel & Leisure market underscores the reduction of carbon emissions in conjunction with meeting leisure demands, thereby fulfilling environmental protection requirements (Yang et al., 2024). This implies that, encouraged by governmental and stakeholder initiatives, environmental burdens in tourism activities need to be diminished, ensuring sustainability and eco-friendliness within associated tourism service processes. In essence, the promotion and utilisation of clean energy will play a pivotal role in achieving carbon neutrality objectives within the Travel & Leisure sector.

There existed a close interrelationship between the clean energy stock and the U.S. travel & leisure market, particularly in terms of alternative energy demand, shared emphasis on sustainable development, and environmental impact. Firstly, the increase in clean energy investments could provide a more stable, economical, and environmentally friendly energy supply for the tourism industry, thereby promoting sustainable tourism development. This point was particularly important for investors, as clean energy investments could not only reduce the operating costs of the tourism industry but also improve the environmental quality of tourist destinations, enhance visitor experiences, and ultimately increase the long-term competitiveness and investment returns of the tourism industry. Secondly, there were some common risk channels between the clean energy and tourism industries that were worth investors' attention. For example, extreme weather events could directly impact the tourism industry while also affecting the operation and power generation efficiency of clean energy facilities. Furthermore, policy changes (such as adjustments to subsidy policies) could simultaneously influence the investment environment for both clean energy and tourism industries. Therefore, monitoring and managing these common risks was crucial for investors. Lastly, from a theoretical perspective, changes in clean energy stock risks could affect the performance of tourism industry stocks through multiple channels. On the one hand, an increase in clean energy stock risks might indicate a deterioration in the overall market environment, thereby negatively impacting tourism industry stocks; on the other hand, a decrease in clean energy stock risks could reflect investors' optimistic expectations for the clean energy industry's prospects, which might encourage more capital inflows into the tourism industry, especially for tourism enterprises that focused on sustainable development. In conclusion, the impact of clean energy use on the tourism industry was multifaceted, involving multiple dimensions such as energy supply, environmental quality, and investment risks, making it worthy of in-depth analysis by investors and researchers.

Considering that the clean energy stock and the Tourism and Leisure Industry index represent the development trends and investment prospects of their respective industries, studying the relationship between these two indices was particularly important for investors in these sectors. On the one hand, the performance of the Clean Energy Index might have affected the cost structure and profitability of the tourism and leisure industry, subsequently influencing the trends of the Tourism and Leisure Stock Index. On the other hand, the development of the tourism and leisure industry could have driven the demand for clean energy, thereby affecting the performance of the Clean Energy Stock Index. Therefore, a thorough understanding of the dynamic relationship between these two indices helped investors better grasp investment opportunities, optimise investment portfolios, and control investment risks.

Lastly, environmental impact constitutes a significant facet linking these two markets. Prior research suggests that the growth propelled by the tourism industry often comes at the cost of environmental degradation, as tourism-related activities necessitate higher energy consumption (Irfan et al., 2023). The proliferation and use of clean energy mitigate environmental harm, yielding positive effects on the Travel & Leisure market (Tian et al., 2021). This can be attributed to the concentration of tourism activities in natural landscapes and cultural heritage sites, where minimising environmental harm aids in preserving these sites' pristine conditions and offering enhanced experiences for tourists.

While both the clean energy market and the U.S. Travel & Leisure market have garnered significant attention in various realms, research into the dynamic relationship between these two markets remains relatively unexplored. Our research motivation lies in checking the risk-dependence function between the clean energy market and the U.S. Travel & Leisure indices. Specifically, our study contributes by employing robust estimation methods to examine the cross-quantile risk predictability between the clean energy market and the U.S. Travel & Leisure market, thus enriching the existing literature. In summary, the primary research questions are as follows: (1) How does the cross-quantile correlation between the clean energy market and the U.S. Travel & Leisure market vary? (2) Is there cross-predictability in risk between specific clean energy assets and U.S. Travel & Leisure market assets, and how does their time-varying dependency pattern manifest? (3) How does the risk-dependence structure evolve under different market conditions and investment horizons? This form of analysis provides useful insights for investors and policymakers, assisting in formulating robust economic policies and enhancing opportunities for diversification of clean energy and tourism-related assets.

This paper made some contributions to the current literature, which were not only theoretically significant but also had practical application value. First, we pioneered the investigation of the risk dependence structure between the clean energy industry and the U.S. tourism and leisure index, filling a gap in the literature. This research helped investors and policymakers gain a more comprehensive understanding of the risk transmission framework between clean energy and the tourism industry, providing an important reference for formulating investment strategies and industrial policies. Second, we innovatively applied the cross-quantile approach to explore the interdependence and predictability between the clean energy industry and the U.S. tourism and leisure index. Compared to traditional linear correlation analysis, the cross-quantile diagram could better capture the nonlinear and asymmetric dependency relationships between financial assets. The application of this method not only expanded the research perspective of the existing literature but also provided investors with a new risk management tool, helping them make wiser decisions in a complex and volatile market environment. Third, we considered the risk dependence at heterogeneous time scales, namely short-run, medium-run, and long-run, to reflect the heterogeneous preferences of investors. This segmentation helped different types of investors (such as arbitrageurs, hedgers, mutual funds, etc.) choose appropriate investment strategies according to their investment horizons and risk preferences (Mensi et al., 2023), thereby improving investment efficiency and controlling investment risks. Fourth, this research applied the recursive cross-quantile dependence method to investigate the dynamic evolution characteristics of the cross-quantile dependence relationship between the clean energy industry and the U.S. tourism and leisure index. This analysis not only deepened our understanding of the risk transmission mechanism between the two industries but also provided new ideas for risk management under extreme market conditions. Investors could dynamically adjust their investment portfolios based on the findings of the recursive process to cope with changes in the market environment. Fifth, we found that there existed significant heterogeneous dependence relationships between the clean energy stock and the U.S. tourism and leisure index, indicating that their responses to market shocks differed. This finding had important implications for policymakers. Policymakers could formulate differentiated regulatory measures and industrial policies based on this characteristic to promote the balanced development of clean energy and the tourism sector, enhancing the stability and sustainability of the economy.

Consequently, the present research has not merely deepened the theoretical comprehension of the risk interdependence betwixt clean energy and the tourism sector but has also furnished invaluable pragmatic perceptions for both investors and policymakers alike. The investigative methodologies and deductions drawn from this study could be straightforwardly utilised in portfolio administration and risk management, thereby assisting investors to attain superior investment outcomes within complex and volatile market conditions. Furthermore, our investigation provided fresh viewpoints for governmental bodies in terms of devising industrial strategies and supervisory procedures, thus contributing to the sustainable progression of both the clean energy and tourism industries whilst simultaneously realising a mutually beneficial scenario for economic development and environmental conservation. Furthermore, our research framework and methods could be extended to other industries and markets, providing references for risk management practices in broader fields. We believe these contributions will positively impact both academia and industry, promoting the continuous deepening and development of research and practice in related areas.

Our research findings can be summarised as follows: (1) Under market stability conditions, there exists a significant positive correlation among the clean energy indices and the U.S. Travel & Leisure index. (2) The U.S. Travel & Leisure index becomes less sensitive to mid and long-term fluctuations from the clean energy market. (3) In the extreme tail, specific clean energy indices and the U.S. Travel & Leisure industry exhibit heterogeneous correlation. (4) From a time-varying insight, the clean energy sector and the U.S. Travel & Leisure index generally present a positive correlation in extreme down-market situations throughout the sample period.

Regarding its impact on investors, the study's observed temporal changes in cross-quantile dynamics and static risk dependencies indicate that portfolio managers should consider the risk characteristics of different sub-indices when formulating relevant diversification strategies. This is especially important during potential crisis periods to enhance the additional value of portfolio diversification. It's important to note that the risk dependencies with intermediate and long-term lags reflect a weakening in risk transmission at these frequencies. As a result, this holds significant advantages for investors who adhere to mid-term and long-term strategies, including fund managers.

From the perspective of policymakers, their focus often revolves around preventing and controlling the spread of risk among asset categories. Our findings demonstrate that during periods of financial stability, monitoring the volatility between the clean energy index and the U.S. Travel & Leisure index will be particularly essential. Specific targeted regulatory policies should be implemented as necessary. Moreover, during a bullish trend in the clean energy sector, efforts to maintain financial stability are expected to yield even better results.

Overall, our study provided new perspectives and insights for investors, policymakers, and the academic community. For investors, a deep understanding of the risk dependency structure between the clean energy sector and the U.S. tourism and leisure index aided in optimising investment decisions and controlling investment risks. For policymakers, our research emphasised the importance of coordinating clean energy and tourism development policies to address the impacts of economic cycles and extreme events. For the academic community, our study offered new approaches and methods for further exploring cross-market linkages between different asset classes. Future research could build on our work to analyse the risk transmission mechanisms between clean energy and tourism in other countries or regions and examine the implications of these linkages for macroeconomic and financial stability.

The structure of this article was organised as follows: In Section 2, an extensive review of the literature was provided, exploring previous studies in the area. Section 3 detailed the methodologies used and described the dataset employed for analysis. Subsequently, Section 4 thoroughly analysed the empirical results and summarised their significant implications. Finally, the conclusions were provided in Section 5.

2. Literature review

Aligned with the primary objectives of this study, we reviewed literature on three central themes: (1) the dynamic interplay between the clean energy market and financial markets; (2) the interactions between the Travel & Leisure market and financial markets; and (3) the connection between clean energy indices and the Travel & Leisure industry.

2.1. Dynamic connection between the clean energy indices and financial markets

Recent trends have shown a boost in financial investments in the clean energy market. As an environmentally sustainable energy form, clean energy has garnered widespread investor attention and interest (Y. Wang, Liu, et al., 2024). This investment growth phenomenon has manifested across various levels, including expanded capital inflows, diversified investment strategies, and innovative financial instrument applications.

Ghosh (2022) investigated the impact of COVID-19 on the performance of three prominent stocks within the clean energy industry. This study acknowledged the escalating necessity of addressing clean energy concerns in light of geopolitical interdependencies. Madaleno et al. (2022) undertook an analysis of the correlations among the assets of green finance and environmental responsibility. The outcomes of their research substantiated notable impacts among these variables. Specifically, the advent of the COVID-19 pandemic led to a reduction in financial market investments directed towards green technology and clean energy.

In a study by Wang et al. (2022), significant progressions within the clean energy sector were documented. The augmentation of carbon quota trading systems and the issuance of green bonds were identified as effective measures for curtailing emissions. Employing a DCC-MIDAS model, the researchers explored the dynamic interrelationships among clean energy and green bonds. The investigation disclosed intricate connections among these markets. The fluctuation between positive and negative trends within the sample timeframe showcased the intricate nature of this interplay. The influence of financial market turbulence, particularly during the COVID-19, was likely to magnify network connections.

2.2. Interaction between the travel & leisure market and financial markets

As the global economy progressed and the tourism industry thrived, the domain of Travel & Leisure evolved beyond conventional cultural experiential activities, transforming into a multifaceted sector spanning various domains. Consequently, its interaction with financial markets adopted a multifarious and intricate nature (Kumar, 2023). Kumar's (2023) research elucidated that the influence of uncertainty variables on Travel & Leisure assets was primarily pronounced in the lower quantiles. Bashir and Kumar (2022) found the heightened responsiveness of Travel & Leisure stock returns to both investor attention uncertainty.

2.3. Linkage among the clean energy market and travel & leisure market

The limited research that focuses on the connection between the clean energy asset and the Travel & Leisure market has revealed certain facts, further confirming the existence of a research gap in this area. Calderón-Vargas et al. (2021) discovered that most renewable energy studies primarily concentrated on sectors such as hotels and transportation, despite their modest scale, due to high energy consumption. They highlighted the necessity of harnessing abundant wind and solar energy resources to establish renewable energy power plants. Gyamfi et al. (2022) selected the E7 economies to explore the connection between tourism and pollutant emissions, as these economies have emerged as major global tourist destinations. The study found that the increase in environmentally friendly tourism activities reduced CO2 emissions in E7 countries.

Existing literature has provided limited insights into exploring the link between the clean energy sector and the Travel & Leisure market, particularly the interrelation between the clean energy industry and the U.S. Travel & Leisure market. In order to fill this research gap, this research delves into the in-depth examination of the reciprocal impact of risk among the clean energy indices and the U.S. Travel & Leisure market during the period from 2014 to 2022.

3. Methodology and data

3.1. Volatility construction

In our study, the conditional variance produced by the GARCH (1,1) function was applied to undertake our empirical investigation (Zeng, Xu, et al., 2024). This method of variance construction was also effective in addressing the issue of heteroskedasticity in returns. For the purposes of this analysis, it is assumed that the stock price from market i at time t was $S_{i,t}$. Then, the conditional variance with one step ahead of GARCH (1,1) is constructed as,

$$\frac{ln(S_{i,t})}{ln(S_{i,t-1})} = \mu_i + \epsilon_{i,t}$$

$$\epsilon_{i,t} \sim N(0, \sigma_{i,t}^2) \tag{1}$$

$$\sigma_{i,t}^2 = \alpha_0 + \alpha_1 \epsilon_{i,t-1}^2 + \beta_1 \sigma_{i,t-1}^2$$

Where μ_i is the mean, $\sigma_{i,t}^2$ points out the asset i's volatility of conditional at period t, $\epsilon_{i,t}$ denotes the i.i.d error function of the asset i at time t. They are set to be following normal distribution with zero and variance in mean, $\sigma_{i,t}^2$.

3.2. Cross-quantilogram (C-Q) method

The cross-quantilogram (C-Q) technique, pioneered by Han et al. (2016), involves the analysis of interdependence and transmission between two variables at stable levels across discrete conditional quantiles.

The quantile-hit of the C-Q, as introduced by Han et al. (2016), is presented as follows:

$$\rho_a(k) = \frac{E[\Phi_{a1}(x_{1,t} - q_1(\alpha_1))\Phi_{a2}(x_{2,t-k} - q_2(\alpha_2))]}{\sqrt{E[\Phi_{a1}^2(x_{1,t} - q_1(\alpha_1))]}\sqrt{E[\Phi_{\alpha2}^2(x_{2,t} - q_2(\alpha_2))]}} \tag{2}$$

At various time lags denoted by variable $k = 0, \pm 1, \pm 2, \cdots$, the focus was on the variable $\Phi_{\alpha_i}(x_{i,t} - q_{i,t}(\alpha_i)) = 1[x_{i,t} < q_{i,t}(\alpha_i)] - \alpha_i$, while the quantile hit process was depicted as $x_{i,t} - q_{i,t}(\alpha_i)$. Simultaneously, the delineation of the quantile-based C-Q dependency was presented by $\rho_a(k)$.

Furthermore, we gauged the Cross-Quantilogram (CQ) at two distinct quantile levels, with $\alpha = (\alpha_1, \alpha_2)$ representing the index 1 of α, pertaining to all the volatilities of Clean Energy indices. Index 2, on the other hand, indicated the volatilities of the Dow Jones Travel & Leisure index. The parameter α captured their cross-correlation for quantiles above and below as $q_l(\alpha_l)$ at time t, along with the volatility data of the Dow Jones Travel & Leisure index for quantiles above or below as $q_j(\alpha_j)$ at time t+1. Therefore, if the condition satisfied Eq. (1) = 0, no predictability or time-lag effect was discerned between the two time-series of volatility of $\alpha_i = q_i(\alpha_i)$.

Conversely, it could be asserted that lagged directional predictability endured if Equation Eq. (1) $\neq$ 0 demonstrated a non-zero outcome:

$$\hat{\rho}_a(k) = \frac{\sum_{t=k+1}^{T} \Phi_{a1}\left(x_{1,t} - q_1(\alpha_1)\right)\Phi_{a2}\left(x_{2,t-k} - \hat{q}_1(\alpha_1)\right)}{\sqrt{\sum_{t=k+1}^{T} \Phi_{\alpha1}^2\left(x_{1,t} - \hat{q}_1(\alpha_1)\right)}\sqrt{\sum_{t=k+1}^{T} \Phi_{\alpha2}^2\left(x_{2,t-k} - \hat{q}_2(\alpha_2)\right)}} \tag{3}$$

In above Equation, $\hat{q}_i(\alpha_i)$ signifies the unconditional sample quantile of $x_{i,t}$. As elucidated by Equation 2, the Cross-Quantilogram (C-Q) characterises the lead-lag quantile dependence from one time series ($x_{2,t}$) to another time series ($x_{1,t}$) for a specified quantile pair (α_1, α_2). This assessment measures the directional predictability as ($x_{2,t}$) approaches ($x_{1,t}$) via $\rho_\alpha(k)$.

Moreover, an additional consideration, with $H_0{:}\rho_a(k) = 0$ contrasted $k = 1, 2, \cdots, p$ against H_1: $\rho_\alpha(k) \neq 0$ based on $\rho_\alpha(k)$, leads to the formulation of the quantile version of the Ljung–Box test:

$$\hat{Q}_a^{(p)} = \frac{T(T+2)\sum_{k=1}^{p} \hat{\rho}_a^2(k)}{T-k} \tag{4}$$

3.3. Granger-causality in quantiles

We employed the novel Granger-causality in quantiles approach, as developed by Troster (2018), to assess Granger-causality across quantiles. This methodology possesses the capability to observe specify-quantile Granger-causality relationships. Let $\mathcal{F}_{t-1}^{Y} = \{Y_{t-1}, Y_{t-2}, \ldots, Y_{t-p}\}$ and $\mathcal{F}_{t-1}^{X} = \{X_{t-1}, X_{t-2}, \ldots, X_{t-p}\}$ represent the historical information sets of Y_t and X_t, respectively. Our objective was to examine the null hypothesis that X_t does not exert Granger-causal influence on Y_t, formulated as $F_Y(w \mid \mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{X}) = F_Y(w \mid \mathcal{F}_{t-1}^{Y})$ for all $w \in \mathbb{R}$.

where $F_Y(\cdot \mid \mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{X})$ is the conditional distribution of Y_t given.

$\mathcal{F}_{t-1} = (\mathcal{F}_{t-1}^{Y}, \mathcal{F}_{t-1}^{X})'$. Let $q_Y^\tau(\cdot \mathcal{F}_{t-1})$ be the τ-quantile of $F_Y(\cdot \mathcal{F}_{t-1})$. Then, $\Pr\{Y_t \leq q_Y^\tau(Y_t|\mathcal{F}_{t-1})|\mathcal{F}_{t-1}\} = E\{1(Y_t \leq q_Y^\tau(Y_t|\mathcal{F}_{t-1}))|\mathcal{F}_{t-1}\}$, for an parameter function $1(\cdot)$ so that we may define Eq. (4) as,

$$H_0{:}E\{\psi_\tau(Y_t - m_\tau(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau)))|\mathcal{F}_{t-1}\} = 0, \text{ for all } \ \tau \in (0, 1), \tag{5}$$

where $m_\tau(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau))$ is a parametric modelling of $q_Y^\tau(|\mathcal{F}_{t-1})$, $m_\tau \in \mathcal{M} = \{m_\tau(\cdot, \theta(\tau))|\theta(\cdot){:}\tau \mapsto \theta(\tau) \in \Theta \subset R^p$, for $\tau \in Q \subset (0, 1)\}$. As Troster (2018), we can transfer Eq. (4) as:

$$H_0^{X \nrightarrow Y}{:}E\{\psi_\tau(Y_t - m_\tau(\mathcal{F}_{t-1}^{Y}\theta_0(\tau)))\exp(iv'\mathcal{F}_{t-1})\} = 0, \ \text{a.s. for all } \tau \in Q \tag{6}$$

against

$$H_A^{X \nrightarrow Y}{:}E\{\psi_\tau(Y_t - m_\tau(\mathcal{F}_{t-1}^{Y}, \theta_0(\tau)))\exp(i\boldsymbol{v}'\mathcal{F}_{t-1})\} \neq 0, \ \text{for any } \tau \in Q, \tag{7}$$

for a weighting framework $\exp(iv'\mathcal{F}_{t-1}) := \exp[i(v_1(Y_{t-1}, X_{t-1})' + \ldots + v_p(Y_{t-n}, X_{t-n})')]$, for all $v \in \mathbb{R}^n$ with $n \leq p$, and $i = \sqrt{-1}$. Next, we can test the null hypothesis of Eq. (11):

$$G_T(\boldsymbol{v}, \tau) \equiv \frac{1}{\sqrt{T}}\sum_{t=1}^{T} \psi_\tau\big(Y_t - m_\tau\big(\mathcal{F}_{t-1}^{Y}, \theta(\tau)\big)\big) \exp\big(i\boldsymbol{v}'\mathcal{F}_{t-1}\big), \tag{8}$$

where $\theta_T(\cdot)$ is a consistent indicator of $\theta_0(\cdot)$. Then as Troster (2018), we through a functional term of $G_T(v, \tau)$, which has significant power than $G_T(v, \tau)$, for checking $H_0^{X \nrightarrow Y}$ of Eq. (6):

$$S_T := \int_T \int_V G_T(\boldsymbol{v}, \tau)^2 dF_v(\boldsymbol{v}) dF_\tau(\tau), \tag{9}$$

Here, $F_v(\cdot)$ represents a normal distribution of weights, while $F_\tau(\cdot)$ conforms to a uniform distribution across a grid $Q \subset (0, 1)$ consisting of equidistant quantiles. The null hypothesis is refuted when S_T reaches a significant magnitude. To compute the p-values of S_T, we employed the sub-sampling technique established by Troster (2018), utilising a subsample denoted as $b = [5T^{2/5}]$, where $[\cdot]$ corresponds to the floor function.

We utilised the Dow Jones U.S. Travel & Leisure Index (TL) as the benchmark index for the U.S. Travel & Leisure market. This index comprehensively covers representative companies within the tourism-related industries, including aviation, hotel services, dining groups, cruise lines, casinos, and tourism services, among others. Moreover, drawing from relevant prior literature (Ren & Lucey, 2022; Zeng et al., 2023), we selected seven distinct clean energy indices as variables for the clean energy index, with the WilderHill Clean Energy Index serving as the composite benchmark for this market. The definitions and abbreviations for the segmented clean energy indices can be found in Table 1. It should be remarked that, based on the definition of the clean energy indices we utilised, the constituent indicators of these indices primarily originated from U.S. companies.

The sample period extended from June 1, 2013, to May 31, 2023. Data was conducted from DataStream database, and data was denominated in US dollars. Then transformed into continuous compounded returns.

Figure 1 illustrates the time series figures of the daily logarithmic returns for all indices. We observed that the return series for all indices exhibited signs of jumps. Notably, during the shale oil crisis of 2014-2015, there was a noticeable volatility in the returns of FUEL. Additionally, the sample periods corresponding to the initial spread of the COVID-19 in early 2020 and the outbreak of the Russia-Ukraine war in early 2022 saw substantial fluctuations in the return rates of all sequences. These observations indirectly substantiate the sensitivity of the return rates of all indices to unfavourable market conditions.

4. Empirical results

Table 2 provides the summary statistics of all indices returns. Concerning daily average returns, except for the BIO returns, the mean daily return rates for all variables were positive. The estimated standard deviations indicate significant price volatility, particularly given the inclusion of the COVID-19 period in our sample, which seems reasonable. Furthermore, we observed that all variables, except for GEO, FUEL, and BIO returns, exhibited significant negative skewness. The kurtosis values for all series considered in this study exceeded three, implying smoother tails for the series of the studied variables. We employed the Jarque-Bera (JB) test to check the normality assumption of the return series for all indices. We rejected the normality null hypothesis at the 1% significance level for all studied series. To test the stationarity of all studied assets, we conducted the ERS stationarity check. The results indicated the stationarity of our return data. Prior to conducting empirical analysis, we transformed the return data into volatility data using the GARCH(1,1) model, as we aimed to provide insights into managing financial market risks for investors and policymakers.

Figure 2 presents a heatmap depicting the cross-risk correlations among clean energy indices and the TL. We set three different lag lengths of 1, 5, and 22 days, corresponding to short-,

Table 1. Variables Definition of Clean Energy Index.

Abbr.	Index name	Definition
WILDER	WilderHill Clean Energy Index	WILDER observed the leading clean energy companies that were listed on the NASDAQ exchange.
BC	NASDAQ OMX Bio/Clean Fuels Index	BC tracked the financial performance of firms involved in producing plant-based fuels.
RE	NASDAQ OMX Renewable Energy Index	RE aimed to assess the performance of firms operating within the renewable energy generation industries, including technologies such as solar and fuel cells.
GEO	NASDAQ OMX Geothermal Index	GEO tracked the financial performance of companies involved in the geothermal power generation sector.
FC	NASDAQ OMX Fuel Cell Index	FC aimed to evaluate the company's financial performance within the fuel cell energy sector.
SOLAR	NASDAQ OMX Solar Index	SOLAR tracked the company's financial performance in the solar energy generation sector.
WIND	NASDAQ OMX Wind Index	WIND assessed the performance of firms involved in energy generation via wind power.

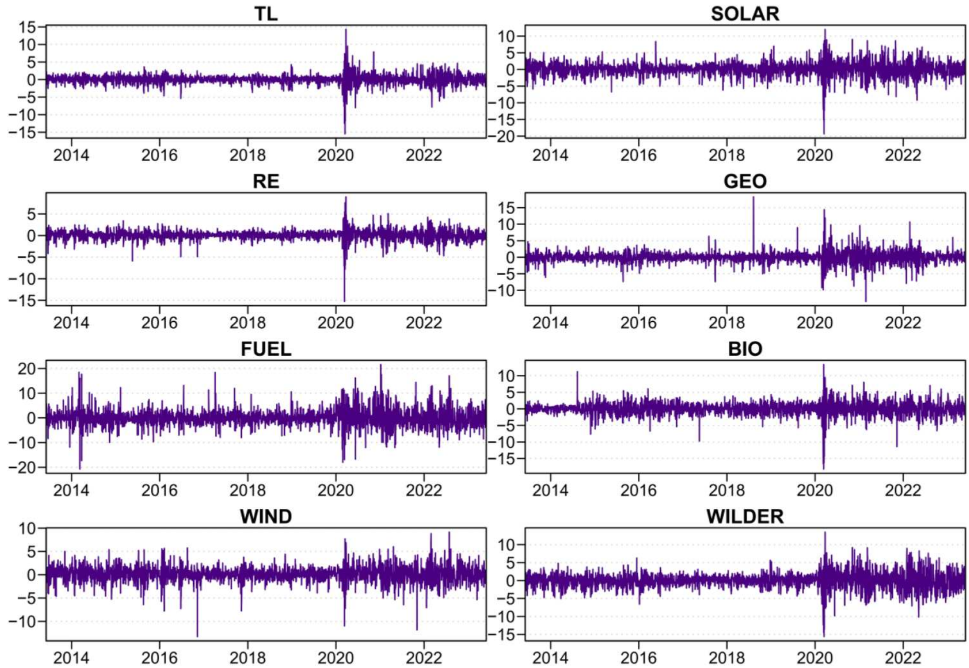


Figure 1. Dynamic of return plot.

medium-, and long-terms investment perspective. This was done to ascertain the duration and strength of cross-quantile risk correlations between indices. This consideration was motivated by the recognition that investor responses to market risks are heterogeneous and time dependent. Thus, different lag lengths facilitated investor observation of risk dependence patterns and the interpretation of asymmetry. Subsequently, we used the Ljung–Box test to assess the significance level of C-Q.

4.1. Cross-quantile correlation between clean energy markets and the U.S. travel and leisure index

Initially, our attention was drawn to the prominent area of red (indicating high correlation) along the diagonal lines of clean energy indices and the TL in Figure 2. This observation was particularly pronounced around the centre of the plot, implying a close and statistically significant risk dependence relationship along the diagonals. In other words, under normal market conditions, there was a heightened co-movement of risks between clean energy indices and the U.S. Travel & Leisure market. Additionally, it's noteworthy that the most substantial cross-risk dependence between clean energy indices and the U.S. Travel & Leisure market appeared in the first-order lag diagonal of the heatmap (deepest red). We observed that the first-order lag exhibited a more pronounced risk correlation than the lag period (with the red colour fading). This indicates that within a day's time, there was a highly correlated risk between clean energy indices and the TL. However, over time (as the lag length increased), the impact of their risk shocks gradually diminished due to market absorption, leading to a reduction in correlation.

Continuing our examination of the risk cross-correlations between specific clean energy indices and the TL (Travel & Leisure) index in Figure 2, we noted that the correlations between GEO, SOLAR, WIND, and TL dissipated in longer lag ranges (lags greater than or equal to 5) and extreme quantiles (manifested as lighter shades of red). This observation suggested a shorter duration of risk impact from these three segmented clean energy indices on the TL. Furthermore, in

Table 2. Summary statistics.

	TL	WILDER	WIND	SOLAR	RE	GEO	FUEL	BIO
Mean	0.030693	0.011065	0.053959	0.080176	0.042959	0.021599	0.031651	−0.004776
Median	0.070117	0.079777	0.060559	0.117499	0.085815	0.084593	−0.07249	0.031032
Maximum	14.31995	13.50273	9.153988	12.05131	8.931169	18.25436	21.61643	13.3931
Minimum	−15.47842	−15.6373	−13.28265	−19.33261	−15.25843	−13.39072	−20.74577	−18.19581
Std. Dev.	1.434297	2.209097	1.702922	2.122463	1.162653	1.771471	3.557571	1.983858
Skewness	−0.788147	−0.340058	−0.379425	−0.521767	−1.102322	0.42991	0.365727	−0.866245
Kurtosis	20.54985	7.534796	8.101711	9.368071	20.62965	15.25931	7.236374	13.30719
Jarque-Bera	31966.71***	2164.898***	2739.033***	4287.317***	32500.34***	15549.8***	1902.864***	11247.13***
ERS	−21.314***	−13.504***	−17.200***	−20.578***	−19.847***	−11.804***	−21.824***	−20.667***

Note: ***,**,* present significance at 1%, 5% and 10% level. ERS: Elliott-Rothenberg-Stock unit root test.

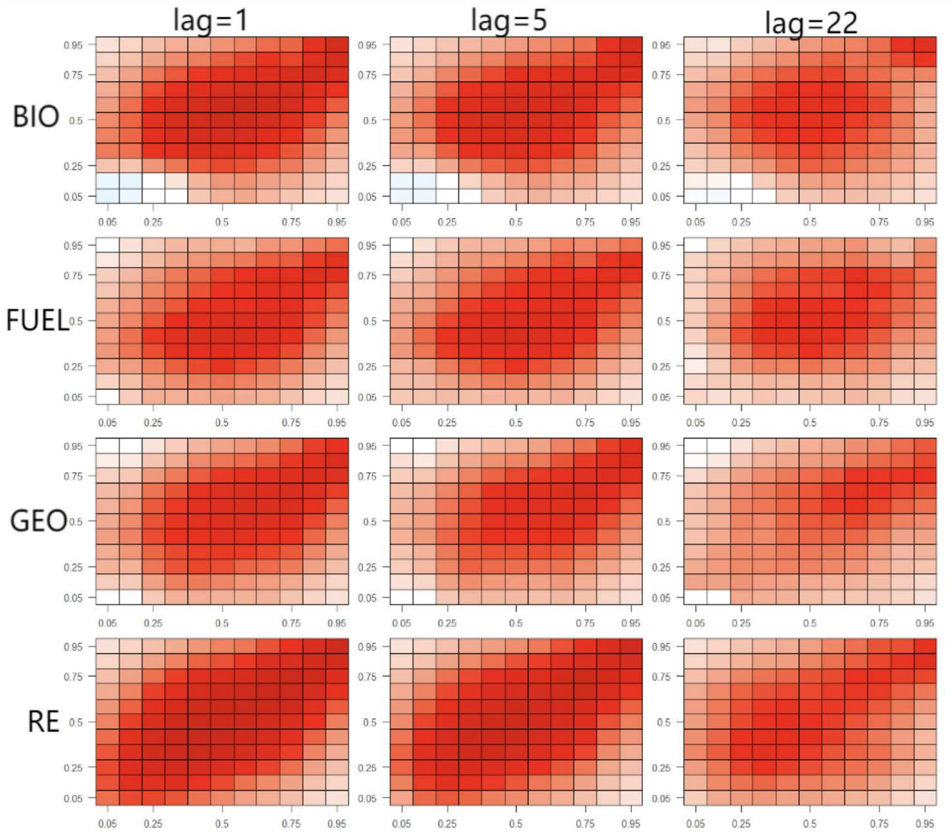


Figure 2. Heatmap of cross-risk correlations between the clean energy market and the U.S. travel and leisure market.

Note: Figure 2 depicts the Cross-Quantilogram (C-Q) through a heatmap representation, wherein darker red hues signify heightened positive correlations, and deeper blue shades indicate intensified negative correlations. Quartile levels devoid of observable directional predictability are designated with a zero value (white). Bounded by rectangles are predictable areas where the Box-Ljung statistic attains statistical significance. In every heatmap, the vertical axis denotes the quantile level of the segmented Clean Energy Index, while the horizontal axis signifies the quantile level of the U.S. Travel and Leisure Index. Lag1, Lag5, and Lag22 represented lags of one day, one week (typically consisting of five trading days), and one month (typically consisting of 22 trading days), respectively.

the face of extreme uncertainty in the market, they exhibited low or no correlation with the TL. Another scenario emerged for BIO and FUEL, where the risk correlation with the TL showed disconnection or negative correlation under extreme market conditions. This evidence indicated the diversification benefits of BIO and FUEL investments in the TL.

To be specific, for lag periods greater than or equal to 5 (representing medium to long-term investment horizons), a negative correlation was present between BIO and the TL under extreme bearish conditions. This suggests that during extreme bear markets, the biotechnology market and the U.S. Travel & Leisure industry became unrelated. This is attributed to reduced tourism demand during economic downturns, causing a decrease in the demand for biotechnology, such as ethanol, which is predominantly utilised as an energy source in the functioning of the tourism industry. The halt in the tourism sector led to a significant decrease in its demand for biotechnology (Ghoddusi, 2017; Sajid, 2021).

Last but not lease, through observations from Figure 2, we discerned that in the case of FUEL and GEO at extreme quantile levels, corresponding to extreme bearish market conditions with the U.S. Travel & Leisure index, our findings presented evidence of non-correlation between these markets. Concerning the cross-quantile graph, overall, our empirical results reported a higher correlation between clean energy indices and the U.S. Travel & Leisure index when market conditions

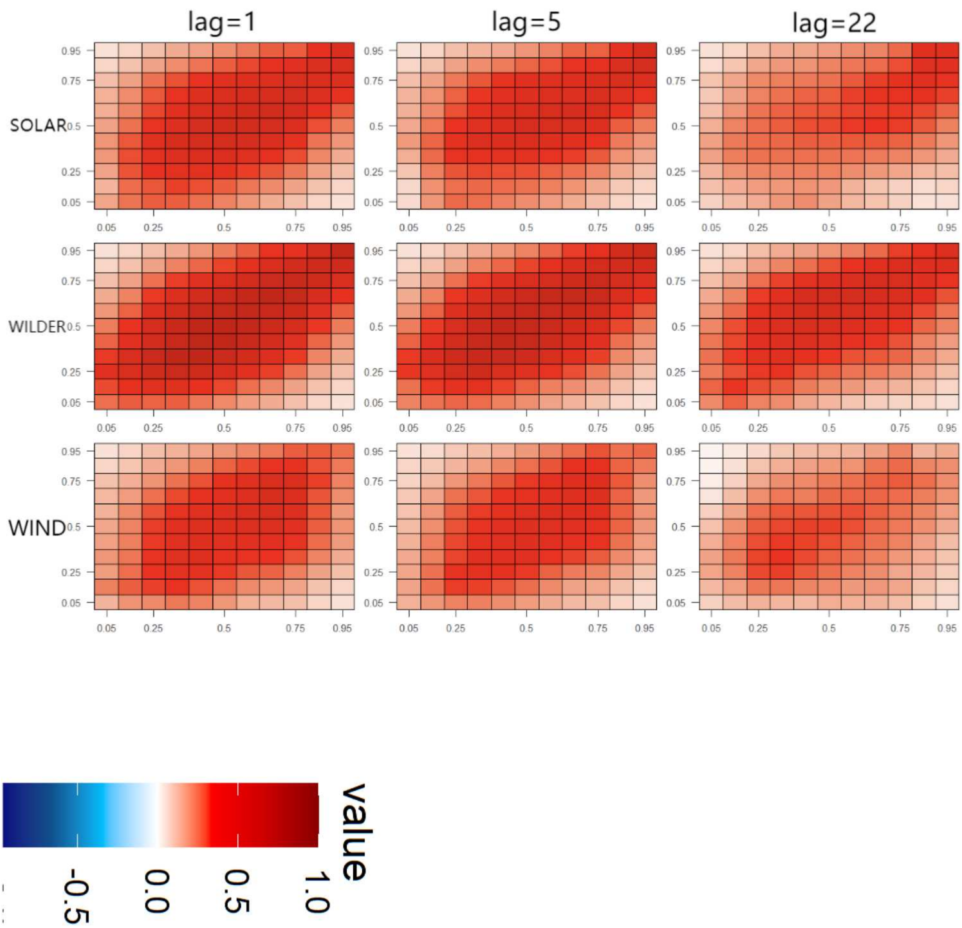


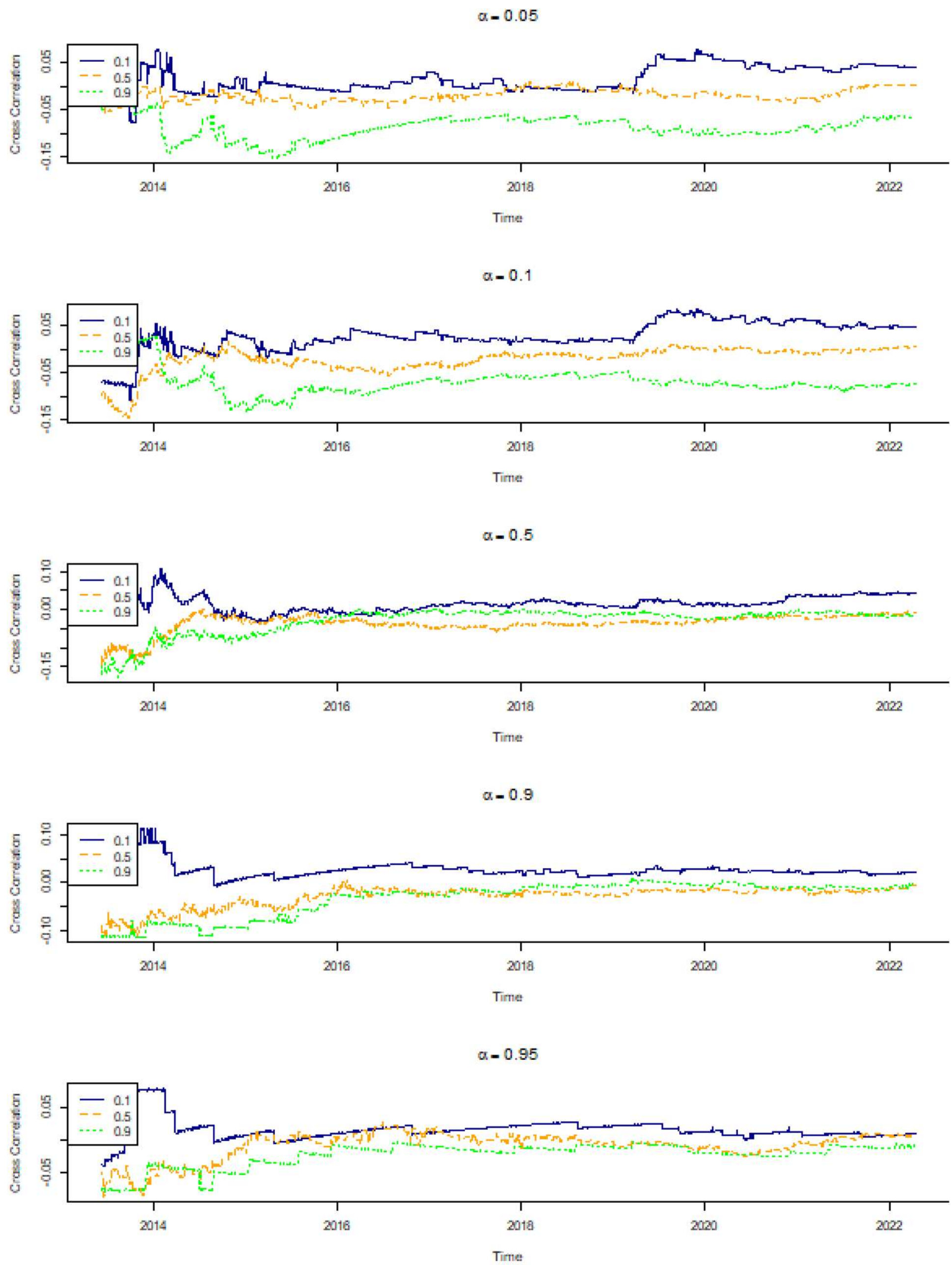
Figure 2 *Continued*

were stable, with few exceptions. However, in the extreme tails, the correlation between specific clean energy stocks and the U.S. Travel & Leisure index displayed heterogeneity.

4.2. Recursive cross-quantile between clean energy markets and the U.S. travel and leisure index

Figure 3 shows the recursive cross-quantile risk dependence among the segmented clean energy indices at lower quantiles (0.1; blue), middle quantiles (0.50; orange), and upper quantiles (0.9; green) concerning the TL index. This addresses the limitations of the previous two-dimensional cross-quantile graph, allowing for an examination of dynamic relationships between variables. In other words, Figure 3 displays the time-varying characteristics using a rolling window with lagged full samples, indicating the evolving risk correlations between TL and the clean energy market under different market conditions. Our subsequent analysis follows the pattern provided by Tiwari et al. (2023).

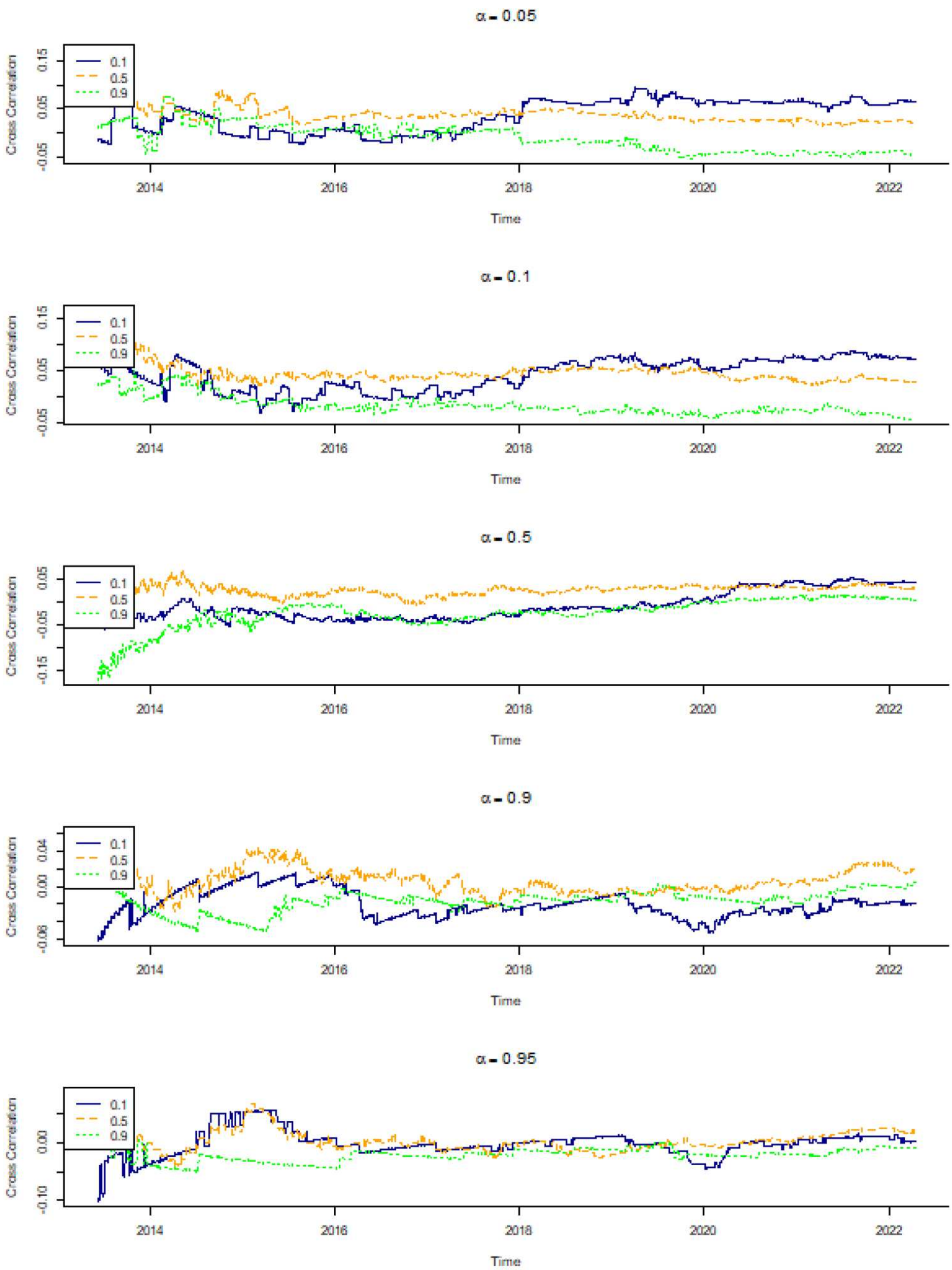
In Figure 3, we observe that TL exhibits the highest correlation with segmented clean energy indices at the median (0.5), indicating that correlation is not symmetric across quantile levels. From a time-domain perspective, post-2016, at all quantile levels, TL is positively correlated with the low quantile (0.1) CQ of segmented clean energy indices. A plausible interpretation of this



(a) TL-BIO

Figure 3. Recursive CQ (cross-quantilogram) analysis between clean energy indices and the US Travel & Leisure index. (a). TL-BIO; (b); TL-FUEL; (c). TL-GEO; (d). TL-RE; (e). TL-SOLAR; (f). TL-WILDER; (g) TL-WIND.

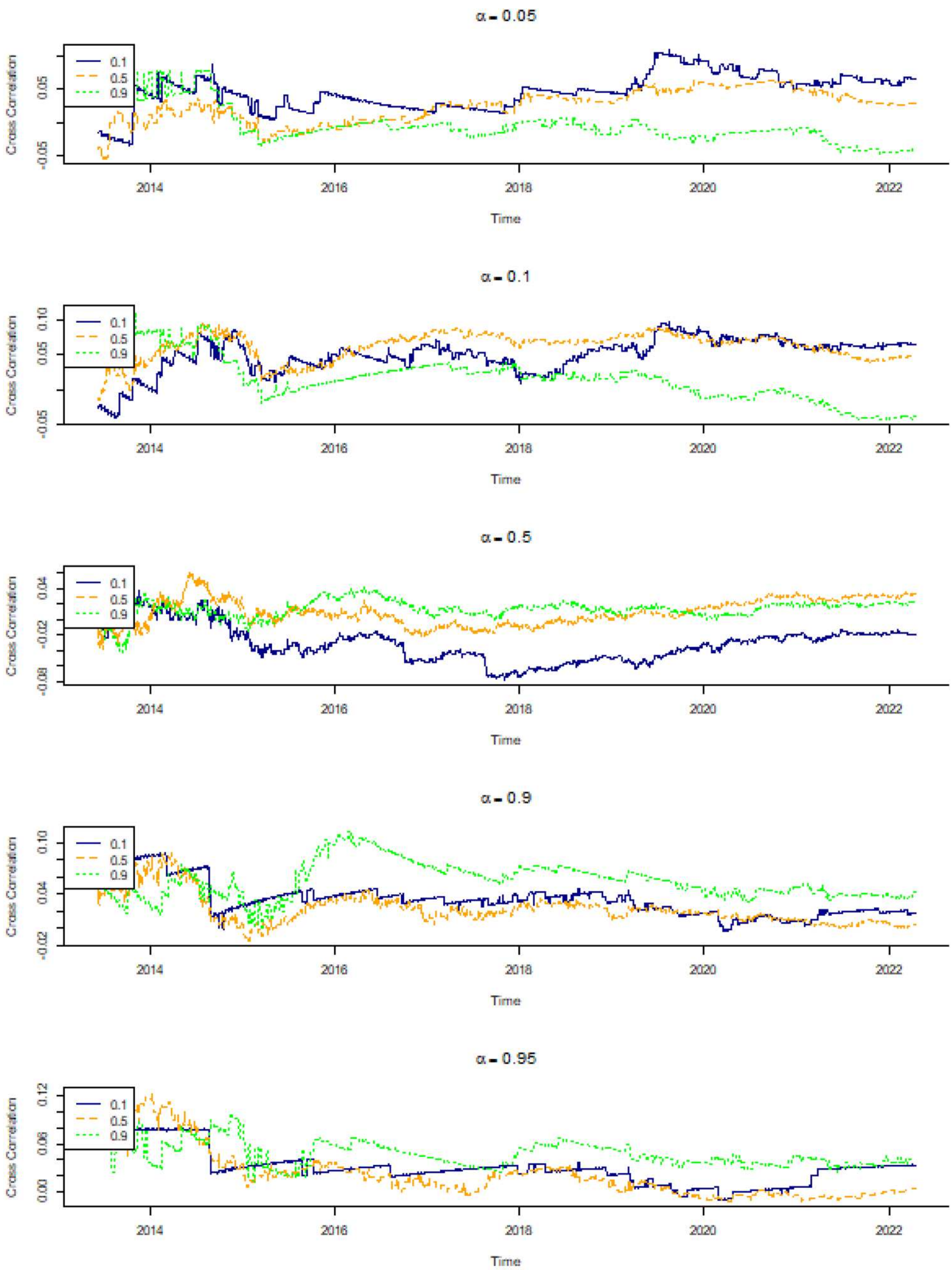
Note: The recursive Cross-Quantilogram (CQ) analysis conducted from the U.S. Travel & Leisure index towards the segmented clean energy indices is denoted by labels (a)-(g). The vertical (horizontal) axis denotes the quantile divisions of specific clean energy indices (time). The starting years of the rolling windows are indicated along the horizontal axis. The columns on the left, in the middle, and on the right respectively present the 5%, 10%, 50%, 90%, and 95% quantiles of the U.S. Travel & Leisure index. The red, blue, and green lines correspondingly represent the 10%, 50%, and 90% quantiles of the clean energy indices, with these settings based on research by Tiwari et al. (2023). The lag parameter, denoted as *p*, is fixed at 1.



(b) TL-FUEL

Figure 3 *Continued*

finding is that even during significant market crises, their high correlation remains unaffected, warranting vigilance among investors and policymakers regarding such interlinkages. Notably, during this period, significant events, such as the United States' withdrawal from the Paris Climate Agreement in 2017, triggered uncertainty in clean energy investments and market prospects. The outbreak of COVID-19 in early 2020 and the subsequent lockdowns severely impacted tourism, aviation,



(c) TL-GEO

Figure 3 *Continued*

hospitality, and other leisure-related industries (Dayour & Adam, 2022). Consequently, the findings in Figure 3 also confirm that recent market crisis events predominantly affected the clean energy market, yet regardless of economic circumstances, TL maintained a positive dependency on clean energy. In summary, from a time-varying perspective, TL tends to exhibit a positive correlation

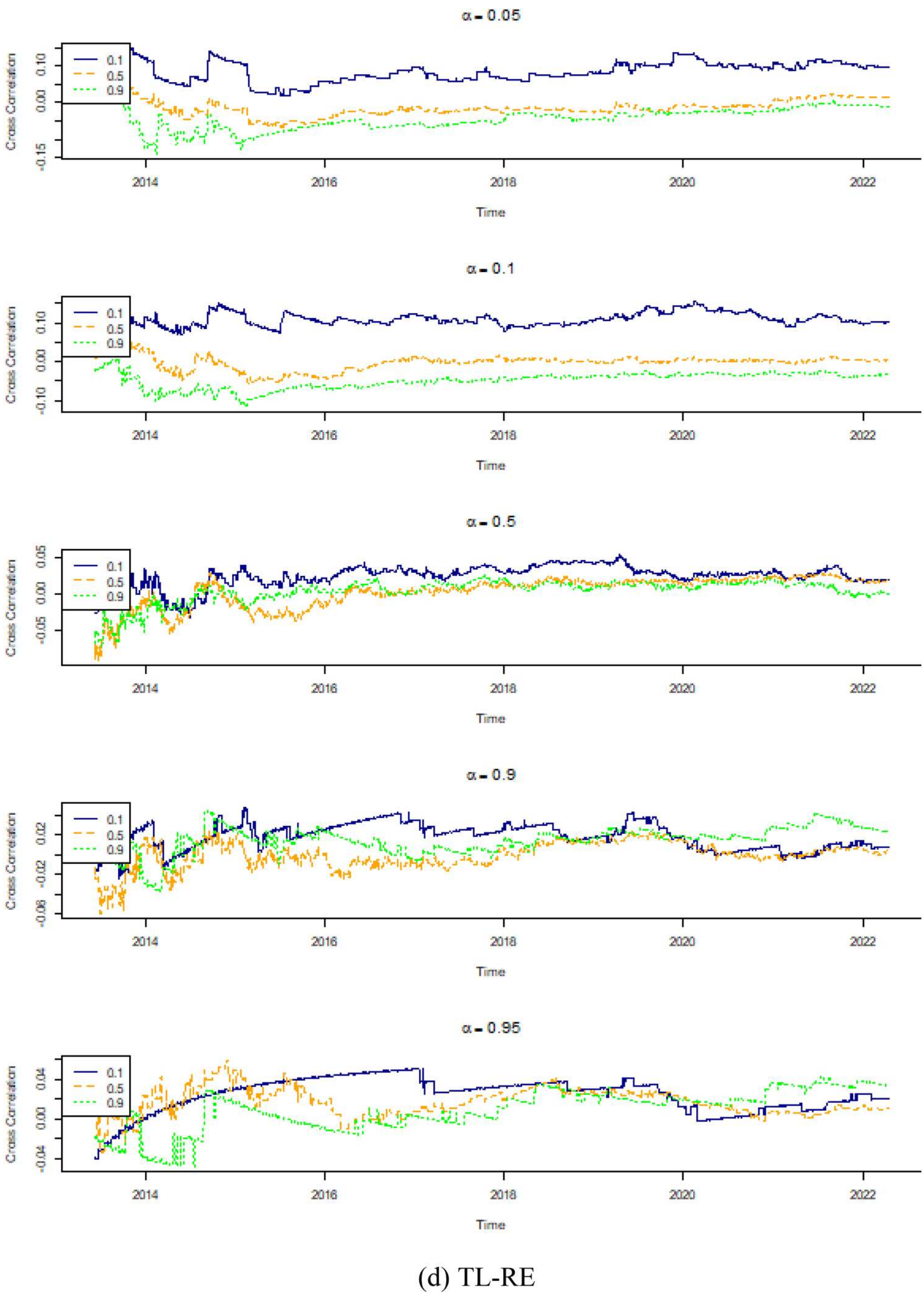
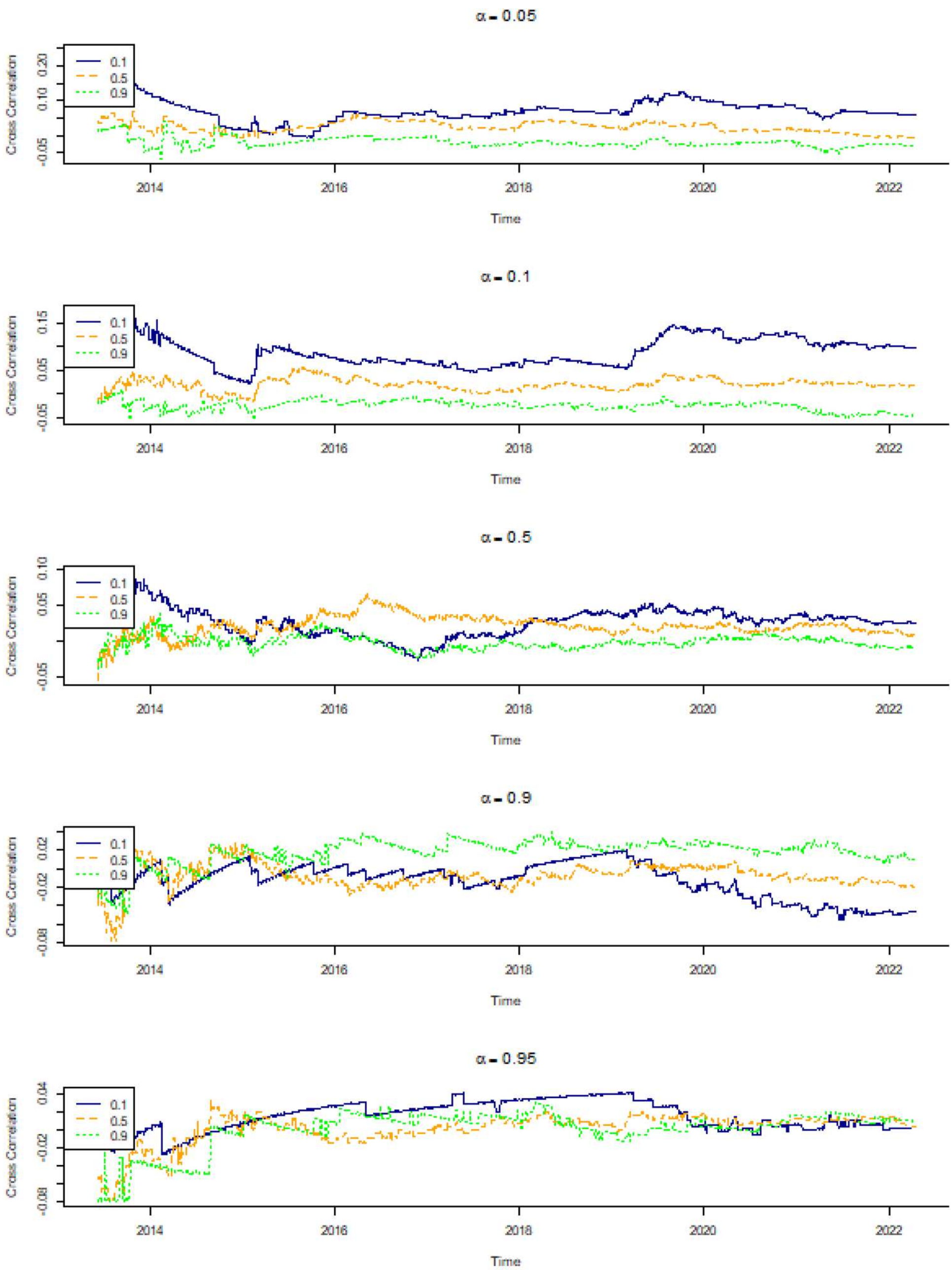


Figure 3 *Continued*

with clean energy indices during most sample periods, particularly when the clean energy index is in an extremely bearish market condition.

However, when BIO, FUEL, RE, SOLAR, and WIND are at the upper quantile of 0.9, and TL is at the lower quantile of 0.1 or 0.05, the CQ correlation between TL and these clean energy indices initially displays a negative correlation at the start of the sample, followed by a steady increase in their

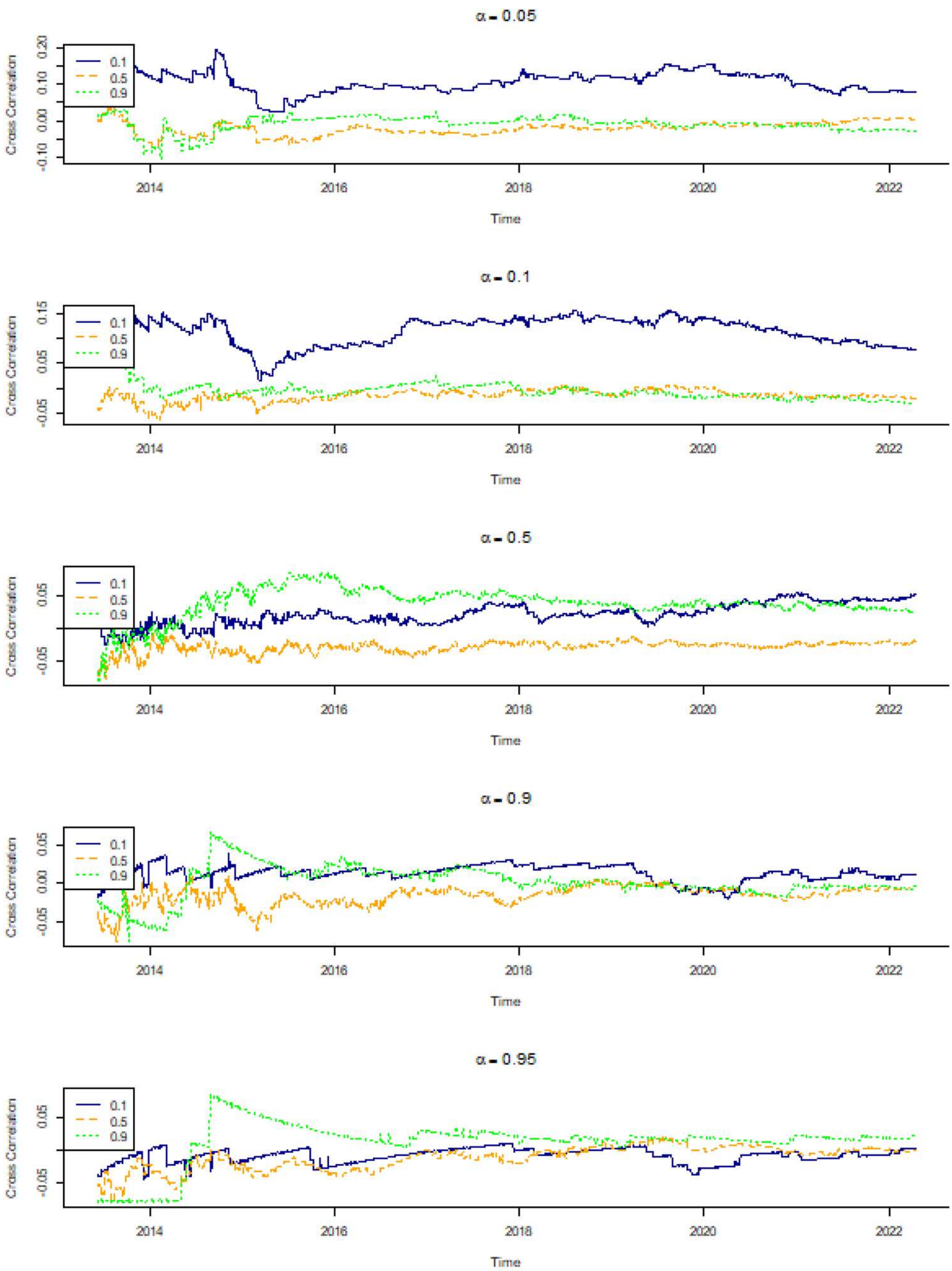


(e) TL-SOLAR

Figure 3 *Continued*

recursive cross-quantile dependency as the sample progresses. These results highlight the diversification potential of the BIO, FUEL, RE, SOLAR, and WIND indices during periods when TL is in a downtrend and they are in an uptrend.

Of note, during the period of the COVID-19 outbreak (early 2020), when TL was in an extreme downturn (0.05 and 0.1 quantiles), an increase in dependency was observed with BIO at the 0.1

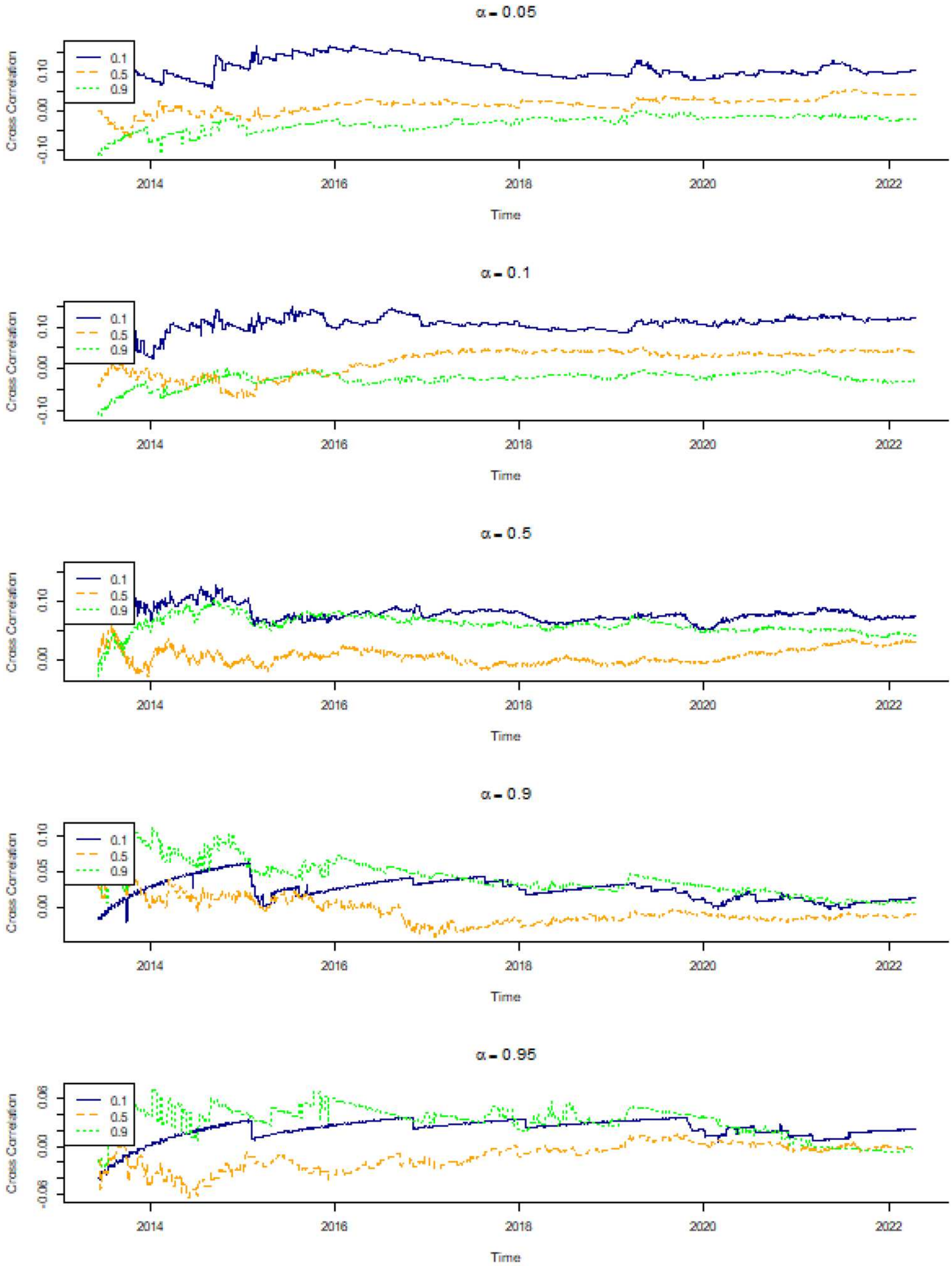


(f) TL-WILDER

Figure 3 *Continued*

quantile. This suggests that the degree of risk dependency between TL and BIO seems to depend on the scale of financial crises and the intensity of risk contagion.

Our empirical findings provide valuable insights for market participants, regulatory bodies, and investors in the clean energy and US Travel & Leisure sectors. The empirical results derived from



(g) TL-WIND

Figure 3 *Continued*

the cross-distribution graphs suggest that the risk correlation among the clean energy market and the US Travel & Leisure market is contingent upon market conditions and timing, while also being heterogeneous and asymmetric.

4.3. Robustness check of granger-causality in quantiles among the clean energy market and the U.S. travel and leisure market

In order to validate the robustness of the previous outcomes and to further expand the estimation of the risk relationship among Clean Energy and the TL index, we conducted a comprehensive validation. Following the method proposed by Troster (2018), we performed a consistent parameter test for quantile Granger causality, aiming to check the Granger-causal dependence between the Clean Energy Index and the TL across different quantile levels of their distributions. Consistent with the approach delineated by Uddin et al. (2023), we utilised this technique to differentiate the Granger-causal relationships in the extreme tails and the median. To be specific, we estimated various quantile levels within Q = (0.05-0.95) range and established quantile autoregressive models (QAR) with a 1-lag under the null hypothesis.

The findings for quantile Granger causality of risk are provided in Table 3. The results outlined in Table 3 denote that the Granger-causal impact of the Clean Energy Index on TL becomes significant when it occurs below the extreme upper quantile (0.95) level, with a significance level of 1%. However, this also implies the absence of a Granger-causal risk dependent between the Clean Energy Index and TL at the extreme upper quantile (0.95). Our research findings substantiated the conclusions put forth by Naeem et al. (2023), as their study evidenced a negative correlation between clean energy and other assets during its extreme downward conditions. Overall, these findings align closely with the previous observations from recursive Cross-Quantilograms (CQ) and cross-quantile plots, particularly in the context of the upper quantiles of Clean Energy, indicating a relatively lower level of risk dependence between Clean Energy and TL.

4.4. Result implications - implications for policymakers and investors

Our empirical findings provided valuable insights for market participants, regulators, and investors in the clean energy and U.S. tourism and leisure sectors. The empirical results derived from cross-distribution plots indicated that the risk correlation between the clean energy index and the TL depended on market conditions and timing, exhibiting heterogeneity and asymmetry. This finding was consistent with previous literature. For instance, Reboredo (2015) found an asymmetric dependency connection between the clean energy market and traditional financial markets, which was more pronounced under extreme market conditions. Our research further revealed differences in risk dependency between clean energy submarkets and the tourism and leisure market, offering more detailed references for investors.

From a macroeconomic perspective, our findings suggested that the risk dependency between the clean energy asset and the tourism and leisure market was influenced by economic cycles. During periods of economic stability, a strong positive correlation was observed between the two markets, possibly reflecting the combined pull of economic growth on energy demand and

Table 3. Tests for Granger-causality in quantiles between the clean energy market and the U.S. travel and leisure market.

	To *TL* From						
τ	*WILDER*	*SOLAR*	*WIND*	*GEO*	*BIO*	*RE*	*FUEL*
All	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.005***
0.05	0.005***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
0.10	0.001***	0.001***	0.001***	0.005***	0.001***	0.001***	0.001***
0.25	0.001***	0.005***	0.001***	0.001***	0.001***	0.001***	0.001***
0.50	0.001***	0.001***	0.001***	0.001***	0.005***	0.001***	0.001***
0.75	0.001***	0.001***	0.005***	0.001***	0.001***	0.005***	0.001***
0.90	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
0.95	0.607	0.562	0.43	0.297	0.603	0.607	0.444

Note: The table presents the consistent parameter test for quantile Granger causality. τ indicates quantile levels. We report the Granger-causal relationships at quantile levels of (0.05-0.95). *, **, and *** denote the rejection of the null hypothesis at 10%, 5%, and 1% significance levels, respectively.

tourism consumption. However, during periods of economic recession or crisis, the correlation weakened or even turned negative, potentially due to economic downturns causing simultaneous contractions in energy demand and tourism consumption, while heightened risk aversion among investors exacerbated negative feedback effects between the markets (Shahzad et al., 2017). This finding suggested that policymakers should implement targeted measures during economic downturns, such as increasing fiscal support for the clean energy and tourism sectors, to mitigate the adverse effects of economic pressures on these industries.

From a financial market perspective, we identified significant differences in risk dependency between clean energy submarkets and the tourism and leisure market. This partly reflected the distinct risk characteristics of different clean energy sub-markets and their varying degrees of association with the tourism and leisure market. For example, we found that BIO and FUEL had negative or insignificant correlations with the tourism and leisure market under extreme market conditions. This could be attributed to these submarkets being more influenced by policy support and technological innovation, and less affected by fluctuations in tourism consumption. In contrast, WIND and SOLAR maintained significant correlations with the tourism and leisure market under extreme conditions, likely reflecting shared interests in addressing climate change and promoting green travel (Zhang et al., 2016). These findings offered investors more detailed references for constructing investment portfolios, aiding in the selection of appropriate clean energy submarkets based on individual risk preferences and investment strategies.

Our study also found that the risk dependency between the clean energy market and the tourism and leisure market exhibited time-varying characteristics, aligning with previous literature (Tiwari et al., 2019). Specifically, we observed dynamic evolution in the correlation between the two markets during the sample period, indicating heterogeneous and time-varying responses to market shocks. This result had critical implications for both investors and policymakers. For investors, it underscored the need to consider the dynamic changes in market conditions when formulating investment strategies and to adjust portfolio allocations flexibly according to different periods to effectively control investment risks. For policymakers, it highlighted the importance of closely monitoring the dynamic changes in the clean energy and tourism and leisure markets and taking timely measures to guide market expectations and prevent risk spillover effects. Particularly during periods of severe market volatility, such as the COVID-19 pandemic, governments needed to increase support for the clean energy and tourism sectors to maintain market stability and boost investor confidence.

5. Conclusions

The aim of this paper was to determine the extreme quantile risk dependency between clean energy indices and the US Travel & Leisure index from 2014 to 2022. Employing cross-quantile graph techniques, we identified a reduction in risk interdependence between the US Travel & Leisure index and clean energy within medium and long-term investment horizons. Simultaneously, during stable market conditions, there was consistently high correlation among the clean energy indices and the US Travel & Leisure index. Conversely, in extreme tails, the correlation between specific clean energy assets and the US Travel & Leisure index was heterogeneous.

Given these outcomes, this study holds significant utility for policymakers and investors, offering insightful reports on the risk interplay between clean energy indices and the US Travel & Leisure index. Confronted with escalating environmental challenges, the present research compels policymakers and regulatory bodies within the US Travel & Leisure market to reassess existing policies in light of ongoing initiatives aimed at enhancing clean resource utilisation. This, in turn, assists them in devising comprehensive strategies and policies to mitigate environmental degradation.

The results of this study had significant implications for not only the United States market but also for the global development of the clean energy and tourism sectors. Firstly, a substantial positive correlation was found between the clean energy index and the tourism and leisure index, highlighting a strong connection between the progress of clean energy and the prosperity of the tourism industry. This finding suggested that governments should consider the synergistic effects between clean energy and tourism when developing economic strategies, promoting the use of clean energy to drive sustainable development in tourism. Secondly, it was observed that, in the medium to long term, the tourism and leisure index exhibited reduced dependency on the risks associated with clean energy. This implied that the advancement of clean energy could mitigate some market risks faced by the tourism industry. This insight encouraged countries to increase investment in research and the application of clean energy technologies to enhance the tourism sector's resilience to risks. Lastly, it was noted that under extreme market conditions, the correlation between the clean energy index and the tourism and leisure index showed heterogeneous characteristics. This observation emphasised the need for investors and policymakers to closely monitor the differentiated impacts of extreme events on these two sectors and to implement targeted risk management measures.

In addition to practical implications, this study also opens up extensive avenues for future academic exploration. Firstly, future research could apply our analytical framework to data from other countries or regions to verify the universality of our findings and to uncover the dynamic relationships between clean energy and tourism in different market environments. Secondly, future studies could incorporate additional influencing factors, such as policy changes and technological advancements, to more comprehensively characterise the complex interactions between clean energy and tourism. Furthermore, while our research primarily focused on the risk dependency between the two sectors, future studies could delve deeper into their connections in terms of returns, volatility, and other aspects to gain a more multidimensional and comprehensive understanding. Lastly, future research could employ other econometric methods, such as copula functions and wavelet analysis, to reveal the dependency structures between clean energy and tourism from different perspectives, further expanding our research conclusions.

Note

1. Source: https://www.condorferries.co.uk/us-tourism-travel-statistics

Disclosure statement

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