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RESEARCH ARTICLE

The impact of COVID-19 on the US renewable and non-renewable energy consumption: a sectoral analysis based on quantile on quantile regression approach

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Abstract

The repercussions of the novel coronavirus (COVID-19) pandemic go well beyond health concerns, affecting virtually every aspect of our lives, including daily energy consumption. Therefore, this study explores the impact of COVID-19 on renewable and non-renewable energy consumption in the USA, which has been severely affected by the recent pandemic. We conducted a detailed analysis of the energy consumption demands of various sectors in response to the COVID-19 outbreak. Our in-depth analysis comprises two parts. Initially, we determine the monthly growth change by utilizing the month-on-month method. Subsequently, we used the quantile-on-quantile approach of Sim and Zhou (2015) on data spanning from December 2019 to August 2021 to explore the impact of COVID-19 on energy consumption across the whole distribution. The study's outcomes underscored that compared to renewable energy, non-renewable energy consumption was more affected by the COVID-19 lockdown, and the overall energy consumption (both renewable and non-renewable) remained low. These findings accentuate global strategic management tools to tackle COVID-19 cooperatively and restore the energy mix. Such measures are critical for energy access, security, and evenhandedness.

Keywords COVID-19 · Renewable and nonrenewable energy · Sectoral analysis · Month-on-month method · Quantile-on-quantile approach

Introduction

Since the late 1970s, energy management strategies have been extensively studied. According to Kraft and Kraft (1978), economic development and energy consumption are interconnected. Therefore, maintaining and regulating the energy sector is crucial for long-term and sustainable economic growth (Ozturk, 2010; Payne 2010; Shahbaz et al. 2017; Yao et al. 2020; Yasmeen et al. 2021a, b, c; Suki et al. 2022). According to Squalli (2007), energy consumption and economic growth have significant repercussions for policymakers. A country can enjoy increased productivity and several other economic benefits with enough energy supply, including a rise in economic competitiveness, new value creation, and unmet demands (Abbass et al. 2022a; Mahmood and Ahmad 2018; Sun et al. 2022; Shah, et al. 2022). Accordingly, renewable and non-renewable energy sources are the primary backers of ensuring long-term development (Kuriqi et al. 2019, 2020; Wang et al. 2020). Consequently, energy consumption is rapidly growing due to industrialization, urbanization, and internationalization.

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Nevertheless, using renewable energy dramatically improves the environment's health (Usman and Hammar 2021). Furthermore, the economic switch from non-renewable to renewable energy is an intriguing way to achieve the 2030 Sustainable Development Goals (Murshed et al., 2021). Similarly, Usman and Makhdum (2021) argued that renewable energy consumption could not underestimate to achieve sustainable development goals.

Regardless of their environmental impact, renewable and non-renewable resources are necessary energy inputs in manufacturing (Khan et al. 2021; Ali et al. 2022). However, a historical review revealed that economic shocks such as the Great Depression, wars, oil crises, and the financial crisis of 2008 proved to be sensitive for energy industries (IEA 2020). The renewable and non-renewable energy market swings with economic instability (Li et al. 2020; Matei 2017). Demand for renewable and non-renewable energy swings in tandem with macroeconomic cycles (Mahmood and Ahmad 2018). Li et al. (2022) say that economic cycles significantly affect energy demand. It would therefore not be incorrect to claim that any economic shocks have a fundamental role in deciding the need for renewable and non-renewable energy.

A recent example of this is the COVID-19 pandemic, which emerged in mid-December of 2019 and quickly spread to over two hundred countries, crossing continents like Europe, Asia, Africa, Oceania, and the Americas (Rita et al. 2021; Mastropietro et al. 2020; Meo et al. 2021). The emergence of the coronavirus devastated the entire world (Abbass et al. 2021; Khan et al. 2021; Norouzi et al. 2020). According to the World Bank and the International Monetary Fund, the COVID-19 pandemic triggered a worldwide recession (Abati, 2020). Faust et al. (2020) stated that the COVID-19 virus could be much more devastating than the 1918 influenza plague. The COVID-19 pandemic did not impact only one industry; this outbreak had an unforeseen influence on all economic sectors, including production, banking, agriculture, academia, health, athletics, and the tourist industry (Nicole et al. 2020). This viral virus has increased the level of fear and anxiety across society (Abbass et al. 2022b). Each country's government immediately imposed social distance and lockdown to halt the epidemic (Mastropietro et al. 2020; Werth et al. 2021). As a result, it disturbed the economic and social cycle of the world economy and created instability in the many sectors of the economy (Abbass et al. 2022c). Abbass et al. (2022d) used the Keynesian theory and identified that the COVID-19 explosion has significantly shaken the domestic and global economy.

Also, the energy sector, by virtue, is not immune to pandemic pressures (Werth et al. 2021; Brosemer et al. 2020). As the International Energy Agency (IEA) reported, the energy demand shock in 2020 is predicted to be more significant than any in the preceding 70 years (IEA 2020). Bompard et al. (2020) highlighted the direct and indirect effects of COVID-19 on the energy sector. They pointed out that there is an indirect relationship between changes in energy markets and the technical performance of energy systems. At the same time, the energy sector is directly affected by the change in energy demand. Chiaramonti and Maniatis (2020) argued that the pandemic reduced worldwide electricity demand by around 15%. In 2020, worldwide energy demand was estimated to shrink about 6% relative to 2019, a sevenfold decrease from 2009 (Jiang et al. 2021). Because of restrictions imposed on people's mobility and activities, significant changes were noticed in renewable and non-renewable energy sources. According to Olabi et al. (2022), renewable energy sources are also significantly influenced by COVID-19, especially wind and solar, which have a considerable share in renewable energy sources. The USA, India, Italy, South Korea, and China experienced a cut down in energy demand and coal output up to 40%, 31%, 20%, 11%, and 9% individually (Brosemer et al. 2020; Asfour et al. 2021). There was a 50% fall in USA jet fuel and a 30% reduction in gasoline consumption, while carbon emissions shrank 15% in the USA (Olabi et al. 2022). Jiang et al. (2021) predicted a demand drop of 626.6 million tons of oil equivalent worldwide under moderate constraints, partial lockdown, and complete lockdown.

Similarly, COVID-19's repercussions on the power industry were explored by Zhong et al.(2020). They said that increased volatility in power consumption put more strain on system operators. Also, many others studies were conducted to find the COVID-19 impact in various scenarios focusing on a particular state. As an example, the examination of the US electric power industry (Ruan et al. 2020), Malaysian solar energy paths are being reviewed by Vaka et al. (2020), and the assessment of African government interventions was done in a specific perspective by Akrofi and Antwi (2020); the Indian electricity industry operations were examined for their potential consequences by Elavarasan et al. (2020). Norouzi et al. (2020) explored the significant impact of coronavirus on energy demand in China.

Similarly, Cheshmehzangi (2020) compared household energy consumption in China before, during, and after the COVID-19 pandemic. Siksnelyte-Butkiene (2021) identified the five main impact areas of the COVID-19 pandemic: consumption and energy demand, air pollution, investments in renewable energy, energy poverty, and energy system flexibility. Likewise, Begum et al. (2022) addressed the global COVID-19 pandemic–related environmental, social, and economic challenges and observed that the COVID-19 outbreak significantly impacted sustainable consumption.

Variations in worldwide energy consumption have suggested that the energy industry is in a state of emergency. In this regard, Steffen et al. (2020) emphasized the importance of implementing policies to deal with the COVID-19 energy crisis. The authors offered three-time horizons: short-, mid-, and long-term strategies to deal with this type of pandemic scenario in the energy sector. These strategies address immediate crisis reaction, medium-term economic recovery in the energy sector, and long-term shock-proofing energy transitions through suitable policy development. If an emergency in the energy sector is not handled promptly and appropriately, it may be devastating (Zhang et al. 2020). Moreover, the pandemic has improved renewable energy production by replacing fossil fuels, but it has also impacted the renewable energy supply chain in another way. The renewable energy sector has experienced a contraction due to production challenges and export woes. Such as Gebreslassie (2022) said, COVID-19 brought significant challenges to solar energy development in Ethiopia, because the pandemic reduced the income of solar technology end-users; several enterprises were forced to close. A shortage of technology supply has hampered the development of renewable energy. The hurdles faced by the energy industry due to the COVID-19 outbreak and its effect on economic growth motivated us to conduct the present study.

The motivation behind investigating the relationships between COVID-19 and renewable and non-renewable energy use in the United States of America (USA) comes from the fact that the USA is the world's largest economy, hardly hit by the COVID-19, with over 3 million confirmed cases (Rita et al. 2021). According to World Health Organization (WHO) (2020) data, the USA was one of the most afflicted countries in April 2020 and August 2020. The Globe Health Organization stunned the world by demonstrating that developed nations and individuals were the most affected and appeared powerless. As a result, in the unexpected and dynamic setting of the COVID-19 epidemic, new contributions are required, and it benefits the entire energy zone and the world by bringing new insights. The main driver is to analyze USA's energy consumption patterns during COVID-19 in broad forms rather than specific statistics. Therefore, we have used monthly data of different sectors focusing on COVID-19 periods. The following are some key contributions of this study: Firstly, we have overviewed vicissitudes in energy consumption in COVID-19. Before the statistical approach, monthly growth change was observed by applying month on month (MoM) analysis. Second, the research included extensive overviews of renewable and non-renewable energy sources. It also measures energy usage by sector in response to COVID-19. Finally, quantile-on-quantile (QQ) approach is used to make critical analysis.

Pandemic eruption — renewable and non-renewable energy demand

Lockdown measures raised by the USA state in response to COVID-19 have created an uncertain situation in the energy sector. During the epidemic, energy consumption fell due to partial or total lockdown, as numerous activities, including programs, economic activity, building, and industrial operations, were stopped and restricted. The USA energy industry could not be exempted from pandemic risks, which reduced energy demand and consumption. We used monthly data to catch up on the impacts of the COVID-19 pandemic on the USA's renewable and non-renewable energy consumption in different USA sectors. Figure 1 shows the USA's renewable and non-renewable energy consumption changes. The renewable and non-renewable energy consumption growth seemed positive in December 2019. After identifying the corona case in the country, the USA also moved to a partial and complete shutdown, negatively affecting the energy industry. Therefore, a sharp decrease can be noticed in non-renewable energy consumption probably in May due to the initiation of quarantine in the USA. After that, energy consumption (renewable and non-renewable) growth is positive with a slow growth rate. Lockdown applications proved to be damaging for the energy industry. For example, the COVID-19 outbreak bankrupted 19 USA energy firms (Crider 2020). The government promptly responded to the energy industry's needs (Akrofi and Antwi 2020).

In July 2020, high-pitched growth (almost 15%) in non-renewable energy consumption was realized due to an uplifted lockdown in June. The USA government decided to reopen nearly all business activities at the end of September. Therefore, a positive change in both energy sources is evident from October 2020 to January 2021. With fewer restrictions and the complete lockdown gradually winched up, a positive change is estimated in energy consumption from April 2021 to August 2021.

In light of the recent disruptions to global energy investments and supply networks, a comprehensive estimate of energy demand variation based on continually updated

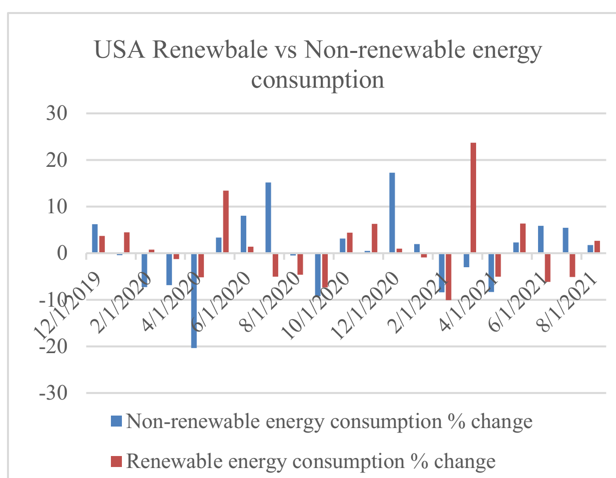


Fig. 1 Non-renewable and renewable energy consumption MoM% change

data is highly required (Broto and Kirshner 2020; Klemeš et al. 2020). Therefore, from a further inclusive assessment standpoint, this research evaluates which USA sectors have been affected by COVID-19 and which have shown resilience to the virus's effects on energy use. The residential, commercial, electric power, industrial, and transportation sectors in the USA were chosen. Industries were also forced to shut down to stop the virus's transmission. As a result, the energy needs of diverse segments of society have been changed significantly. Figure 2 shows the monthly variation in the residential sector's renewable end non-renewable energy consumption. There is positive growth noticed from September 2020 to January 2021.

However, 78% growth in non-renewable energy consumption was estimated in October 2020. Comparatively, renewable energy consumption shows fewer variations. In contrast to the residential and commercial sectors (Fig. 3), renewable energy consumption was estimated to be higher in December 2020, probably 48%. In the industrial sector (Fig. 4), in response to the shutdown, the cut down of renewable and non-renewable energy consumption was assessed probably 15% and 16% during May 2020. Transport sector activities were restricted, resulting in non-renewable energy consumption decreased around 24% in April 2020. Renewable energy consumption was reduced by 21% in May 2020 (see Fig. 5). The results of energy demand reduction can be verified by Sönnichsen (2022) who claimed that global oil demand fell by 9.1 due to COVID.

Similarly, Jiang et al. (2021) found a 9% reduction in USA energy demand. Electric power growth change has been shown in Fig. 6. Substantial positive growth was seen in non-renewable energy consumption by 33% in June 2021. Similarly, renewable energy use fluctuates with a varied ratio month to month. However, it gives the impression of the growing movement that renewables appear to be accelerating the trend of fossil fuel replacement.

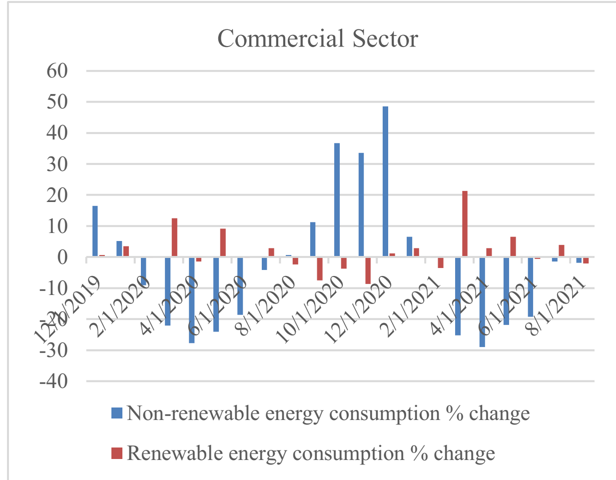


Fig. 3 Commercial non-renewable and renewable energy

Data description and methodology

Coronavirus has impacted people's social and economic life all around the world. Lockdown entails restricting economic activity, and social contacts are restricted. Lockdown includes closing international and domestic airports; closing automobile parks to prohibit inter-city transport; closing schools, markets, and factories; restricting social activities such as weddings, burials, parties, clubbing, athletic events,

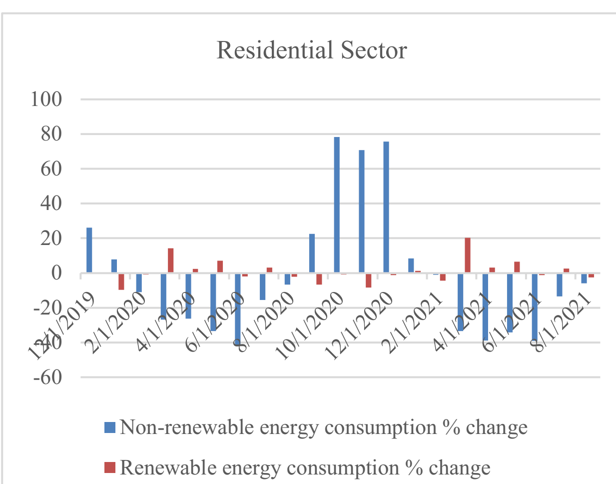


Fig. 2 Residential non-renewable and renewable energy consumption MoM% change

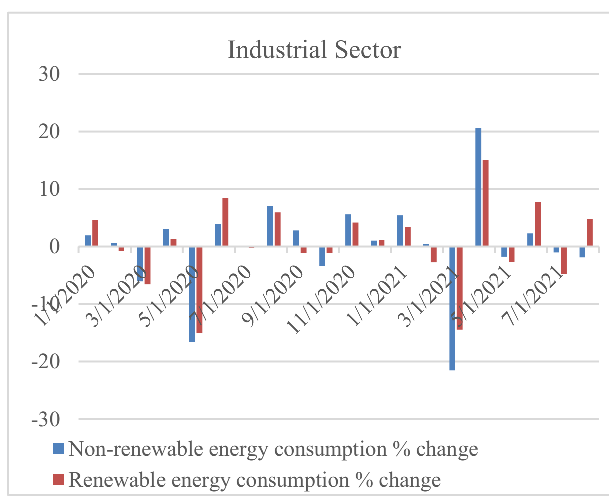


Fig. 4 Industrial non-renewable and renewable energy consumption MoM% change

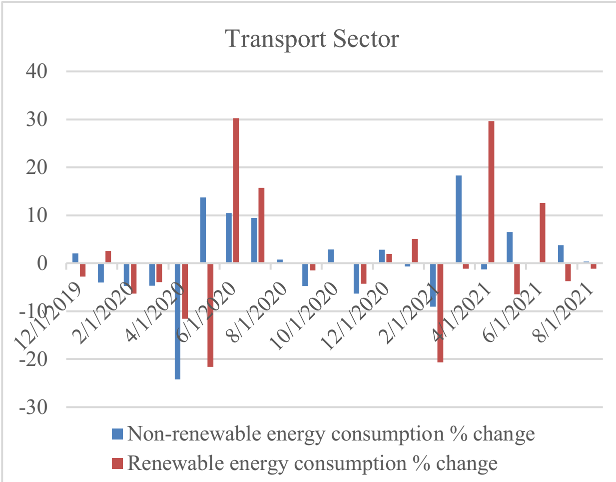


Fig. 5 Transportation non-renewable and renewable energy

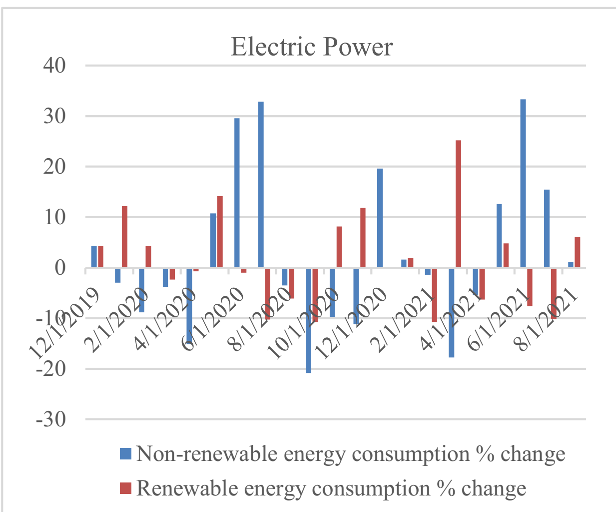


Fig. 6 Electric Power Non-renewable and renewable energy consumption MoM% change

and other festivities; sealing intra and international borders. Only necessary operations such as food and allied businesses, medicines, medicals, utilities, banking, and communication are permitted (Rita et al. 2021). The goal of the lockdown is to prevent crowding, which increases the chance of enormous community transmission. Still, on the other hand, the COVID-19 pandemic lockdown has reduced economic activity and restricted social involvement, both of which impacted energy consumption. The restrictions on transport and economic activities such as shutting down businesses, markets, mining, and working from home mean that energy consumption would be reduced significantly. Therefore, the study quantifies the COVID-19 epidemic impact on the US's renewable end non-renewable energy consumption. The USA is one of the biggest economies globally that have been highly affected by the coronavirus. Under this perspective, monthly data was used for renewable and non-renewable energy consumption. The total confirmed cases of COVID-19 were used for epidemic virus impact. The energy consumption data is extracted from the "USA Energy Information Administration" and the COVID-19 case from "Our World in Data" (https://ourworldindata.org/covid-stringency-index). The period from December 2019 to August 2021 is considered the coronavirus started by December 2019.

The descriptive statistics for renewable and non-renewable energy consumption and COVID-19 have been given in Table 1. The mean value of the non-renewable energy consumption (NREs) (6.268145) is higher than renewable energy consumption (RNEs). Similarly, the maximum value of non-renewable energy consumption (7.235305) is more than that of renewable energy (1.100763). These differences indicated that renewable energy consumption could not be a significant source of energy consumption yet. However, the Jarque–Bera probability value shows the normality of the data. Tables 2 and 3 correlate renewable energy, non-renewable energy consumption, and COVID-19. The results indicated that overall, COVID-19 declined the non-renewable energy consumption.

In comparison, renewable energy consumption is not affected significantly by the epidemic. However, the positive/negative relationships and correlation strength varied with sectors, such as the residential sector shows a high correlation between the concerned variable, while transport showed low power in the relationship. People might get more spare time and move out for outings, even during lockdown presser.

Quantile on quantile regression approach

In this study, the quantiles on quantiles (QQ) approach proposed by Sim and Zhou (2015) is used to analyze the impact of COVID-19 and renewable and non-renewable energy consumption. Developer of traditional Quantiles approaches, Koenker and Bassett (1978) employed this method to assess the independent indicator on distinct quantiles of a

Table 1 Descriptive summary

Variable(s)	*RNEs*	*NREs*	*Covid*
Mean	0.984422	6.268145	445,000,000
Maximum	1.100763	7.235305	1150,000,000
Minimum	0.881153	4.953632	0.000000
Std. Dev	0.060120	0.635673	434,000,000
Jarque–Bera	0.278579	0.572711	2.586560
Prob	0.869976	0.750995	0.274369

Table 2 Correlation between renewable energy consumption and COVID-19

USA and sectors	Correlations	*p*-value
Overall	0.158594	0.0000
Residential	0.516648	0.0000
Commercial	0.448490	0.0000
Industrial	−0.158996	0.0000
Transport	−0.011603	0.0000
Electric power	0.073744	0.0000

Table 3 Correlation between Non-renewable energy consumption and COVID-19

USA and sectors	Correlations	*t*-value	*p*-value
Overall	−0.216020	−21,387.05	0.0000
Residential	0.841604	150,631.8	0.0000
Commercial	−0.807507	−132,336.1	0.0000
Industrial	−0.132953	−12,967.30	0.0000
Transport	−0.012312	−1190.258	0.0000
Electric power	−0.373749	−38,952.15	0.0000

regression coefficient. The QQ method extends the conventional quantiles regression to address the numerous flaws in traditional quantile regression, given that the QQ method combines standard quantile regression and nonparametric estimations. Furthermore, quantile regression is a well-accepted classic linear regression model extension. QQ technique is the appropriate tool for modeling the relationship between the two variables. This method allows us to evaluate the dependent and independent variables (Baur and Dimpfl 2018). Aside from that, QQ regression will enable us to examine a set's top and bottom quantiles, allowing us to assess the overall connection between the variables over time (Shahbaz et al. 2018; Sharif et al. 2021). As a result, the study was also motivated to use the single-equation framework provided by Sim and Zhou (2015). The $\tau-$ quantile of renewable and the non-renewable energy consumption is the function of its lagged values; the study now extant the $\tau-$ quantile of $Covid_t$ as a function of COVID-19 represented in equation form as follows:

$$Energy_t = \beta^{\theta}\left(Covid_t\right) + \mu_t^{\theta} \tag{1}$$

For energy, the factor loading β^{θ} (.) is unknown, whereas μ_t^{τ} is the quantile residual term with zero conditional $\tau-$ quantile. Described function informs us of the varying effects of the coronavirus outbreak over quantiles of energy consumption in the USA. This study also examines Eq. (1) in the vicinity of $Covid^{\tau}$ using local linear regression. By taking the first order of Taylor expansion of θ (.), the linear equation is as follows:

$$\beta^{\theta}\left(Covid_t\right) \approx \beta^{\theta}(Covid^{\tau}) + \beta^{\theta'}(Covid^{\tau})(Covid_t - Covid^{\tau}) \tag{2}$$

Ensuing Sim and Zhou's (2015) work, one should reconsider $\theta(Covid^{\tau})$ and $\beta^{\theta'}(Covid^{\tau})$ as $\beta_0(\theta,\tau) + \beta_1(\theta,\tau)$ correspondingly. Then, Eq. (2) is adaptable as follows:

$$\beta^{\theta}\left(Covid_t\right) \approx \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(Covid_t - Covid^{\tau}) \tag{3}$$

By substituting Eq. (3) into Eq. (1), we arrive at Eq. (4) as follows:

$$Energy_t = \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(Covid_t - Covid^{\tau}) + \mu_t^{\theta} \tag{4}$$

whereas $\beta_0(\theta,\tau) + \beta_1(\theta,\tau)(Covid_t - Covid^{\tau})$ is the θth conditional quantile of renewable and non-renewable energy consumption, where Eq. (4) illustrates the relationship between θth conditional quantile of renewable and non-renewable energy consumption and the τth quantile of COVID-19, akin to the conditional quantile regression. We opt for the bandwidth parameter, $h=0.05$, in our estimation, as Sim and Zhou's (2015) proposed.

Results and discussion

This section offered the QQ regression's key outcomes between renewable and non-renewable energy consumption and COVID-19 for the USA economy. Figure 7 shows the estimates of the slope coefficient $\beta_1(\tau,\theta)$, that encapsulates the influence of the τth quantile of COVID-19 (both energy consumption) on the θth quantile of energy consumption (COVID-19) at different values of τandθ for the US residential, commercial, and industrial; transportation; and electric power sectors under concerned. In the overall renewable energy case, the QQ approach shows a negative shock of COVID-19 on renewable energy consumption at lower quantiles. Medium quantiles show fluctuations in renewable energy consumption. For the upper quantile, it seemed to increase renewable energy consumption trends. According to IEA 202, fossil energy demand drops, but renewable energy demand upturns. Conversely, non-renewable energy consumption remains consistent at a lower quantile. At the middle quantile (0.3 to 0.7), non-energy consumption fluctuates, showing non-renewable energy consumption instability. However, the higher quantile shows a high-pitched decrease in non-renewable energy caused by implementing lockdown strategies. We notice an increasing trend in non-renewable energy consumption at 0.7 to 0.8 upper quantile rank. The growing trend is expected as energy consumption recovers

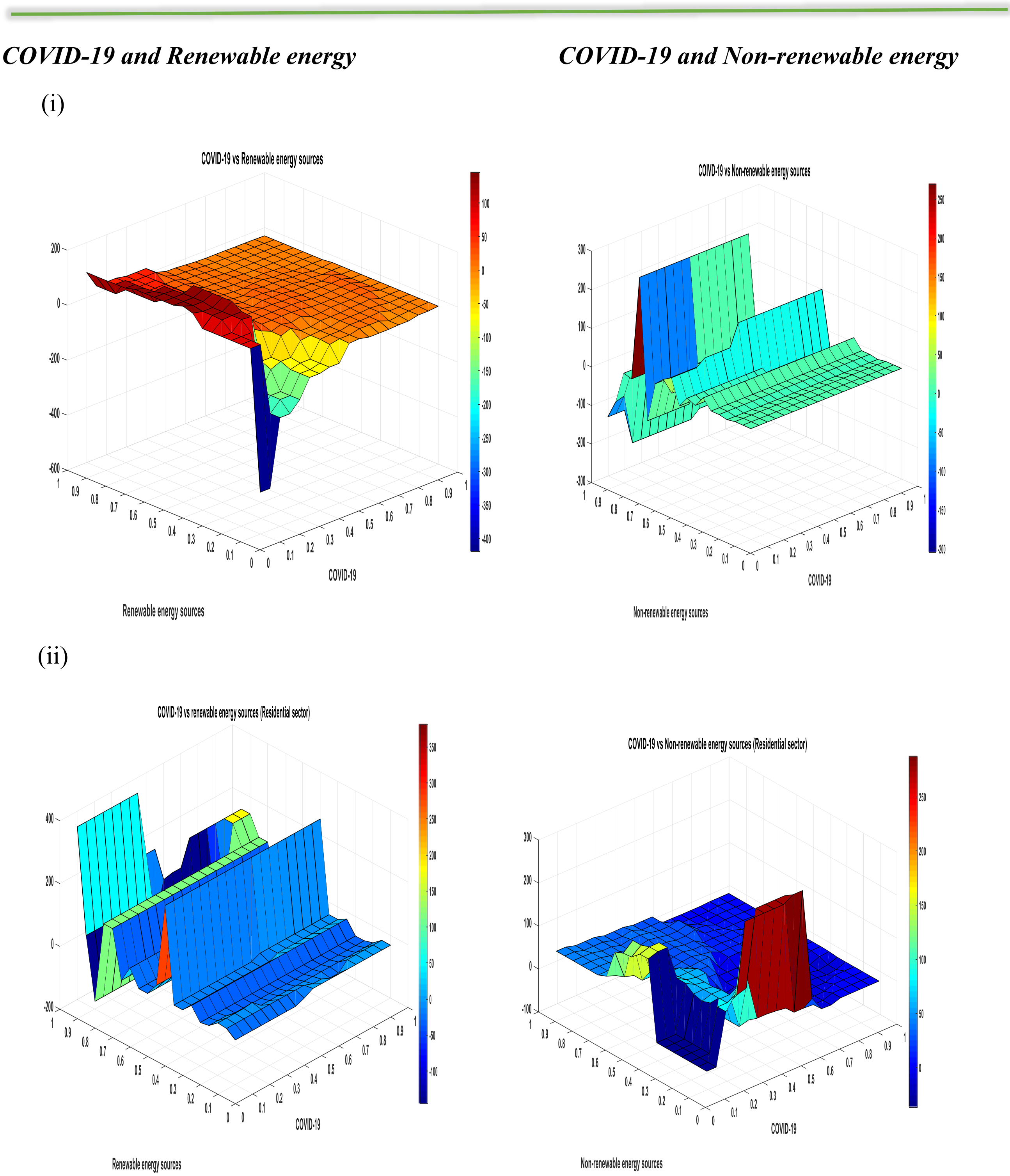
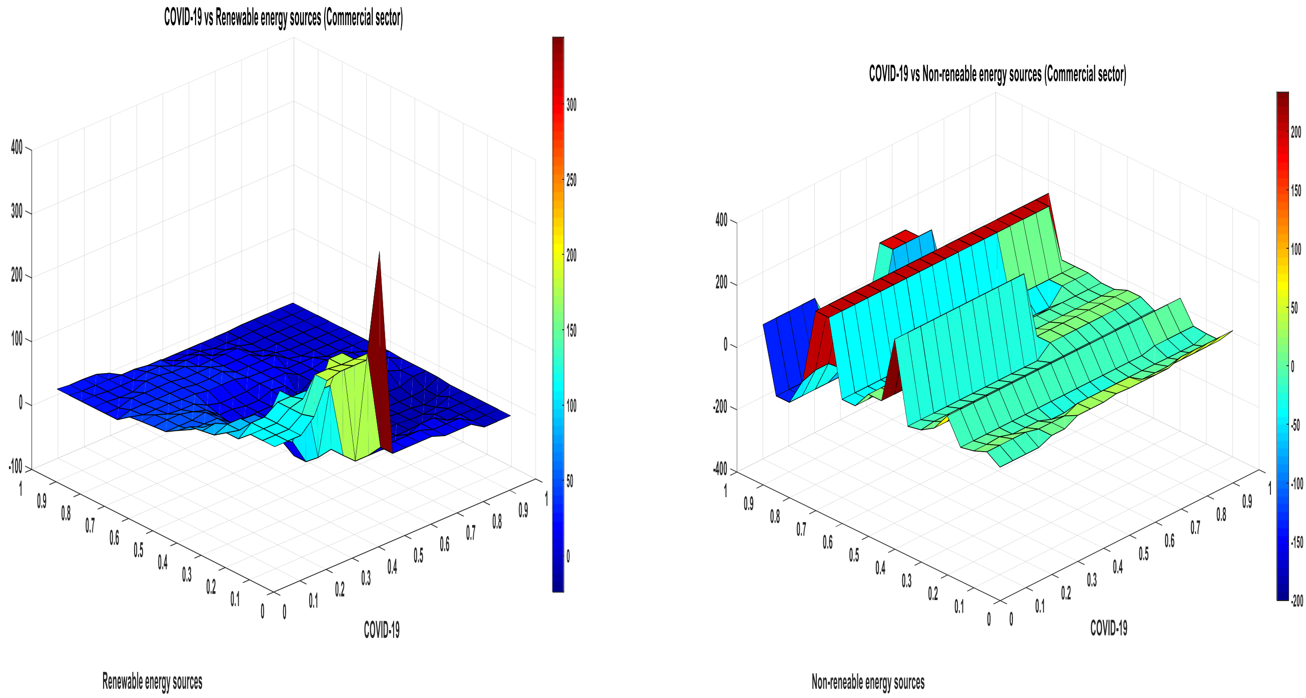


Fig. 7 Quantile-on-Quantile (QQ) estimates of the slope coefficient, β (τ, θ,). (i) USA energy consumption. (ii) USA Residential Sector. (iii) USA Commercial Sector. (iv) USA Industrial Sector. (v) USA Transport Sector. (vi) USA Electric Power Sector. The figures depict estimates of the slope coefficient β_1 (τ, θ) as in the *z*-axis compared to the quantiles of renewable and non-renewable energy (COVID-19). The *y*-axis and the COVID-19 quantiles (renewable and non-renewable energy consumption) are on the x-axis

(iii)



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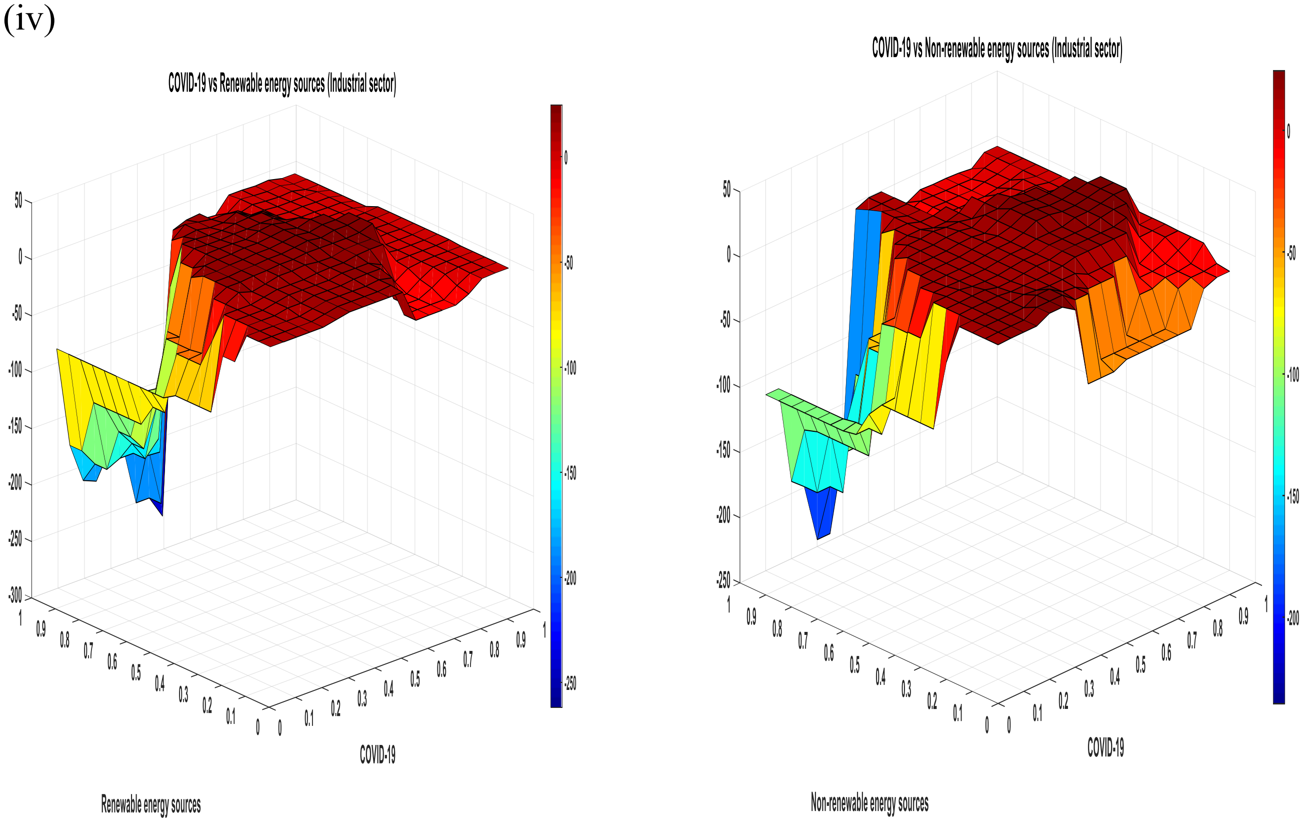


Fig. 7 (continued)

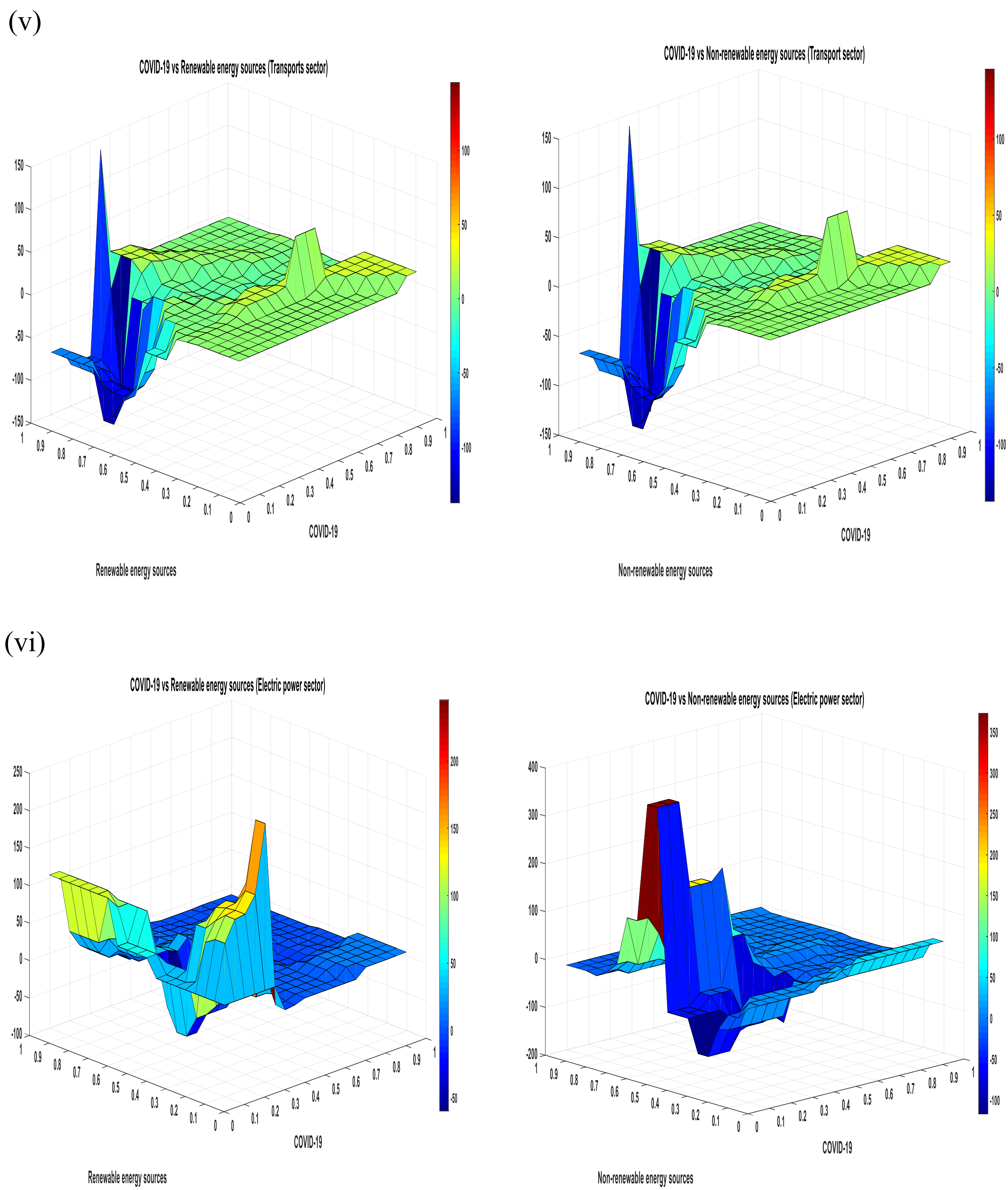


Fig. 7 (continued)

after relaxing lockdown measures. However, this positive trend was short term, and energy consumption was reduced again. The study concluded that the COVID-19 outbreak reduced the USA economy's renewable and non-renewable energy consumption. However, non-renewable energy consumption seems to be much affected and decreased by virus eruption, while renewable energy consumption increased. Furthermore, energy consumption varies along with COVID-19 measures.

The energy variations in different sectors are expected to be different. In first-hand discussion, we focused on the Residential sector. The residential sector is the most direct pathway for energy consumption. Renewable energy consumption in the residential industry decreased at a lower quantile due to confinement measures such as working from home (Saadat et al. 2020), limiting exposure to germs and viruses, and using antiseptic/disinfectants (e.g., gloves, face shields, protective suits, and fast test kits). Still, a sudden spike can be noticed at mid-quantile, indicating renewable energy consumption increased in the residential sector. According to EIA (2021), USA renewable energy consumption increased dramatically in 2021. Less energy consumption is found at a lower quantile with virus shock. However, the middle quantile shows a positive change in non-renewable energy consumption. The results can be verified by Asfour et al. (2021). The daily residential energy consumption increased about 6 to 8% in the upper quantile, showing a consistent but lesser consumption with COVID-19. It is not surprising as America has imposed restrictions on frequent transportation and stated plans to work online, consequently increasing energy consumption in the domestic sector.

Overall, the commercial sector consistently consumes at a higher quantile (0.5–0.9). COVID-19 shows a spike increment in virus at 0.5–0.6 quantiles. It means that commercial activities lead to increasing virus augmentation. On the other hand, the retail sector shows a different picture of non-renewable consumption. Vacillations can be observed throughout the diagram. The outcomes inferred that non-renewable energy consumption increases and decreases with COVID-19 cases. At a higher quantile (0.9), energy consumption substantially decreased. A significant upsurge has been detected at (0.4–0.5) quantile. There is a considerable reduction in non-renewable energy consumption with the COVID-19 case at mid-quantile. The relationship between COVID-19 and non-renewable energy consumption is lower at a lower quantile. The energy consumption level seems to be lower at a lower quantile because the virus affects regular working activities, eventually reducing the energy consumption. The world faces significant challenges in reducing regular energy consumption, especially during a crisis (Jefferson 2020). The typical morning peak time decreases energy consumption demand (Chen et al. 2020). Secondly, non-renewable energy has a significant part of the energy consumption compared to renewable energy; thereby, the affected rate is higher for non-renewable sources.

The industrial sector's renewable energy consumption level did not decrease much at the lower quantile. In other words, it follows the flat path at the lower quantile. However, from 0.3 to 0.7, quantiles illuminate high consumption and low consumption (variations) during the lockdown period, but there is a sharp decline at the higher quantiles of the industrial sector. There is a negative relationship between renewable energy consumption and virus-contained cases at lower to middle quantiles. Non-renewable energy consumption decreased overall in the industrial sector. A significant reduction is evident in non-renewable energy consumption at the upper quantile. Many industries have been impacted by the COVID-19 epidemic, including the manufacturing and energy industry (Nicole et al. 2020). At 0.1 to 0.3, it shows a positive trend in non-renewable energy consumption. It might reflect relaxation in prevention actions because politicians/officials keep people healthy and regain energy and the economy. As Jiang et al. (2021) said, the transport, production, and services sectors gradually recovered as the lockdown relaxed or lifted.

The transport sector shows a negative association between renewable and non-renewable energy consumption and the COVID-19 epidemic at a higher quantile. However, 0.4–0.5 offers little augmentation in non-renewable energy consumption. Energy consumption at a lower quantile remains consistent, but the consumption level seems lower throughout the crisis period. Interestingly, the overall behavior of the transport sector remained similar for the renewable and non-renewable energy sources. These outcomes indicate that energy consumption increased after reducing the transportation sector, but the consumption level could not reach the highest average level.

The electric power sector shows a little positive relationship between renewable energy consumption and COVID-19 case at a lower quantile. At the middle quantile, renewable energy consumption shows moderate behavior. Non-renewable energy consumption is significantly dropped at lower quantile and moderate at probably 0.2 to 0.4 quantile. There is positive growth that can be noticed in non-renewable energy consumption at the middle quantile (0.5–0.7). Higher quantiles (0.8–0.9) show consistent consumption negatively. Overall, energy consumption was reduced due to the virus impact. The primary study findings suggested that the USA's energy consumption was affected by the COVID-19 virus. The study found the instability in consumption at different quantile in selected economic sectors. This difference is not surprising as the economy faces partial lockdown and distance measures carried by the government sporadically (Olabi et al. 2022; Jiang et al. (2021);. Therefore, consumption decreased sharply during and after lifting the lockdown. Moya et al. (2020) [50] stated that the relevance of modeling and reviewing disruptive situations, particularly in light of the current COVID-19 crisis, cannot be overstated. Thus, the US government took prompt measures and sometimes relaxed in lockdown to stabilize the economy and conserve regular energy consumption. During the COVID-19 pandemic, the convex energy curve of steady demand and the concave energy curve of extra energy consumption may be overlooked due to their negative trends. Therefore, it would not be wrong to say that proper decision-making is needed on urgent grounds to make the economy less infected by viruses and stabilize energy consumption simultaneously. The USA government realized this urgency, and therefore, the development of vaccination was started quickly.

Validity of the QQ application

Decomposition of the standard quantile regression estimates allows for specific estimates for different quantiles of the explanatory variable. The quantile regression model in this study is based on regressing the θth quantile of the COVID-19 pandemic impact on renewable and non-renewable energy consumption. The quantile regression parameters are indexed by θ. Furthermore, through averaging the QQ parameters along τ, the quantile regression parameters are only indexed by θ, such as the slope coefficient of the quantile regression model that measures the influence of COVID-19 on the distribution of renewable and non-renewable energy consumption is represented by $\gamma_1(\theta)$ and is able to be acquired as follows:

$$\gamma_1(\theta) \equiv \overline{\widehat{\beta}}_1(\theta) = \frac{1}{s} \sum \tau \widehat{\beta}_1(\theta, \tau) \tag{5}$$

Quantile regression (QR) parameters can be tested compared to averaged QQ regression parameters. Therefore, the study plots Fig. 8 to reach the quantile regression and the averaged QQ estimates of the slope coefficient, which measures the impact of the COVID-19 pandemic on US renewable and non-renewable energy consumption for various sectors under exploration.

All sectors' QQ estimates of the slope coefficient were similar to the QR estimates. The validation process found that the QQ regression trend lines are identical for QR in the validation process. The said visual illustrates how the QQ methodology works by summing the more detailed information in the QQ estimates to recover the QR model's main features. We have found variations in the lower to middle quantile. Furthermore, it validated that the US economy faced a significant reduction in renewable and non-renewable energy consumption. That is yet a challenge for the USA economy.

Conclusion and policy implications

The COVID-19 pandemic has grown into one of the most severe challenges in human history as it attacked the global economic structure on a large scale. This pandemic outbreak disrupted the energy demand and supply chains. Undoubtedly, the challenges will continue to grow and have a more significant impact on the energy industry. As a result, this research analyzes the effects and challenges of COVID-19 pandemics on energy demand and consumption in the USA. The importance of the study falls in the following points. First, the main driver of this study is to analyze the USA's energy consumption patterns in different sectors: industrial sector, residential sector, power industry, transport sector, and commercial sector during COVID-19 in broad forms rather than specific statistics. Accordingly, the study used monthly data from different sectors focusing on COVID-19 periods. Secondly, before the statistical approach, monthly growth change was observed by applying month on month analysis. This approach highlights the differences in renewable and non-renewable energy consumption by sector in response to COVID-19. Demand for both energy sources fluctuated because of the lockdown and shutdown regulations implemented during COVID. Thirdly, the quantile-on-quantile approach is used to make critical analysis. The quantile-on-quantile framework describes the overall dependence structure between the concerned indicators instead of using OLS or quantile regression to describe the overall dependence structure between the concerning indicators. Accordingly, we empirically estimated the impact of COVID-19 on the USA's renewable and non-renewable energy consumption from December 2019 to August 2021. Renewable and non-renewable energy consumptions have different potentials in terms of environmental and economic angles; therefore, we considered both energy sources to obtain comprehensively quantitative.

The most important findings are that COVID-19 negatively affects the USA's energy consumption. Consumption patterns along the growing COVID-19 scenario fluctuate each month. The study highlighted that non-renewable energy consumption was disturbed more than renewable energy consumption. Lockdown measures regarding lifting/shutting made the energy consumption rate unstable and smaller. Since no cases were reported and the pandemic had not begun, renewable and non-renewable energy consumptions were positive in December 2019. Due to the lockdown applications, the USA experienced a sharp fall in non-renewable energy use, particularly in May. Indeed, the energy business suffered as a result of the protection measures. Shutting down applications damaged the energy industry, reduced investment in the energy storage industry, and interrupted the supply chains from cells to installers. Different industries use different amounts of energy. Different quantiles offered different consumption rates. For example, renewable energy consumption in the residential sector decreased at the lower quantile while increasing at the middle quantile. The commercial industry shows a negative association between renewable and non-renewable energy consumption and COVID-19 at a higher quantile. The industrial sector was also severely affected and showed low energy consumption (both energy sources) throughout the

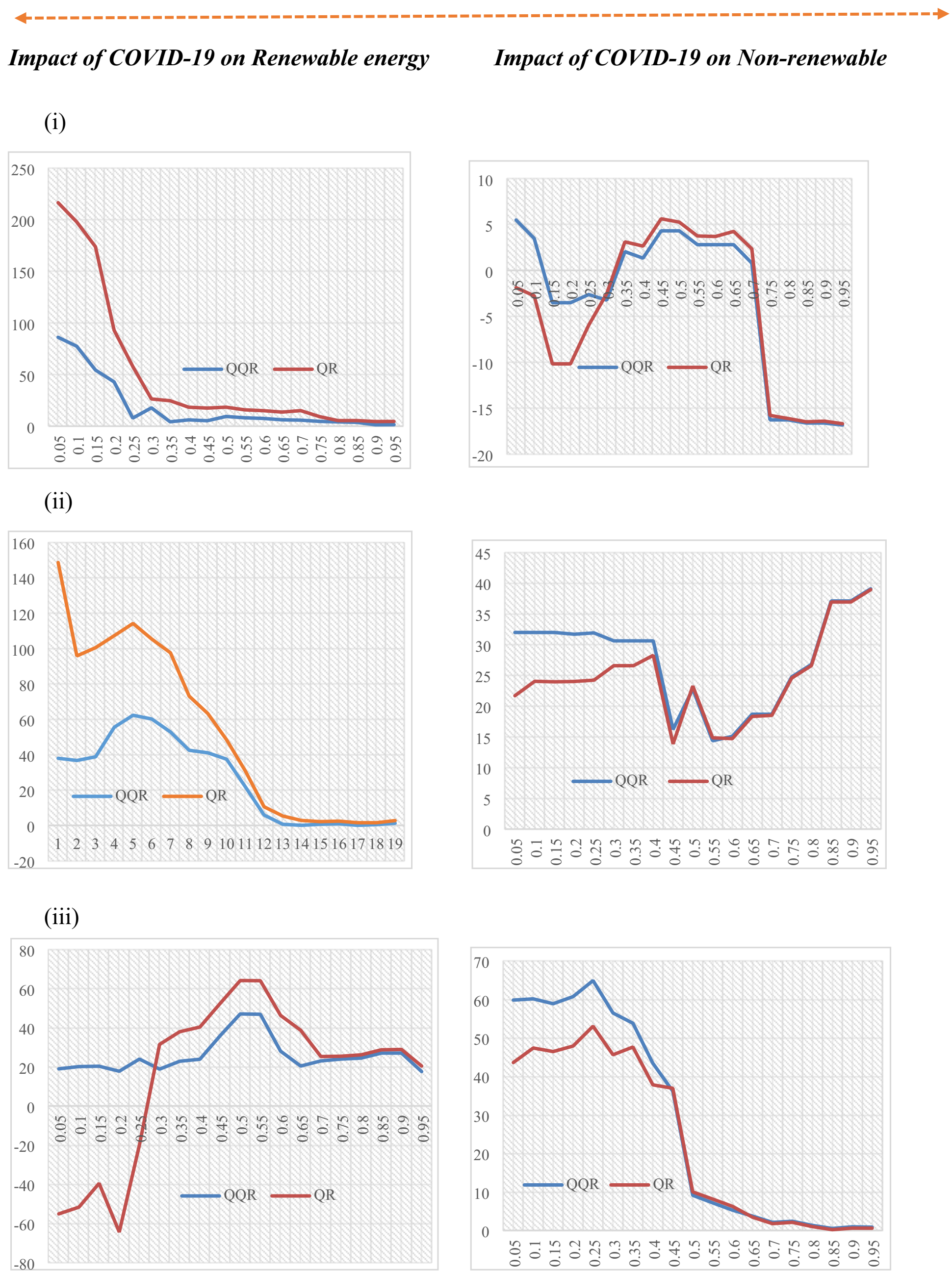
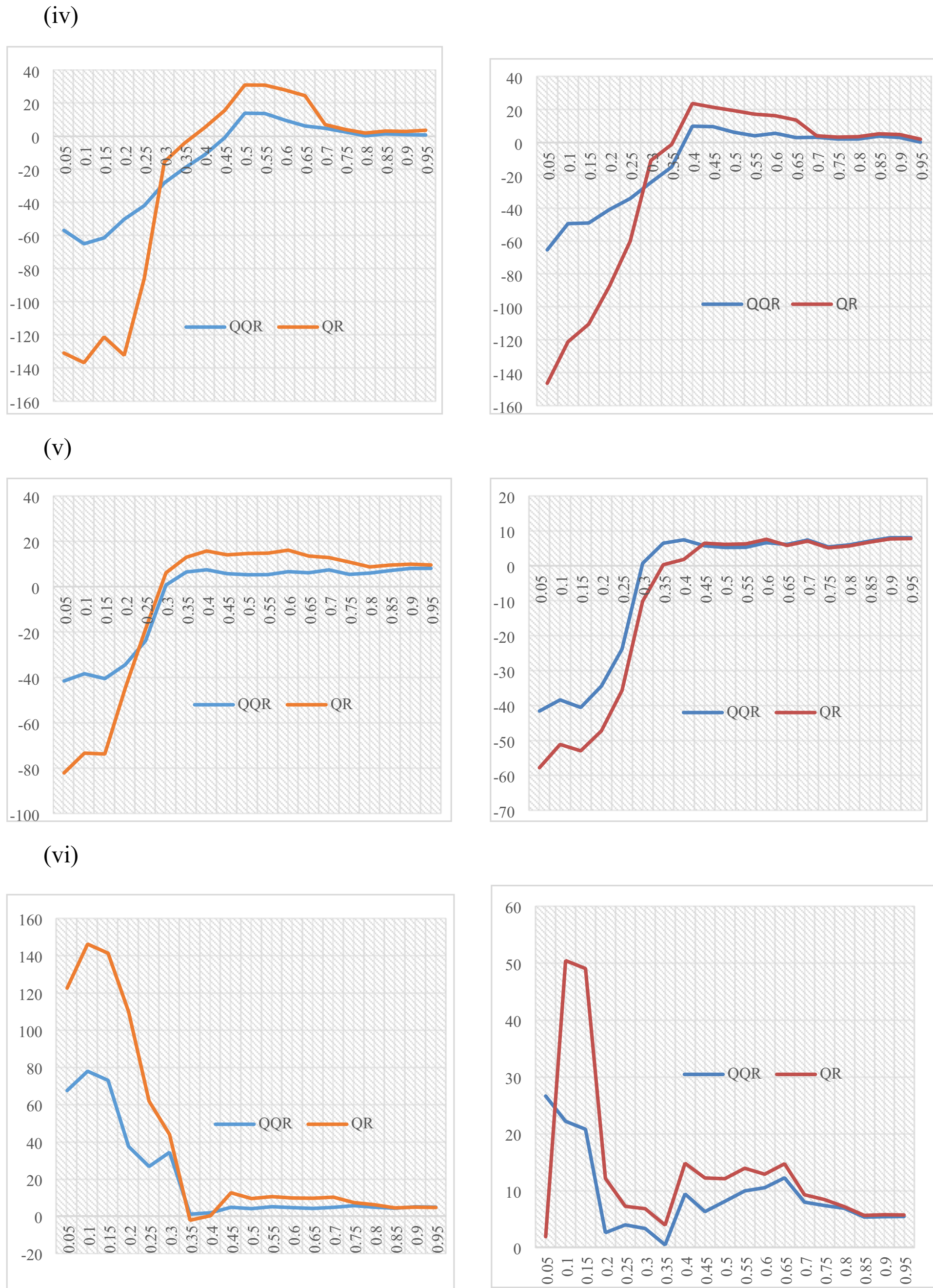


Fig. 8 Comparison of quantile regression (QR) and quantile-on-quantile regression (QQR). (i) USA energy consumption. (ii) USA residential sector. (iii) USA commercial sector. (iv) USA industrial sector. (v) USA transport sector. (vi) USA electric power sector

quantile. Transport energy consumption (renewable and non-renewable) remained negative at a higher quantile. Lower and higher quantile showed a strong negative association between non-renewable energy consumption and COVID-19 for the electric power sector.

The energy consumption pattern presents heterogeneous characteristics in each sector. The historical review suggested that energy demand typically recovered after the passing crisis. However, the heterogeneous findings consider how an economy can recover energy demand and fight the coronavirus. Accordingly, the worst situation would be stable by ending the COVID-19 virus. Several elements such as strategies, sociological aspects, and geographical factors influence the energy sector to be recovered. Every problem mobilizes resources, allowing the researcher to comprehend the current situation better and plan for a future with higher energy efficiency and lower carbon emissions. The world's economy, as well as the USA, must wisely manage the four fundamental energy difficulties: (i) fluctuating demand and risks, (ii) structural and pattern changes, (iii) related environmental implications, and (iv) the difficulty to recover energy demand. Furthermore, the energy sector can be stable through coordination and collaboration to fight COVID-19. Managing global energy resources and policy in the wake of pandemics

Fig. 8 (continued)



will necessitate quantitative improvements to the strategic management framework. Every difficulty provides an opportunity to look into the future and devise solutions for dealing with catastrophic events and minimizing their effect. Furthermore, new implementation methods should be used to reset or maintain the sustainable development of the energy sector.

We conducted this study till August 2021. Therefore, researchers should investigate whether the relationship between energy demands of USA sectors gets stable vis-à-vis the COVID-19 with time. It is worth mentioning that the COVID-19 vaccine has been developed, lockdown measures have been removed, and life is gradually returning to normal in many countries, including the USA. So, it is expected that the prevailing situation of energy demand in each sector may differ significantly. In this respect, future studies may undertake comparative analyses of energy demand during initial waves of COVID-19 and after COVID-19 vaccination. This study can give meaningful feedback on the USA energy demand variations to future research works.

Author contribution Rizwana Yasmeen, Wasi Ul Hassan: conceptualization, formal analysis, writing—original draft. Gang Hao: supervision, methodology. Assad Ullah: formal analysis. Yunfei Long: writing and review.

Data availability Data can be available at US Energy Information Administration and the COVID-19 case from "Our World in Data" (https://ourworldindata.org/covid-stringency-index).

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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