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The impact of the COVID-19 pandemic on the energy market – A comparative relationship between oil and coal

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ABSTRACT

The COVID-19 epidemic has severely affected the world economy and energy markets. In order to alleviate the shock, stabilize the financial market, and promote economic recovery, the Fed announced an unlimited QE policy. In order to understand the impact of the policy on the energy market under the extreme events, the study selected WTI crude oil and coal prices from January 1, 2018 to May 7, 2021 as the research objects. Taking the two years before the epidemic, the epidemic stage was further divided into four small stages according to the three peaks of the epidemic in the US. The MF-DCCA model calculations show that coal and WTI crude oil have an interactive relationship. The risks between them are not just averaged and superimposed, but transmitted and interacted. The MF-DFA model calculation results show that due to the disorder of energy supply and demand under the epidemic, market efficiency in the first quarter of 2020 has dropped rapidly. However, market efficiency decoupled from the development of the epidemic in the second half of 2020. Especially after the announcement of the QE policy, market efficiency has improved significantly. However, under the excessive monetary policy, market efficiency declined in the first half of 2021. This shows that the policy has a certain impact of this crisis, the US government updated a new round of energy views. In particular, it has also dynamically implemented an unlimited quantitative easing monetary policy in the economy. But. since June, WTI crude oil and coal prices have continued to rise. And the inflationary pressures have also increased concerns about the future development of the energy market.

Obviously, COVID-19 and the fiscal policies of the Federal Reserve’s QE have had a certain impact on the energy market. That is, the efficiency of the energy market is not only affected by itself, but also restricted by other market fluctuations. At the same time, it is also affected by the external environment such as epidemic and extreme events. With the development of economic globalization and financial liberalization, energy market price efficiency has an increasing impact on corporate investment and market transactions. And it will affect the country’s import and export trade and sustainable economic and social development. It will receive greater attention in the future. Moreover, the COVID-19 pandemic continues. Therefore, it

1. Introduction

The global COVID-19 pandemic has not only brought a huge threat to human health, but also changed people’s production and lifestyles [1]. As the number of confirmed cases continues to increase, countries have taken measures such as lock-downs to prevent the spread of the epidemic. Because of these measures, the global supply chains were interrupted, and the world entered a period of economic blockade [2]. It caused the energy market to collapse, the stock market crashed and the global economy slowed [3,4]. WTI crude oil futures are one of the financial markets most affected by COVID-19 [5]. On April 20, 2020, WTI crude oil futures fell to a negative value, from $18 per barrel to -$38, which was the first time in history [6]. The slump in crude oil futures prices triggered panic in the global market economy. The price of coal futures, which are alternatives to each other, also fell from $70.68 on March 27 to $51.62 on April 27. The market have since entered the depression. In order to stabilize the market economy and defuse the
is necessary to study the correlation and risk of the US energy markets during this period. In particular, the Fed’s QE policy is constantly changing. It is imperative to further analyze the energy market efficiency before and after the epidemic in combination with the economic policies and the changes on the energy supply and demand side.

Current research on the crude oil and coal markets during the COVID-19 pandemic mainly focuses on the relationship between the epidemic and single energy futures market [12–14]. For example, Sczzygielski et al. [15] found that COVID-19 has added uncertainty to the energy markets of all countries through bibliometric methods. Zhu et al. [16] found that during the COVID-19 period, the risk of US oil inventory spillover was significantly stronger than during normal periods. Narayan [17] analyzed the impact of COVID-19 and fluctuations in oil prices on future oil prices. Le et al. [18] proposed that COVID-19 caused the current oil price to plummet, and this effect is long-term. Gil-Alana and Monge [19] also proved that the impact of COVID-19 on oil prices is short-lived, but has long lasting. Huang and Zheng [20] focused on the relationship between investor sentiment and crude oil futures prices during the COVID-19. Leach et al. [21] and Plumer [22] analyzed the impact of the outbreak on the coal industry in Canada and the US, especially the power generation market, and the results showed that power generation in these two countries has dropped significantly. Norouzi et al. [23] also found that in China’s energy market, where the epidemic was first contained, the price of coal also showed a downward trend. Another part of the research explored the economic impact of oil price changes on other industries [24,25]. For example, Mensi et al. [26] compared and analyzed the efficiency of oil and oil markets during the COVID-19. Research shows that the oil market will show a downward trend in the future, while the price of gold will rise. Prabheesh et al. [27] found that the correlation between oil prices and the stock market increased significantly during the first two months of the outbreak. Wang et al. [28] studied the impact of COVID-19 on the relationship between crude oil and agricultural futures markets. After the emergence of COVID-19, the multifractal correlation of all agricultural futures has increased except for the orange juice futures market. Fu and Shen [29] analyzed the economic impact of the collapse of WTI oil prices during the epidemic on companies in the energy industry. OEI et al. [30] found that COVID-19 caused a global economic recession and a plunge in oil prices, and the coal industry was also affected.

There are few studies that quantitatively analyze the changes in the risk transmission of the two energy markets during the epidemic. Moreover, there is still uncertainty about the effectiveness of the Fed’s QE policy. This is important because under extreme events, the relationship between any markets may change due to changes in external factors. Therefore, this study uses the MF-DCCA method to compare and analyze the efficiency changes of independent markets and interactive markets before and during the epidemic. In addition, the MF-DCCA method is also used to analyze the risk transmission between the WTI crude oil market and the coal market.

The rest of this paper is organized as follows: Section 2 introduces the sources of data and related statistical information. Section 3 introduces the application process of MF-DFA and MF-DCCA methods. Section 4 analyzes and discusses the changes and risk transferability of WTI energy and coal market efficiency at different stages based on the MF-DFA and MF-DCCA methods. Finally, Section 5 shows the main conclusions.

2. Data and analysis

2.1. Data collection and descriptive analysis

The World Health Organization announced on January 30, 2020 that the COVID-19 epidemic is a Public Health Emergency of International Concern (PHEIC) [31]. The number of confirmed cases in the United States has increased rapidly. Fig. 1 collects the data of daily new cases in the United States from January 30, 2020 to May 7, 2021. It comes from the US Centers for Disease Control and Prevention [32].

Fig. 2 shows the daily closing price fluctuations of WTI crude oil and coal, from two years before the COVID-19 to the fourth peak of the epidemic (2018.1.1–2021.5.07).

In order to ensure the time series of the sample is synchronized, eliminating the non-trading and non-matching missing days data. So, it is a total of 775 data. The data of WTI crude oil comes from the US Energy Information Administration (EIA) website [33]. Coal data comes from the Trading Economics website [34].

Fig. 2 can be seen that the volatility of the two markets before and after the epidemic has changed greatly. The market price curve exhibits nonlinear and non-stationary characteristics. After the epidemic, the closing prices of WTI crude oil and coal all show unusual characteristics and trends in the short time. In particular, WTI crude oil futures even became negative on April 23. This phenomenon shows that market occurred extreme events “COVID-19” epidemic during this period, which changed the original volatility of the market. This has increased the volatility and risks of the entire market. In order to adjust the energy
market, the Federal Reserve introduced an unlimited QE policy to alleviate the “serious damage” caused by the epidemic to the energy market economy. The intuitive change is, after that, the volatility decreased and prices rose slowly, even higher than before. At the same time, it is worth noting that the changes trend of WTI crude oil and coal price are very similar. There is a certain correlation between the two energy markets, showing a phenomenon of “synchronization”.

2.2. Data processing and statistical analysis

In order to further quantify the risk status and the correlation between the two energy markets, we perform logarithmic difference processing on the original data to eliminate possible heteroscedasticity in the time series. Convert the time series of futures prices into a series of logarithmic returns \( \{ r_t \} \):

\[
r_t = \ln P_t - \ln P_{t-1}, \quad t = 1, 2, \cdots, N
\]

Here, \( N \) is the actual effective trading days in the time series; \( P_t \) is the price of the futures on the \( t \)th trading day; \( r_t \) is the daily return rate after conversion. Fig. 3 is the time series of WTI oil and Coal price returns.

As shown in Fig. 3, the return series of the two energy futures prices fluctuate around zero. When the epidemic first broke out, the coal

![Fig. 3. The time series of WTI oil and Coal price returns.](image)
characteristics. Traditional statistical analysis methods cannot be directly used to analyze their fluctuation characteristics and the relationship between them. The multifractal detrended fluctuation analysis (MF-DFA) method proposed by Kantelhardt et al. [38] has great advantages in studying non-stationary time series. It can compare and analyze the risk and volatility of the two markets through the q-order Hurst index. However, the relationship between the two markets is usually more complex, interrelated and mutually transmitted. Therefore, this paper introduces the multifractal detrended cross-correlation analysis (MF-DCCA) developed by Zhou et al. [39] to further analyze the cross-correlation of the overall market and the risk conduction effect between the two markets.

Before studying the cross-correlation relationship, we first used the MF-DFA method to separately quantify the risk of WTI crude oil and coal futures markets, and used the Hurst index of the return rate series to represent the persistence characteristics and risk volatility of the two futures markets during the epidemic. Generally speaking, $h(q)$ changes with the change of $q$. When $q = 2$, it is the Hurst exponent (H). When $h(q - 2) > 0.5$, the time series has a long-term continuous development trend, that is, the market will maintain the same trend and continue to develop after this. When $h(q - 2) < 0.5$, the time series has an anti-sustainable development trend, that is, the market will show a different development trend from before. And, the greater the value of $\Delta h$, the greater the volatility of the market during this period and the greater the market risk.

Next, based on the overall market level, we use the MF-DCCA method to analyze the risk transmission between the two markets. The process is as follows:

Step 1: Construct the side sequence.

First, set the time series of the returns of WTI crude oil and coal futures markets as $x_t$ and $y_t$.

$$X_t = \sum_{i=1}^{N} (x_t - \bar{x})$$

$$Y_t = \sum_{i=1}^{N} (y_t - \bar{y})$$

Where $\bar{x}$ and $\bar{y}$ denotes the average over the whole time series. $t = 1, 2, \ldots$,

$$N, \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i, \bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i$$

Step 2: Divide the profile. $(\{x_t\})_{t=1}^{N}$

Divide the profile $X_N$ into $N_s/N_s$ ($N_s$ means rounds) nonoverlapping segments of equal length $s$. Since $N_s$ is not necessarily an integer, in order not to discard the remaining data at the end of the time series. In order not to disregard this part, the same procedure is repeated starting from the opposite end. So, get $2N_s$ parts, that is, $\{X_{ij}\}_{j=1}^{s}$ and $\{Y_{ij}\}_{j=1}^{s}$.

It can be expressed in detail as:

$$\{X_{(i-1)s+1:j}\}_{j=1}^{s}, v = 1, 2, \ldots, N_s, j = 1, 2, \ldots, s$$

$$\{X_{1:s}\}_{j=1}^{s}, v = N_s + 1, N_s + 2, \ldots, 2N_s, j = 1, 2, \ldots, s$$

$$\{Y_{(i-1)s+1:j}\}_{j=1}^{s}, v = 1, 2, \ldots, N_s, j = 1, 2, \ldots, s$$

$$\{Y_{1:s}\}_{j=1}^{s}, v = N_s + 1, N_s + 2, \ldots, 2N_s, j = 1, 2, \ldots, s$$

Step 3: Use the least squares method to fit the local trend of $2N_s$ subsequences to obtain the $v$th fitting polynomials $X_{v(0)}$ and $Y_{v(0)}$. Then use it to eliminate the local trend of each subsequence to get the covariance:

$$f^2(v, s) \sum_{j=1}^{s} \left| X_{1:s} - X_{v(0)} \right| \left| Y_{1:s} - Y_{v(0)} \right| v = 1, 2, \ldots, 2N_s$$

Step 4: Calculate the $q$ fluctuation function.

### Table 1

| Period                  | Statistics | Before COVID-19 (2018.1.1–2020.1.29) | During COVID-19 (2020.1.30–2021.5.07) |
|-------------------------|------------|--------------------------------------|---------------------------------------|
|                         | Mean       | -0.0003                              | 0.0024                                |
|                         | Maximum    | 0.1326                                | 0.0596                                |
|                         | Minimum    | -0.0792                               | -1.0000                               |
|                         | Std. Dev.  | 0.0213                                | 0.0131                                |
|                         | Skewness   | 0.0295                                | -3.4051                               |
|                         | Kurtosis   | 7.5819                                | 39.2059                               |
|                         | J-B        | 391.0678                              | 25278.7300                            |

| Basic statistics of WTI crude oil and coal returns. |
|----------------------------------------------------|
| Period                  | Statistics | Before COVID-19 (2018.1.1–2020.1.29) | During COVID-19 (2020.1.30–2021.5.07) |
| Mean       | -0.0003                              | 0.0024                                |
| Maximum    | 0.1326                                | 0.0596                                |
| Minimum    | -0.0792                               | -1.0000                               |
| Std. Dev.  | 0.0213                                | 0.0131                                |
| Skewness   | 0.0295                                | -3.4051                               |
| Kurtosis   | 7.5819                                | 39.2059                               |
| J-B        | 391.0678                              | 25278.7300                            |
\[
f(s) = \left\{ \frac{1}{2N_s} \sum_{i=1}^{2N_s} [f^2(v,s)]^q \right\}^{1/q}, \quad q \neq 0
\]
(7)

\[
F(s) = \exp \left\{ \frac{1}{4N_s} \sum_{i=1}^{2N_s} \ln [f^2(v,s)] \right\}, \quad q = 0
\]
(8)

Step 5: If there is a certain power-rate cross-correlation relationship between the two markets, the following relationship hold:

\[
f_q(s) \sim s^{h_{xy}(q)}
\]
(9)

\[
\log f_q(s) = \log C + h_{xy}(q) \log s
\]
(10)

Change \(q\) to obtain \(h_{xy}(q)\) corresponding to different \(q\), where, for each \(q\) value, use the least-square (OLS) to linearize \(\log f_q(s)\) and \(\log s\) return, then draw a scatter plot, where the slope of the regression line \(h_{xy}(q)\) is a power law exponent, called the generalized-cross correlation exponent.

If \(h_{xy}(q)\) has nothing to do with \(q\), it means that there is no cross-correlation relationship between the two market systems. On the contrary, it proves that there is a correlation and shows a multifractal feature. Subdivided further, if \(h_{xy}(q) > 0.5\), this cross-correlation relationship is long-persistent. It implies that when the price of one market rises (decreases), another market also will show an upward (decreasing) trend. If \(h_{xy}(q) < 0.5\), then this cross-correlation is anti-persistent. This means that when the market changes, another market also shows an opposite trend. In addition, when \(q < 0\), \(h_{xy}(q)\) reflects the scaling behavior of small fluctuation factors in the market. When \(q > 0\), \(h_{xy}(q)\) reflects the scaling behavior of market fluctuation factors.

Step 6: Analyze multifractal spectrum.

If the correlation between these two markets is non-linear and has multifractal characteristics, then it can further get the Renyi mass exponent \(\tau(q)\):

\[
\tau(q) = q h(q) - 1
\]
(11)

Using the Legendre transformation, the singular exponent \(\alpha(q)\) and the multifractal spectrum \(f(\alpha)\) can be finally obtained.

\[
\alpha(q) = \frac{d\tau(q)}{dq} = h(q) + q h'(q)
\]
(12)

\[
f(\alpha) = q^{\alpha - \tau(q)} = q^{[\alpha - h(q)] + 1}
\]
(13)

In addition, the multifractal intensity is generally expressed by the multifractal spectrum width \(\Delta \alpha\) and strength \(\Delta h\):

\[
\Delta \alpha = \alpha_{max} - \alpha_{min}
\]
(14)

\[
\Delta h = h_{xy}(q)_{max} - h_{xy}(q)_{min}
\]
(15)

If the curve of the multifractal spectrum \(f(\alpha) \sim \alpha\) is single-peaked and bell-shaped, it shows that the cross-correlation relationship between the two markets does have multifractal characteristics. In addition, the greater the value of the multifractal strength, the more complex the cross-correlation relationship and the greater the risk conduction effect.

Fig. 4. Double log chart of WTI crude oil and coal futures markets. Notes: a is the period before the epidemic (2018.1.1–2020.1.29); b is the period of the epidemic, divided into four stages: I-the first stage (2020.1.30.–2020.4.6.), II-the second stage (2020.4.7–2020.7.17), III- (Phase 3 2020.7.18–2021.1.8), IV (Phase 4 2021.1.9–2021.5.7).
4. Results and discussion

4.1. Research on the multifractal characteristics of the markets

(1) The autocorrelation relationship of markets

The MF-DFA analysis method was used to test the fractal characteristics of the time series in the WTI crude oil futures market and coal futures market before and during the epidemic. The value of q is $-4, -3, ..., 3, 4$, and the fluctuation function ($\log f \sim \log s$) of the two energy futures markets is obtained. It can be seen from Fig. 4 that before and after the outbreak, the market’s volatility function $\log f$ and scale logs always have a significant non-linear trend. That is, these two energy futures markets have always had multifractal characteristics. The deteriorating development of the epidemic has not affected the multifractal characteristics of these two independent markets.

Further analyze the volatility of the energy market during the four stages of the epidemic. As shown in Fig. 5 and Fig. 6, the volatility of the energy market at different stages is significantly different. In the third stage, market volatility is significantly weakened. This stage is a period of relatively stable market development so far. In the fourth stage, the market’s volatility increased significantly. On the whole, the second
stage is the most volatile period in the WTI market so far, while the coal market is the most volatile in the fourth stage. These preliminary calculation results are similar to the actual market fluctuations in Figs. 2 and 3. At the same time, based on the overall comparison of the two markets, it can be found that the volatility of the WTI market was greater than that of the coal market in the first two periods. In the later period, the volatility of the coal market was more severe than that of the WTI market. Despite the number of new cases per day in US hit a peak again, the above results show that market volatility is not completely affected by the epidemic.

(2) The cross-correlation relationship of markets

Crude oil and coal because of their mutual substitution, their markets also exist mutual interference and connection. Therefore, during the epidemic, investors who enter the energy futures market for trading and regulators who formulate relevant policies should consider these two markets as a whole related to each other. If only consider one of them, and ignore another market, it will lead to deviations in the overall understanding of the market. But due to the differences between the two markets and the interference of the external environment, this relationship cannot be directly observed. Based on this, this article further uses the MF-DCCA method, using multifractal spectrum and related parameters to further reveal the nonlinear dynamic characteristics during the epidemic.

Fig. 7 shows the multifractal spectrum between the two energy market return series. It can be seen from the double logarithmic graph of the covariance fluctuation function that for different q. When changing from -4 to 4, the corresponding double logarithmic surface is uneven. It indicates that there is a power-law cross-correlation between function and time scale. The mass exponent \( \tau(q) \) and cross correlation exponent \( h(q) \) both increase nonlinearly with the change of q. At the same time, the multifractal spectrum \( f(\alpha) \) chart presents a single-peak bell shape. In summary, it is shown that there is a cross-correlation between the returns of the WTI crude oil and coal market in the research interval.

4.2. Research on the development situation of markets

In Table 2 and Table 3, when \( q = 2 \), the persistent characteristics of the independent energy market in the research interval can be judged from the Hurst exponent \( h(q) \). The cross-correlation exponent \( H_{xy}(q) = 2 \) can determine the impact of the correlation between the two energy markets. The value of \( \Delta h \) represents the multifractal degree of the market structure and the market efficiency. The smaller the value, the higher the efficiency of the market.

Comparing the market efficiency of the four periods of the epidemic
with that of the market before, it is found that after the epidemic, Δh increased rapidly, and the market efficiency decreased significantly. In particular, the first stage is most obvious. In Table 3, the Δh index of WTI and coal market in the first stage is 0.6550 and 0.4965 respectively, and the market efficiency has dropped by 87% and 17%. But the decline of coal market is smaller. The Hurst exponent of the WTI crude oil futures market is 0.2846. This means that the WTI crude oil market has anti-persistence at this time. The small fluctuations in the WTI market increased rapidly, and the market efficiency decreased significantly. At the same time, it is observed that the Hurst index (h(q = 2)) of the WTI crude oil futures market is 0.5308, which has long-persistence. The later development will continue the trend of this stage. The Hurst index of the coal market is 0.3720, showing anti-persistence characteristics. This means that the follow-up development trend is different from this stage.

In the stage III, as the development of the epidemic enters a new peak period, the Fed’s QE policy has further increased. At this time, the efficiency of independent markets and interactive markets continued to increase significantly. The Δh of WTI market decreased from 0.6480 to 0.4918, and the market efficiency increased by 34.86%. The Δh of Coal market decreased from 0.4221 to 0.4449, and the market efficiency increased by 9.54%. The efficiency of interactive market increased by 9.54%. And the market’s Hurst exponent (h(q = 2)) and cross-correlation exponent Hxy(q = 2) are both greater than 0.5. The entire market shows long-persistence characteristics and “synchronization” trends. However, after entering the stage IV, market efficiency declined. The Hxy(q = 2) of the interactive market is 0.4953, that is, the development of the two markets is not completely synchronized. Among that, the h(q = 2) of the WTI crude oil market is 0.4751, and the market is anti-persistent. The h(q = 2) of the coal market is 0.5028, and the market exhibits long-persistent.

In summary, it can be seen from Table 3 that the development status of WTI and coal markets in the four periods is different. However, whether it is a single market or an interactive market, market efficiency decreases significantly after the epidemic.

### Table 2

Statistics related to market development (Before the epidemic).

| Stage | q | WTI oil market | Coal market | Average market | Comprehensive market | Interactive market |
|-------|---|----------------|-------------|----------------|---------------------|-------------------|
| Before COVID-19 (2018.1.1-2020.1.29) | -4 | 0.7626 | 0.8395 | 0.8011 | 1.6021 | 0.8496 |
| | -3 | 0.7168 | 0.7945 | 0.7556 | 1.5112 | 0.8078 |
| | -2 | 0.6697 | 0.7457 | 0.7077 | 1.4154 | 0.7622 |
| | -1 | 0.6257 | 0.7031 | 0.6644 | 1.3288 | 0.7180 |
| | 0 | 0.5860 | 0.6684 | 0.6272 | 1.2544 | 0.6792 |
| | 1 | 0.5480 | 0.6205 | 0.5842 | 1.1685 | 0.6451 |
| | 2 | 0.5074 | 0.5475 | 0.5275 | 1.0549 | 0.6131 |
| | 3 | 0.4616 | 0.4731 | 0.4674 | 0.9348 | 0.5823 |
| | 4 | 0.4127 | 0.4159 | 0.4143 | 0.8286 | 0.5539 |
| Δh | 0.3499 | 0.4236 | 0.3868 | 0.7735 | 0.2958 |

### Table 3

Statistics related to market development (During the epidemic).

| Stage | Stage I (2020.1.30-2020.4.6) | Stage II (2020.4.7-2020.7.17) | Stage III (2020.7.18-2021.1.8) | Stage IV (2021.1.9-2021.5.7) |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| q | WTI oil market | Coal market | Average market | Comprehensive market | Interactive market | WTI oil market | Coal market | Average market | Comprehensive market | Interactive market | WTI oil market | Coal market | Average market | Comprehensive market | Interactive market |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| -4 | 0.8580 | 1.0298 | 0.9439 | 1.8878 | 0.9623 | 0.9598 | 0.7640 | 0.8619 | 1.7238 | 0.6699 |
| -3 | 0.8154 | 0.9836 | 0.8995 | 1.7990 | 0.9128 | 0.9308 | 0.7121 | 0.8214 | 1.6428 | 0.6660 |
| -2 | 0.7576 | 0.9221 | 0.8399 | 1.6797 | 0.8431 | 0.9022 | 0.6466 | 0.7744 | 1.5488 | 0.6671 |
| -1 | 0.6660 | 0.8470 | 0.7565 | 1.5131 | 0.7539 | 0.8916 | 0.5727 | 0.7321 | 1.4643 | 0.6701 |
| 0 | 0.5167 | 0.7656 | 0.6412 | 1.2824 | 0.6626 | 0.9058 | 0.4996 | 0.7027 | 1.4054 | 0.6485 |
| 1 | 0.3710 | 0.6882 | 0.5296 | 1.0591 | 0.5900 | 0.7649 | 0.4325 | 0.5987 | 1.1974 | 0.5501 |
| 2 | 0.2846 | 0.6234 | 0.4540 | 0.9080 | 0.5385 | 0.5308 | 0.3720 | 0.4514 | 0.9028 | 0.4055 |
| 3 | 0.2352 | 0.5726 | 0.4039 | 0.8079 | 0.5020 | 0.3913 | 0.3182 | 0.3548 | 0.7095 | 0.2947 |
| 4 | 0.2030 | 0.5333 | 0.3681 | 0.7362 | 0.4755 | 0.3118 | 0.2722 | 0.2920 | 0.5841 | 0.2255 |
| Δh | 0.1650 | 0.4965 | 0.5278 | 1.1515 | 0.4868 | 0.6480 | 0.4918 | 0.5609 | 1.1598 | 0.4827 |

Notes: The average market represents the average value of the two energy futures markets without mutual influence. The integrated market represents the direct addition of the two energy futures markets. The interactive market represents that the two energy futures markets are mutually influencing and restricting each other.
has rapidly declined after the epidemic. However, with the continuous development of the epidemic in US, market efficiency in the second and third stages has not declined, but has improved. Especially in the stage III, the market efficiency of WTI crude oil market increased by 34.86%. The market efficiency of coal market increased by 9.54%. The efficiency of the interactive market has increased by 38.64%. After entering stage IV, market efficiency declined rapidly. They dropped by 33.81%, 37.43% and 53.49% respectively. Moreover, the persistence characteristics (q = 2) of the market in the first three stages are consistent with the actual development trend, which shows that the value of h (q = 2) can describe the development trend of the energy market in the short term. In addition, it is worth noting that when the WTI crude oil and coal markets are analyzed as independent individuals and as a whole, the risk of the interactive market is greater than the average market and less than the integrated market. This also fully shows that there is transitivity and contagion between the two markets.

4.3. Discussion and analysis

In this study, compared with the energy market efficiency two years before the outbreak of the epidemic, we analyzed the changes in market efficiency during the three peak periods of the epidemic. On the whole, after the outbreak of the epidemic, market efficiency declined rapidly and risks increased. However, it is different because of the Fed’s QE policy, global energy supply and demand relationship and energy views of US. Next, this paper discusses the causes of the interactive market after the outbreak, and focuses on analyzing the phased changes in energy market efficiency.

(1) The previous calculation results show that the WTI crude oil and coal markets have always had an interactive relationship before and after the epidemic. Specifically, in phase I and phase II, the two markets have a long-persistent correlation, showing a lagging trend of “same rise and fall”. This shows that the changes in the WTI crude oil market may lead to similar developments in the coal market. In phase III and phase IV, the two markets showed opposite development trends. Moreover, when q > 0, the $h_0$ value of the interactive market return sequence is lower than 0.5, and the two markets are inversely correlated. However, the response of the two markets to internal factors is still a long-lasting cross-correlation. During the epidemic, external factors dominate. That is, the epidemic, the economy (unlimited quantitative easing policy) and energy policies have a greater impact on the WTI crude oil and coal market.

Moreover, there is risk transmission in the interactive markets. As shown in Table 3, the risk of a single market is less than the risk of an interactive market at each stage. To a certain extent, the risks of low-efficiency markets are passed on to high-efficiency markets, and high-efficiency markets also weaken the risks of low-efficiency markets. This shows that the risks within the two markets with interactive correlations are not only averaged and superimposed, but transmitted and interacted. coal and crude oil, as part of the replacement relationship of two important fossil energy sources, determine the cross-correlation and risk transmission of the two futures markets. That is, the shift in demand for crude oil and coal by related industries and products will cause relative changes in the prices of the two markets. For example, when crude oil prices continue to remain high, large energy consuming countries usually look for alternative energy sources. For countries with abundant coal reserves or more convenient to import coal, energy consumption has shifted from crude oil to relatively cheap and stable supply of coal. Increased demand for coal has pushed up coal prices. Since March, the global epidemic has escalated and the US epidemic has worsened. The economic operation has encountered huge challenges, and the supply chain of some industries has broken. Global energy demand has fallen by 4.5% this year, and demand for crude oil has also shrunk sharply [40]. People’s investment in the crude oil futures market has declined. At the same time, oil-producing countries have not put in place measures to reduce production, and the storage of US crude oil warehouses continues to increase, which also exacerbates the imbalance between supply and demand in the crude oil market. Crude oil prices fluctuated and dropped, driving prices in the international bulk commodity market to fall across the board. Therefore, during the entire supply-demand imbalance and the special period of economic depression, the coal market, which is also an energy fuel but also a substitute for oil is also affected. EIA predicts that by 2020, coal consumption in the US power industry will drop by 18% [41]. At the same time, apart from the influence of external factors, the rise in coal prices has also had a short-term impact on WTI crude oil prices. Crude oil prices also rebounded briefly.

(2) In different stages of the epidemic, the relative relationship between the market efficiency of the two is not consistent. In the first two stages, the generalized Hurst exponent of the WTI crude oil yield series has a larger variation than the coal futures market. This shows that the efficiency of the WTI crude oil market is lower than that of the coal market at this stage, and the market risk is greater. Mainly because WTI crude oil is one of the most important energy sources in American industrial production. At the same time, crude oil futures are also an important investment product in the commodity financial market. Their trading volume and market activity are both high, and price fluctuations are more susceptible to the external environment. After the epidemic, the global oil market is undergoing in-depth adjustments, and there is a serious imbalance between supply and demand.

On the supply side, the oil production reduction agreements reached by the Organization of the Petroleum Exporting Countries (OPEC) and a number of non-OPEC oil-producing countries have been slow to implement and failed to make clear commitments to reduce production [42, 43]. Worries about oversupply have increased. While US commercial crude oil inventories have grown, the demand has continued to shrink. On the consumer side, when the COVID-19 global pandemic began, the global economy fell rapidly and global demand was weak. With the intensification of the epidemic in the United States and the implementation of blockade measures in other countries, the large-scale cancellation of international flights has greatly reduced the demand for crude oil. “Global Energy Review 2020” reports that global energy demand fell by 3.8% in the first quarter. Oil demand fell by 5% year-on-year [44]. International oil prices continued to fall sharply, and even showed a negative value (−37.63 USD/barrel) for the first time from April 20th.

Relative to oil, thermal coal prices remain elastic, albeit at a low level. Since the 21st century, as countries continue to pay attention to global climate change and accelerate the adjustment of energy structure, many developed countries have gradually adopted clean energy to replace coal energy consumption. Therefore, coal supply is gradually decreasing. Under the first round of the epidemic, the coal market was less affected than the crude oil market. The crude oil market is less efficient than the coal futures market.

Starting in the second half of 2020, the efficiency of the coal market is lower than that of the WTI crude oil market. Affected by the epidemic and mismatch of supply and demand, coal prices have continued to decline. Although coal prices in the fourth stage began to rise, this is essentially a cumulative outbreak of contradictions between supply and demand in the thermal coal market after the outbreak.

On the supply side, coal prices fell during the epidemic. Many companies have closed some mining areas and reduced production. The production capacity has not been fully released. In 2019, Australia’s coal production was 13.21 EJoules. In 2020, coal production fell by 6.2%. Global coal production has also fallen by 5.1% [40]. Although coal prices continue to rise in third stage. However, in the fourth stage, coal...
demand shifted to the off-season, and coal price adjustments fell. The epidemic in Europe spread again. It casts a shadow on the global economy. Most markets have adjusted significantly. Industrial chain companies such as steel and coking are facing severe and complex market risks. Stable supply and demand in the steel and coal markets are facing challenges. In particular, coal market prices fluctuate sharply, and corporate market demand for hedging has increased. As a result, the risk of the coal market in the fourth stage has increased. On the whole, from the second half of 20 to the first half of 21, the coal market is less efficient than the crude oil market. And this is precisely the interaction between the markets, leading to changes in the coal market risk later than the crude oil market.

(3) Whether it is a single energy market or an interactive market, since the global outbreak of COVID-19, market efficiency has dropped significantly. The epidemic has had a significant impact on the world economy and energy market, and the supply and demand of energy are seriously imbalanced.

After the epidemic in January 2020, the efficiency of the energy market has dropped significantly, and the prices of WTI crude oil and coal have fallen: In the short term, COVID-19 has had a significant impact on the operation of the global energy market. On the one hand, energy demand has been drastically reduced. Under the epidemic, the global economy is weak, and many countries have stopped work and production to curb the spread of the epidemic. On the other hand, coal supply has been delayed, but crude oil production has not decreased. Some countries are generally implementing the “limited production” policy. However, the OPEC crude oil producing countries have not made a commitment to reduce production for a long time, and US crude oil inventories are backlogged. Disorders in the supply chain have exacerbated the imbalance of world commercial supply and demand, leading to skyrocketing inventories, plummeting prices, declining investment, and declining market efficiency.

Since then, the US has experienced two peaks, but the efficiency of the energy market has not continued to decline as speculated. Instead, it has improved in the second and third phases. Especially in the third stage, the improvement is quite obvious. The overall energy market price showed a “V”-shaped trend. In the first half of 2020, the global economic downturn has affected energy prices sharply. However, as the Fed’s continues its unlimited QE policy, energy prices continue to rise. The Federal Reserve maintains near-zero interest rates and strongly pushes up the prices of energy commodities. Market efficiency has been greatly improved. At the same time, measures such as employment subsidies, interest rate cuts and loans have stimulated the market, which has also stabilized the investment sentiment of market traders. To a certain extent, it offset the impact of the epidemic on the energy market economy. The market efficiency improved.

Further combine the analysis of the supply and demand side. From the fourth quarter of 2020, under the stimulus of continued fiscal policy, the US economy has recovered. At the same time, the weather is getting colder and energy demand is gradually returning to normal. Production capacity has gradually recovered, and crude oil inventories have continued to fall. The global energy market gradually balances supply and demand. The Australian Thermal Coal Price Index and WTI crude oil prices rebounded rapidly in the fourth quarter of 2020, gradually returning to their pre-epidemic levels.

However, as the Fed continues to increase its quantitative easing policy, the scale of US debt continues to expand. Inflation pressure continued, energy prices continued to rise, and the energy crisis began. The excessive fiscal policy has weakened the economic market’s stimulus, and market efficiency has declined. In addition, the Biden government has implemented a broader clean energy plan. On the first day of his tenure, Biden signed an administrative order to cancel the construction of the Keystone XL oil pipeline. In April, Biden’s government announced the abolition of subsidies to fossil fuel companies. This move will promote a certain increase in US oil exports in the short term. At the same time, after the US rejoined the “Paris Climate Agreement” and set a carbon neutrality goal, the country’s demand for fossil energy decreased and consumption fell. It also brought heavy losses to the crude oil and coal markets.

On the whole, the Fed’s unlimited QE policy has stabilized the US economy under the epidemic. In the short term, it does play an important role in saving the financial crisis and alleviating the economic recession. However, excessive reliance on monetary stimulus, interest rate cuts, subsidies and other policies cannot actually promote the continued growth of the market. Excessive fiscal stimulus policies have caused commodity prices to rise and inflation to last longer. In the future, the volatility and risk of the energy futures market will increase.

5. Conclusion

The COVID-19 epidemic has had a major impact on the US energy market and caused severe market turbulence. After the epidemic, the US quickly adopted unlimited QE policies to stabilize and restore the energy market economy. This paper selected coal and WTI crude oil prices from January 1, 2018 to May 7, 2021 as the research objects. Taking the two years before the COVID-19 as a control, the epidemic was further divided into four stages based on the three peaks of the epidemic in the US. The paper used the MF-DFA and MF-DCCA methods to compare the market efficiency and risk transmission effects of these two markets at different stages, and further analyzes the impact of factors such as the COVID-19 epidemic and QE policies. The main conclusions are as follows:

First, calculations using the MF-DCCA method show that there is a cross-correlation relationship between WTI crude oil and coal markets. This shows that in two markets with interactive correlations, risks are not only averaged and superimposed, but are transmitted and interacted with each other. There is a partial substitution relationship between coal and crude oil in fossil energy. The shift in demand for crude oil and coal by related industries and products will result in relative changes in the prices of the two markets.

Second, at different stages, the relative relationship between the efficiency of the WTI crude oil market and the coal market is not consistent. When the epidemic first broke out, due to the disorder of supply and demand in the energy market, WTI crude oil futures, as an important investment product in the bulk commodity financial market, their price fluctuations were first affected by the external environment. The market efficiency is lower than that of the coal market, and the market risk is greater. After entering the second half of 2020, the contradiction between supply and demand accumulated in the coal market broke out. In addition, the global coal policy and climate policy are more unfavorable to the coal market. The efficiency of the coal market in the later period is lower than that of the WTI crude oil market, and the market’s volatility has intensified.

Third, whether it is a single energy market or an interactive market, since the global outbreak of the COVID-19 epidemic, market efficiency has dropped significantly. However, after the Fed announced the unlimited QE policy, despite the two outbreak peaks in the US, the efficiency of the energy market began to improve. Especially in the fourth quarter of 2020, the improvement is quite obvious. This policy has a certain effect on alleviating the impact of the epidemic on the energy market and stabilizing the market economy. However, market risks increased again in 2021 and market efficiency declined. Therefore, in the long term, the stimulus of excessive monetary policy to the economy gradually weakens. It will even cause commodity prices to rise and inflation. In the future, the volatility and risk of the energy futures market will increase.

Author contribution statement

Qiang Wang: Conceptualization, Methodology, Software, Data
curation, Writing – original draft preparation, Supervision, Writing- Reviewing and Editing. Xuan Yang: Methodology, Software, Data curation, Investigation Writing – original draft, Writing- Reviewing and Editing. Rongrong Li: Methodology, Data curation, Investigation Writing – original draft, Writing- Reviewing.

Declaration of competing interest

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

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References

[1] B.B. Ahundjanov, S.B. Akhundjanov, B.B. Okhunjanov, Risk perception and oil and gasoline markets under COVID-19, J. Econ. Bus. 115 (2021) 105979.
[2] C.T. Vidya, K.P. Prabhesh, Implications of COVID-19 pandemic on the global trade networks, Emerg. Mark. Finance Trade 56 (2020) 2408–2421.
[3] M. Ali, N. Alam, S.A.R. Rizvi, Coronavirus (COVID-19) — an epidemic or pandemic for financial markets, Journal of Behavioral and Experimental Finance 27 (2020) 100341.
[4] D. Zhang, M. Hu, Q. Ji, Financial markets under the global pandemic of COVID-19, Finance Res. Lett. 36 (2020) 101528.
[5] R. Gerlagh, R.J. Heijmans, K.E. Rosendahl, COVID-19 tests the market stability reserve, Environ. Resour. Econ. 76 (2020) 855–865.
[6] C. Gharib, S. Mefteh-Wali, S.B. Jabeur, The bubble contagion effect of COVID-19 outbreak: Evidence from crude oil and gold markets 38, Finance research letters, 2021, p. 101701.
[7] Y.D. Wang, Y. Wei, C.F. Wu, Analysis of the efficiency and multifractality of gold markets based on multifractal detrended fluctuation analysis, Phys. Stat. Mech. Appl. 390 (5) (2021) 817–827.
[8] R. Ichev, M. Marinic, Stock prices and geographic proximity of information: Evidence from the Ebola outbreak, Int. Rev. Financ. Anal. 56 (2018) 153–166.
[9] J. Wen, X.X. Zhao, C.P. Chang, The impact of extreme events on energy price risk, Energy Econ. 99 (2021) 105308.
[10] R. Van Eyden, M. Difeto, R. Gupta, M.E. Wohar, Oil price volatility and economic growth: evidence from advanced economies using more than a century’s data, Appl. Energy 223–234 (2019) 612–621.
[11] L.Y Zhang, H. Li, W.J. Lee, H. Liao, COVID-19 and energy: influence mechanisms and research methodologies, Sustainable Production and Consumption 27 (2021) 2134–2152.
[12] A.A. Salisu, G.U. Ebah, N. Usman, Revisiting oil-stock nexus during COVID-19 pandemic: some preliminary results, Int. Rev. Econ. Financ. 69 (2020) 280–294.
[13] S. Corbet, J.W. Goodell, S. Gündüz, Co-movements and spillovers of oil and renewable firms under extreme conditions: new evidence from negative WTI prices during COVID-19, Energy Econ. 92 (2020) 104978.
[14] H.W. Zhong, Z.P. Tan, Y.L. He, L. Xie, C.Q. Kang, Implications of COVID-19 for the electricity industry: a comprehensive review, CSEE Journal of Power and Energy Systems 6 (2020) 489–495.
[15] J.J. Szczypinski, J. Brzeszczyński, A. Charteris, P.R. Bwanya, The COVID-19 storm and the energy sector: the impact and role of uncertainty, Energy Econ. (2021) 105258. In press.
[16] F.P. Zha, Y. Tang, Y. Wei, T.T. Lu, Multidimensional risk spillovers among crude oil, the US and Chinese stock markets: evidence during the COVID-19 epidemic, Energy 231 (2021) 120949.
[17] P.K. Narayan, Oil price news and COVID-19 — is there any connection? Energy Research Letters 1 (2020) 13176.
[18] T.H. Le, A.T. Le, H.C. Le, The historic oil price fluctuation during the Covid-19 pandemic: what are the causes? Res. Int. Bus. Finance 58 (2021) 101489.
[19] L.A. Gil-Alana, M. Monge, Crude oil prices and COVID-19: persistence of the shock, Energy Research Letters 1 (2020) 13200.
[20] W.I. Huang, Y.Q. Zheng, COVID-19: structural changes in the relationship between investor sentiment and crude oil futures price, Energy Research Letters 1 (2020) 13665.
[21] A. Leach, N. Rivers, B. Shaffer, Canadian Electricity markets during the COVID-19 pandemic: an initial assessment, Can. Publ. Pol. 46 (2020) S145–S159.
[22] B. Plumer, In a First, Renewable Energy Is Pooled to Eclipse Coal in US 13, New York Times, 2020.
[23] N. Norouzi, G. Zarazua de Ruberos, S. Choupanpiesheh, F. Enevoldsen, When pandemics impact economies and climate change: exploring the impacts of COVID-19 on oil and electricity demand in China, Energy Research & Social Science 68 (2020) 101654.
[24] A. Dutta, D. Das, R.K. Jana, X.V. Yo, COVID-19 and oil market crash: revisiting the safe haven property of gold and Bitcoin, Resour. Pol. 69 (2020) 101816.
[25] C.L. Chang, M. McAlear, Y.A. Wang, Herding behaviour in energy stock markets during the Global Financial Crisis, SARS, and ongoing COVID-19, Renew. Sustain. Energy Rev. 134 (2020) 110349.
[26] W. Menci, A. Sensyu, X.V. Yo, S.H. Kang, Impact of COVID-19 outbreak on asymmetric multifractality of gold and oil prices, Resour. Pol. 69 (2020) 101829.
[27] K.P. Prabhesh, R. Padhan, B. Garg, COVID-19 and the oil price-stock market nexus: evidence from net oil-importing countries, Energy Research Letters 1 (2021) 13745.
[28] J. Wang, W. Shao, Junseok. Kim, Analysis of the impact of COVID-19 on the correlations between crude oil and agricultural futures, Chaos, Solit. Fractals 136 (2020) 109896.
[29] M.Y. Pa, H.Y. Shen, COVID-19 and corporate performance in the energy industry, Energy Research Letters 1 (2020) 12967.
[30] B. Oei, P.Y. Parra, C. Hasenfeld, COVID-19-final straw or deathknell for a global coal industry at the verge of collapse, IARE Energy Forum/Covid-19 Issue (2020) 33–37.
[31] World Health Organization, Novel Coronavirus(2019-nCoV) Situation Report-10, 20, https://www.who.int/docs/default-source/coronaviruse/situation-reports/ 20200310-sitrep-10-covd.pdf?sfvrsn=d082e480_2. (Accessed 26 October 2021).
[32] COVID Data Tracker, Trends in Number of COVID-19 Cases and Deaths in the US Reported to CDC, by State/Territory, 2021. https://covid.cdc.gov/covid-data-tracker/#trends/dailytrendscases. (Accessed 2 July 2021).
[33] U.S. Energy Information Administration, NYMEX Futures Prices, 2020. http:// www.eia.gov/dnav/pet/pet_pri_fut_s1_d.htm. (Accessed 26 October 2021).
[34] Trading Economics, Coal Prices, 2020. https://tradingeconomics.com/commo dity/coal. (Accessed 26 October 2021).
[35] C. Binder, Coronavirus fears and macroeconomic expectations, Rev. Econ. Stat. 102 (2020) 721–730.
[36] C. Fuentes-Albero, J.M. Roberts, Inflation Thresholds and Policy-Rule Inertia: Some Simulation Results, Board of Governors of the Federal Reserve System (US), 2021.
[37] A. Cukierman, COVID-19, seignorage, quantitative easing and the fiscal-monetary nexus, Comp. Econ. Stud. 63 (2021) 181–199.
[38] J.W. Kantelhardt, S.A. Zschiegner, E. Koscielny-Bunde, S. Havlin, A. Bunde, H. E. Stanley, Multifractal detrended fluctuation analysis of nonstationary time series, Phys. Stat. Mech. Appl. 316 (2002) 87–114.
[39] W.X. Zhou, Multifractal detrended cross-correlation analysis for two nonstationary signals, Phys. Rev. 77 (6) (2008), 066211.
[40] Trading Economics, Coal Prices, 2020. https://tradingeconomics.com/commo dity/coal. (Accessed 26 October 2021).
[41] BP, Statistical Review of World Energy 2021, https://www.bp.com/en/ global/corporate/energy-economics/energy-outlook.html. (Accessed 15 October 2021).
[42] U.S. Energy Information Administration, HORT-TERM ENERGY OUTLOOK, 2020. https://www.eia.gov/outlooks/eto/ . (Accessed 26 July 2021).
[43] I.V. Filimonova, V.D. Kozhevnik, V.Y. Nenov, A.V. Komarova, M.V. Mishenin, Supply as a factor in the destabilization of the oil market, Energy Rep. 6 (2020) 74–79.
[44] S. Stanco, T. Franz, Y. Dafermos, E. Van Waeyenberge, COVID-19 and crises of capitalism: intensifying inequalities and global responses, Can. J. Dev. Stud. 42 (2021) 1–17.
[45] U.S. Energy Information Administration, Global Energy Review 2020, 2020. http:// www.eia.gov/forecasts/annualenergyreview/2020 . (Accessed 20 October 2021).
[46] U.S. Energy Information Administration, OPEC Shift to Maintain Market Share Will Cause Global Inventory Increases and Lower Prices, 2020. https://www.eia.gov/ today/energyichief/ detail.php?id=43175. (Accessed 15 October 2021).