

Article

The Impact of the Ukrainian War on Stock and Energy Markets: A Wavelet Coherence Analysis

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Abstract: This study attempts to examine the existence of interdependencies between specific stock market indices, exchange rates and crude oil for the period January 2021 to July 2022 with daily data. In the period we have chosen, the post-vaccination phase against COVID-19, as well as the war in Ukraine, is covered. The variables selected for this study are RTSI, Eurostoxx, S&P 500, EUR/USD and RUB/USD exchange rates and crude oil prices. The selection of the specific variables was made because they are directly related to the pre-war period that coincides with the post-vaccine period of the pandemic, which allowed us to characterize it as the normal period and to characterize the period of the war in Ukraine that coincides with the energy crisis as the unstable period. In this way, the present study covers the markets of Russia and other developed economies. For empirical purposes, we applied a wavelet coherence approach in order to investigate the possible existence of simultaneous coherence between the variables at different times and scales for all the considered times. The findings of the study reveal the existence of strong correlations between all variables, during different time periods and for different frequencies during the period under review. Of particular interest is the finding that shows that during the crisis period, the RTSI significantly affects both the European and American stock markets, while also determining the evolution of the Russian currency. In addition, it appears that capital constraints in the Russian stock market, combined with increased demand for crude oil, determine the interdependence between RTSI and crude oil. Finally, an interesting finding of the study is the existence of a negative correlation between the US stock index and crude oil in low-frequency bands and the RTSI and Eurostoxx with crude oil for the post-vaccination and pre-war periods in the medium term. These findings can be used by both investors and portfolio managers to hedge risks and make more confident investment decisions. In addition, these findings can be used by policy makers in the planning of regulatory policies regarding the limitations of the systemic risks in capital markets.

Keywords: crude oil; energy crisis; exchange rates; Russo-Ukrainian war; stock market; wavelet coherence

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1. Introduction

At a time where the global economy seemed to have overcome the global financial crisis of 2007 and many countries were in a recovery phase, with positive growth rates and central banks implementing extensive programs to ease interest rates and other unconventional measures, two new crises appeared. The coronavirus pandemic and the war in Ukraine constituted the first generalized cases of black swans for the global economy in the 21st century. More specifically, after the end of the lockdown due to the pandemic and the return to “normality”, the war broke out in Ukraine, followed by the imposition of serious sanctions between the Western states and Russia, resulting in the beginning of a new crisis, the energy crisis, with concern about the emergence of another severe recession

and possibly a global food crisis. These possible developments as a consequence of the war in Ukraine led us to carry out the present study.

The period before the war in Ukraine marked a return to normality for the capital markets [1]. In addition, according to [2,3], the post-vaccination period is the period when societies returned to normality and the vaccination program positively affected economies across the world, recording positive growth rates. However, this period of normality abruptly ceased due to the outbreak of the Russia–Ukraine war. As expected, the most important sanctions imposed by Russia upon the European Union were related to the restrictions of energy resources. However, this resulted in soaring energy prices, adding to the already looming inflationary levels that had not been witnessed in Europe since the Second World War. This setting naturally created intense recessionary situations and ominous prospects. The impact of the energy crisis in Europe seems to be much more pronounced than in other developed economies, due to the greater dependence of European countries on Russian energy sources.

After this double shock, investor sentiment continues to remain under pressure, with the war in Ukraine showing no signs of abating as the inflationary pressures continue to rise. The emerging situation is forcing central banks to decide on interest rate hike policies in order to support currencies and social cohesion, thus fueling the global economic concerns of a possible severe slowdown or even recession, which, together with inflation, would result in extremely adverse situations.

As the operations of multinational corporations continued to shrink, reducing their profitability and recording significant losses to shareholders, the earnings scenario inevitably began to be revised. This situation was extended with the fall in the prices of most shares and the decline in the industrial stock indices. Specifically, as the global energy crisis intensifies, on the one hand, there is a direct negative impact on the shares of companies and stock market indices associated with energy consumption, while on the other hand, there is a positive impact on the shares of companies associated with the production of energy resources [4]. What is certain is that, currently, we live in a vulnerable period, which may be maintained for the coming years, forcing all the competent bodies to take the necessary measures to limit the economic losses and improve the prospects for their societies.

According to [5], fluctuations in oil prices, resulting from the dynamics of demand and supply, directly affect economic performance, applied energy policies, energy markets and indirectly government finances, which are concentrated almost exclusively on dealing with the crisis. Oil, regardless of its type, is the main driver of growth for all economies worldwide. Thus, the fluctuation of international crude oil prices affects the stability and prospects of all economies [6]. Furthermore, oil itself is a very important trading good, which transcends the sphere of economics and extends its influence into politics and diplomacy, offering the power of a military weapon [7].

The negative outlook of the E.U., due to the ongoing energy crisis is mainly due to the fact that the crisis mainly affects the German industry, which is the engine of the European economy, increasing the likelihood of a recession.

The preceding analysis, combined with the literature review presented in the next section, points to a gap in the literature that arises from the fact that the war in Ukraine and its market effects have not been thoroughly studied. A comparison with different periods, including the post-vaccination period, has also not been carried out. The present study attempts to fill this gap and contribute to the existing literature.

In this context, our study attempts to investigate the interaction between the oil market, general stock market indices and exchange rates. For this purpose, we use daily data for the period between 5 January 2021 and 25 July 2022, in order to cover the post-vaccination period that signals the beginning of an attempt to return to health, social and economic normality and the beginning of the war in Ukraine. In the empirical analysis, we apply the wavelet coherence methodology that allows the simultaneous capture of the co-movement between two different time series in two different fields, time and frequency. Due to its specificity, by determining both the changes in the frequency structure and the changes

in this structure over time, the method provides us with a simultaneous localization in the time and frequency domain, separates the fine details in a signal and has the ability to extract both local spectral and temporal information.

The method applied in our study has been used in the past to investigate previous crises, including COVID-19.

The paper is structured as follows: in Section 2, the literature review is presented, which focuses on the examined indices and variables used and the applied empirical methodology. Section 3 presents the data and the applied methodology, while Section 4 thoroughly analyzes the empirical results. The paper closes with main conclusions and proposed implications.

2. Literature Review

2.1. Oil Prices, Stock Markets and Exchange Rates: A General Overview

In financial literature, it is generally accepted that there exists an inverse relationship between commodities and stock markets. This may be considered as a sign of good portfolio diversifiers from a commodities perspective [8–17]. However, there are also a few studies that indicate a positive relationship between commodities and stock markets [18–21].

Several studies focus on the dependence relationship between the factors that we also deal with in our paper, i.e., oil price, stock markets and foreign exchange rates [22], suggesting the existence of a statistically significant relationship between stock exchange markets, foreign exchange rates and oil price fluctuations.

As expected, most of the literature shows the negative impact of oil prices on stock returns, when examining different economies throughout different periods [23–25]. Other studies [26] focus on the impact of oil price shocks on stock market returns of the GCC countries. Their results show that it is more likely that stock markets and the oil market will either simultaneously increase or fall apart together [27], whereas other studies deal with the COVID-19 pandemic as a new risk component on top of economic and market uncertainty that affects oil prices and volatility. Moreover, [1] shows that in periods characterized as normality, such as before COVID-19 and after the announcement of the availability of vaccines for the public, there is no interrelationship between crude oil and stock prices. On the contrary, in volatile periods, the causality between the stock markets and oil prices is more evident and that both exporting and importing crude oil countries are influenced on the same level.

During crisis periods such as the global financial crisis, there is clear evidence of stock market contagion worldwide [28,29]. Ref. [30] investigated the influence of oil price changes in the stock market returns of five developed countries (USA, Germany, France, Italy, and Japan) and five emerging ones (Tunisia, Argentina, Thailand, Brazil, and Jordan). In their empirical analysis, they used panel data for the period 2004 to 2014 and found that stock returns for developed markets are affected when the oil prices are higher, while in the opposite case, no significant impact is observed. Ref. [31] applied a DCC model in order to examine the existence of any correlations between gold, bitcoin and stock markets during the war in Ukraine. They found that the correlations between gold and stock markets, bitcoin and oil and between gold and bitcoin were less evident during the war in Ukraine. Similar reasoning was developed by the authors of [32], who examined the impact of the Russo-Ukrainian War on the commodity markets of oil, wheat, and natural gas, applying exponential and threshold asymmetry GARCH models. The empirical results verify the existence of anti-leverage effects on the wheat and natural gas commodity markets and proved the existence of the leverage effect in the Brent market. Moreover, Ref. [33] found that, after the beginning of the war, green bonds, gold, silver, the Swiss franc, and real estate proved to be the best hedge against geopolitical risk.

As far as foreign exchange rates are concerned, Ref. [34] concluded that exchange rate fluctuations occur at different scale levels during each time period. Moreover, it has been argued that oil price shocks have a negative impact on market stock prices and US dollar exchange rates in the short term [35]. Moreover, Ref. [36] suggested that the onset of the

Russo-Ukrainian war has led to the rapid depreciation of the Russian currency, leading to intraday price fluctuations.

In their empirical study, Ref. [37] concluded that crude oil prices affect the exchange rates of oil-exporting countries in a negative, statistically significant manner, while [7] concluded that there is a weak relationship between international crude oil prices and the exchange rates of oil-importing countries. Correspondingly, exchange rates' vulnerabilities directly affect all countries' economies [25].

In this context, policymakers, investors, managers, and all actors of an economy may follow a certain value-at-risk approach when making necessary decisions and may pursue the appropriate strategies for risk mitigation for both crude and clean oil routes, restricting the freight rate fluctuations [38,39].

2.2. Studying Financial Time Series through Wavelet Coherence Approach

The global economy has experienced several intense crises during the last 15 years. This situation has triggered deep and endless discussions among academics, managers, investors, policymakers and think tanks related to market, macroeconomic and monetary factors (i.e., stock exchanges, oil market and exchange rates) and their exact impact on the economy, markets, risk management, asset allocation and portfolio management. In order for all the actors of an economy to take the necessary measures to solve the current issues, it is necessary the application of a method that provides all the details of the examined time series. This method should take into consideration both time and frequency dimensions at different time periods, and a structure that is able to create the most effective combination of a well-diversified portfolio. This method is the wavelet coherence approach [6].

The wavelet approach effective at investigating and analyzing the course, the combination, and the attitude of specific variables, which produce economic shocks, taking into consideration both the time and frequency dimensions, at every moment [40–42].

According to [43], the wavelet approach, except for the more comprehensive answers it provides in almost all of the published studies, and in comparison with the correlation method, also takes into account how the investigated time series linkage evolves over time. Moreover, the wavelet coherence method informs us about the progress of the time series, while other widely applied methods cannot provide us with this information [41,44,45]. Ref. [46] found that during the COVID-19 outbreak, almost all of the European stock markets caused more spillovers to other stock markets than they received.

In recent years, several studies have been published, focusing on the relationship between commodities, exchange rates and stock market returns, using the wavelet coherent approach [25,43,47–50]. Ref. [51], by applying a wavelet coherence approach, found that during turmoil periods, gold, commodities, crude oil and the shipping index seem to be safe-haven assets for investors, in order to improve their portfolio diversification strategies.

More specifically, the dependence relationship between stock markets and oil price is incompatible on a short-term scale [49]. Furthermore, Ref. [8] examined the nexus between oil market stock markets in East Asia and concluded that there is an in-phase impact of oil prices on stock market returns and that in the long run, oil prices lead to stock market returns. Ref. [43] concluded that the co-movement between oil prices in OPEC and the largest African stock markets is relatively low. Ref. [52] suggested that the contribution of stock market shocks to other markets is substantially more important than that of commodities; however, their analysis reveals that the link between market returns is greater in the short run.

Ref. [53] used the wavelet coherence approach in order to examine the case of connectedness between most developed stock market indices worldwide, oil prices, gold and the most important cryptocurrencies, during the COVID-19 pandemic. They found strong co-movements and strong volatility spillover effects between stock markets [54–57] and they concluded that the US index greatly affects the examined stock markets. Moreover, they propose that investors should invest in gold [22] and cryptocurrencies [58] as

a safer investment project. Nevertheless, Ref. [57] contradicted this view by arguing that cryptocurrencies can act as safe-haven assets.

Ref. [59] applied wavelet coherence approach to investigate whether there are any correlations between a range of commodities and the Dow Jones Islamic Market World Index between 1999 and 2015. They reported the existence of interdependencies, which vary according to time and frequency, and high volatility. Moreover, they concluded that the induction of commodities such as gold, natural gas, and grains in a portfolio can result in a better diversifiable portfolio than oil and heavy metals.

According to [60], there is a correlation between stock markets and oil prices, with stock indices being the leading factor in this relationship, while after the 2008 global financial crisis, energy, and industrial metals, such as Brent oil and copper, seem to co-move with stock indices and be the most integrated commodities in stock markets [20]. On the other hand, Ref. [61] argues that the leading factor in this interrelationship is the oil prices.

Correspondingly, Ref. [62] applied a coherence wavelet method and uncovered the uncommon effect of pandemic and oil price shocks on the geopolitical risk levels, economic uncertainty and stock market volatility in high-scale domains, while [63], by applying the same method, identified flight-to-quality episodes in the relationship between stock and bond returns, during the COVID-19 period.

Ref. [64] examined whether the global financial crisis affected key metal future returns. They used the bivariate GARCH model, which shows the existence of time-varying volatility spillovers between the returns of the metals examined during the different stages of a crisis and suggested that a contingent linkage exists between gold and copper during all the period of crisis.

Ref. [6] examined the time–frequency relationship between oil price, stock returns and exchange rates using daily data, for the period February 1999 to March 2021. This study's sample includes the S&P 500 Index and the Bombay stock market index. Ref. [6] applied a wavelet coherence technique to capture the co-movement between time and frequency time series. The empirical results indicate the existence of robust, common tendencies between stock markets and oil price, as well as between oil price and rupees per dollar in India, while they do not seem to exist in the case between the stock market and exchange rate. Moreover, the study's findings suggest that stock returns and oil prices move in the same direction, while exchange rates and oil prices move in opposite directions.

Ref. [65], by applying a wavelet coherence approach, found that the Russia–Ukraine war played a key role in the evolution of oil prices and that a transition towards renewable energy sources would be the most deterministic solution to the energy crisis and to mitigate the war's impact. The geopolitical risk induced by the prevailing war in Ukraine led [66] to prove that investing in African firms' stocks could perform as hedging against market shocks induced by the Russian-Ukrainian geopolitical conflict.

3. Data and Methodology

Daily data of four major stock indices (EUROSTOXX Index, RTS Index, DAX Index and S&P 500 Index) and crude oil and exchange rates (EUR/USD, RUB/USD) are analyzed. A short description of the aforementioned variables is presented below.

- EUROSTOXX 50 Index: an index that covers 50 stocks from 12 Eurozone countries, representing a blue-chip leader's sector in the Eurozone.
- RTS Index: a cap-weighted composite index created from the prices of the most liquid Russian stocks of the largest and fastest-growing Russian issuers listed on the Moscow Exchange.
- S&P 500 Index: a stock market index that measures the stock performance of 500 large companies listed on US stock exchanges.
- RUB/USD: the Ruble to United States dollar exchange rate (the price of Russia's currency in terms of United States dollars).
- EUR/USD: the euro to United States dollar exchange rate (the price of European countries' currency in terms of United States dollars).

- Brent crude oil: a continuous contract that includes the front-month futures of crude oil, which are listed on the New York Mercantile Exchange.
- Chicago Board Options Exchange Volatility Index (VIX): The market's expectations for the upcoming price fluctuations of the S&P 500 Index. This index is used only for conducting robustness tests.

Data have been obtained from Investing.com and were taken on a daily basis from 5 January 2021 to 25 July 2022.

In order to examine possible interdependencies between the returns of widely known stock indices and the returns of crude oil and exchange rates, we applied the wavelet coherence method. For our empirical approach, we applied the continuous wavelet transformation created by Ref. [66] between $z(s)$ and $u(s)$ time series (Equation (1)).

$$C_{z,u}(s, f) = C_z(s, f)C_u^*(s, f) \quad (1)$$

where

$z(s)$ and $u(s)$ are represented by $W_z(s, f)$ and $W_u(s, f)$, respectively;

s represents the time;

f corresponds to the frequency;

$*$ determines the complex conjugation.

The continuous wavelet transformation is used for the computation of the cross-wavelet power. Moreover, the cross-wavelet power spectrum stresses the locations in the time–frequency domains that have considerable mutual power, thus revealing the restricted covariance between the two time series across all metrics.

The wavelet analysis used in Ref. [67] is a useful tool for analyzing time series with many different timescales or changes in variance and demonstrates all interdependency relationships between the time series examined and their different directions, shifts and robustness of the correlation across different time and frequencies.

The coefficient of squared wavelet coherence is calculated as follows, according to [68].

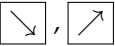
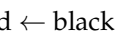
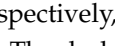
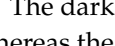
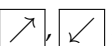
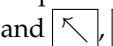
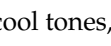
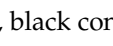
$$R^2(s, f) = \frac{|m(mW_{z,u}(s, f))|^2}{m(m^{-1}|W_z(s, f)|^2)m(m^{-1}|W_u(s, f)|^2)} \quad (2)$$

where “ m ” represents the time–frequency smoothing operator. The range of the squared wavelet coefficient lies between 0 and 1. Values closer to 1 correspond to a stronger relationship between the two series, whereas values closer to 0 represent a weaker relationship.

Based on the wavelet squared coherence process, it is restricted to accept only positive values, as it does not recognize the negative values and it is not able to clarify the time series directions. Thus, to solve this problem, we applied the phase difference process described in [69], as indicated in the following equation.

$$\varphi_{z,u}(s, f) = \tan^{-1} \left(\frac{\text{Im}\{m(m^{-1}W^{zu}(s, f))\}}{\text{Re}\{m(m^{-1}W^{zu}(s, f))\}} \right) \quad (3)$$

where Re and Im represent the smoothed cross wavelet transformations' real elements and imaginary elements, respectively.

Cross-wavelet coherence analysis generates a visual analysis that contains the following five key elements: black arrows that point in eight directions ($\leftarrow$, $\rightarrow$, $\uparrow$, $\downarrow$, , , , ) , warm and cool tones, black contours, two axes, and a cone. The $\rightarrow$ and $\leftarrow$ black arrows indicate an in-phase (positive) and out-of-phase (negative) correlation, respectively, whereas ,  and ,  highlight the first (second) series' leading effect. The dark contours in the plots show sections that exhibit coherence significance at 5%, whereas the bell-shaped curve illustrates the cone of influence.

4. Empirical Analysis

The aim of this study is to investigate the evolution in the prices of main stock markets (Russia, Europe and USA), Brent crude oil, EUR/USD and RUB/USD for the period between the post-vaccination period of COVID-19 and the Russia–Ukraine war.

From the returns' evolution of the above indicators and through applying the wavelet coherence analysis, we attempt to compare the interdependencies between the stock markets, the exchange rates and crude oil during two recent crises of different types that affected the global economy; that is the coronavirus pandemic after the official onset of vaccination programs and the Russia–Ukraine war. This analysis is expected to help us decide whether the stock indices of large and developed markets worldwide can be a safe investment choice during a war period and whether these results differentiate compared with a health crisis.

The descriptive statistics presented in Table 1. As it can be observed, almost all variables examined, except those implying currency exchange rates, exhibit high average values. This can be considered as a sign of high volatility, while Crude oil seems to exhibit a medium level of volatility. These results seem to be logical, as the period under consideration is a very volatile period, accompanied by the exit of global societies from quarantine due to the pandemic and the energy crisis as a result of the war in Ukraine. Table 1 also reveals that crude oil is positively skewed (0.63), while all the other variables are negatively skewed, which implies the existence of negative asymmetry. Furthermore, the kurtosis of the RUB/USD exchange rate is leptokurtic, as suggested by the value of 6.56, while all the other selected variables are platykurtic, as their maximum frequencies are relatively small. Finally, at the 5% level of significance, the Jarque–Berra test rejects the null hypotheses of normality for all variables.

Table 1. Descriptive statistics.

	EUROSTOXX Index	RTS Index	S&P 500 Index	EUR/USD	RUB/USD	Brent Crude Oil	Chicago Board Options Exchange Volatility Index
Mean	3953.17	1461.53	4262.56	1.14	0.013	84.59	22.22
Median	4012.28	1494.12	4298.83	1.16	0.013	76.73	21.32
Maximum	4401.49	1919.58	4796.56	1.23	0.019	137.00	37.21
Minimum	3359.83	742.91	3666.77	1.00	0.001	53.88	15.01
Std. dev.	251.91	262.24	286.55	0.05	0.001	19.49	5.05
Skewness	−0.37	−0.61	−0.18	−0.66	−0.027	0.63	0.67
Kurtosis	2.09	2.62	1.96	2.44	6.56	2.23	2.52
Jarque–Bera	22.48	26.38	19.65	33.50	204.49	35.24	31.17
Obs	386	386	386	386	386	386	386

Figure 1 illustrates the interdependencies between the Russian Stock Exchange Index (RSTI) and the most important stock exchange indices (Eurostoxx and S&P 500), exchange rates (EUR/USD and RUB/USD) and Brent crude oil.

More specifically, at the end of 2021 and before the beginning of the Ukraine war, we observed a positive short-term correlation between Eurostoxx and RTSI led by RTSI can be observed. This situation changed for the same frequency band after the beginning of the war and RTSI was no longer the leading indicator. However, in the medium term, after the outbreak of the energy crisis (03/2022), we observed a positive correlation between Eurostoxx and RTSI, led by RTSI (Figure 1a).

For the US stock exchange index (S&P 500), since the end of 2021 and until August 2022, we observed an in-phase correlation between RTSI and S&P 500 in the medium- and the long-term periods, with RTSI leading this dependency (Figure 1b). This outcome is contingent with the conjecture between RTSI and Eurostoxx. In Figure 1c, it is evident that in the lower bands (16–32 days) in the first semester of 2021, there is a negative correlation between RTSI and crude oil, with RTSI being the leading indicator. However, for the same bands and for higher ones, the situation changes radically after the unfolding of the war,

where there is evidence of in-phase correlation between these two indices, which is led by crude oil. After the outbreak of the energy crisis, there is a co-movement between the examined indices in the medium term.

Moreover, the EUR/USD exchange rate affects positively RTSI in the medium term during the first semester of 2021 and this seems to be the only dependency relationship between the two series (Figure 1d). As far as the wavelet coherence between RTSI and RUB/USD is concerned, we observed a robust interdependency for all the examined periods and for all the frequency bands (Figure 1e). The relationship shows either signs of a positive correlation led by RTSI, or co-movement intervals, mainly at 32–64 frequency bands, during the first semester of 2021.

An interesting output derived from the analysis of the first series is that for medium-frequency bands, and during the COVID-19 period, we observed a diversification effect between the Russian Stock Exchange Index and Brent crude oil. This effect is no longer evident, not even at medium or high frequencies during the pre-war or war period. In addition, the fear of war is driving stock market behavior in Europe and the U.S.

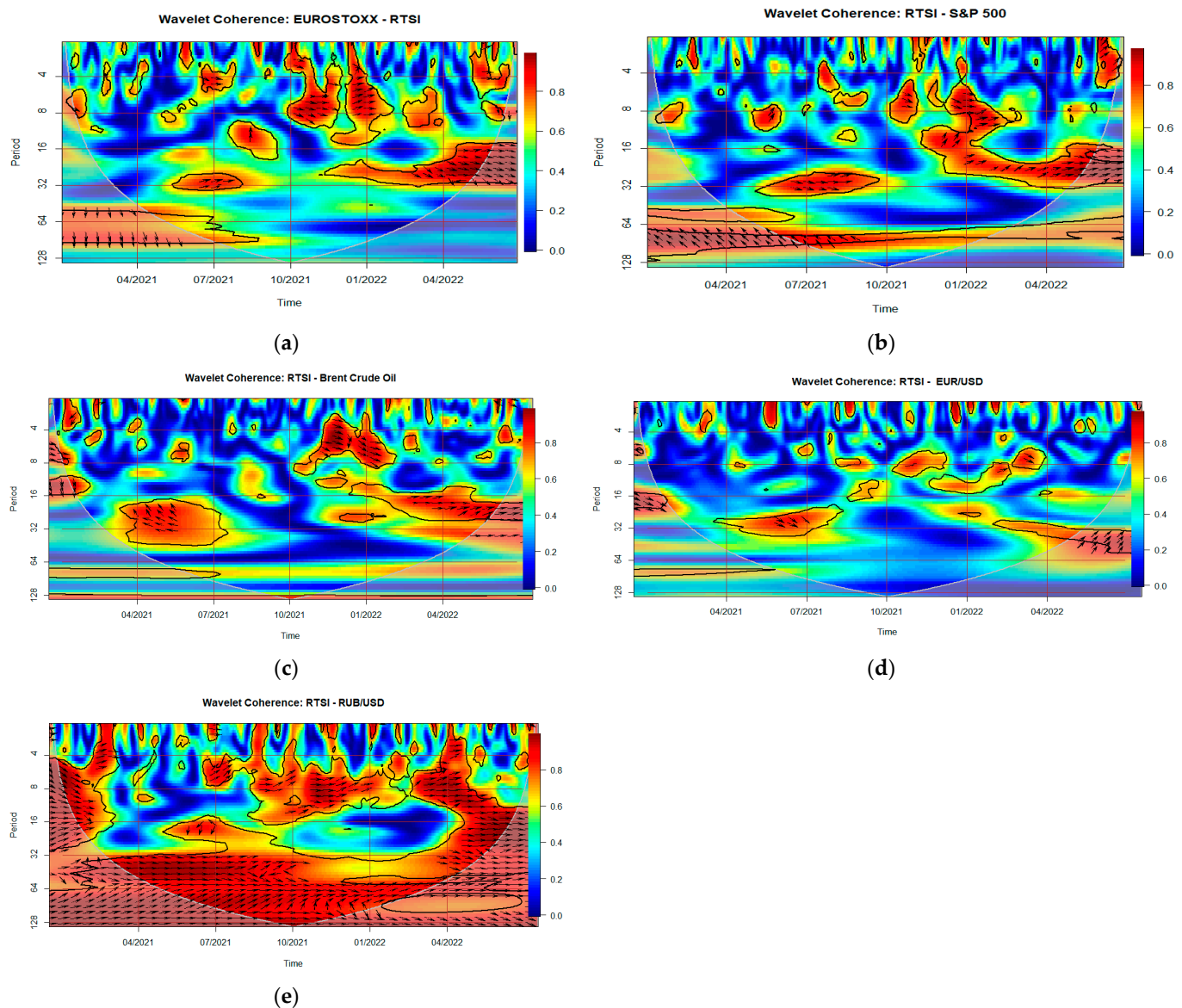


Figure 1. (a–e) Wavelet coherence between RTSI and (a) Eurostoxx, (b) S&P 500, (c) Brent crude oil, (d) EUR/USD and (e) RUB/USD.

Figure 2 displays the correlations between the European Stock Exchange Index (Eurostoxx) and the above-analyzed indices. At the beginning of 2021, before the outbreak of the war, we can observe a medium-term negative correlation between Eurostoxx and crude oil (Figure 2a). Therefore, this situation changed at the start of the war. From the second half of 2021 to the beginning of the war, crude oil positively affects Eurostoxx's course at high level frequency bands and from the outbreak of the energy crisis until August 2022, there is a co-movement between the two indices examined. The aforementioned behavior seems to be similar to that of RTSI in relation to Brent oil (Figure 1c).

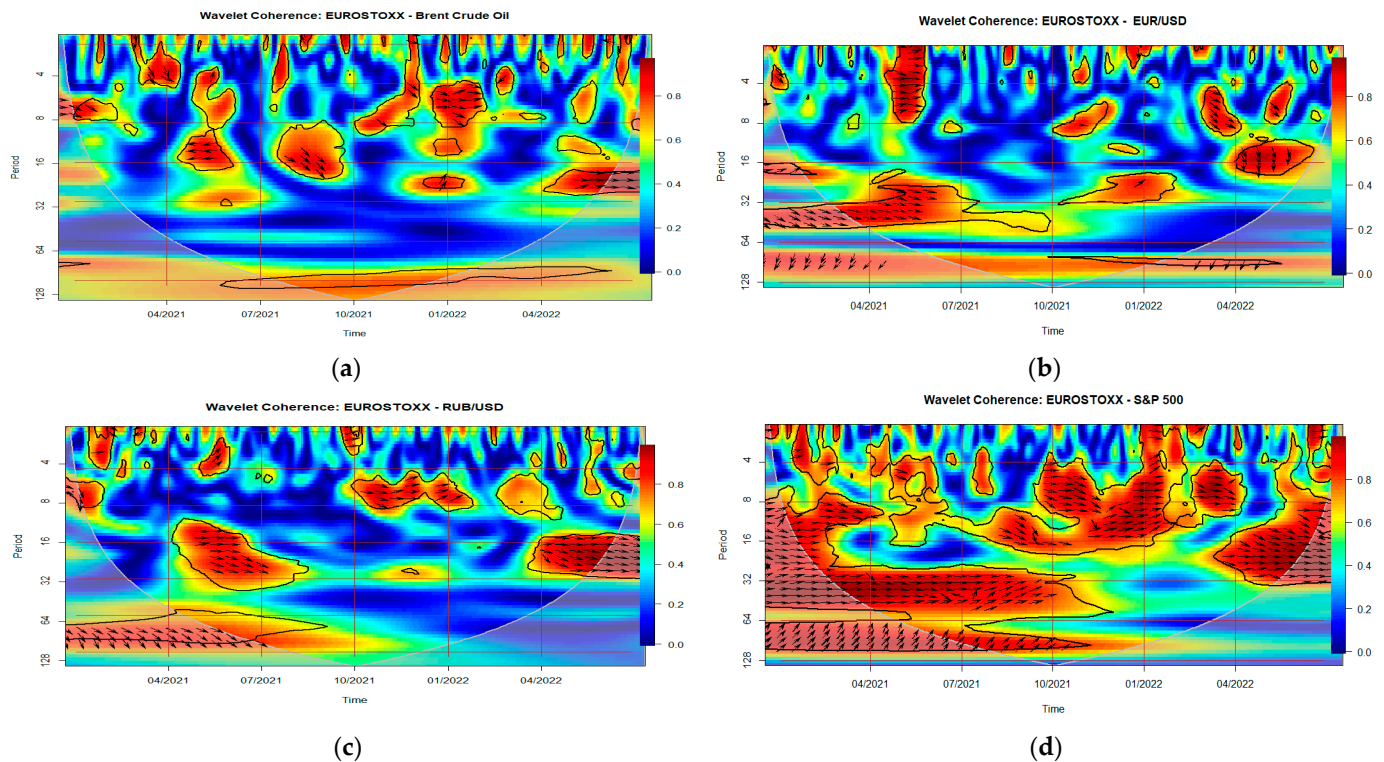


Figure 2. (a–d) Wavelet coherence between Eurostoxx and (a) Brent crude oil, (b) EUR/USD, (c) RUB/USD and (d) S&P 500.

In both the short and long term, there is an evident impact of the EUR/USD exchange rate on Eurostoxx during both the first half of 2021 and after the outbreak of the energy crisis for the same frequencies (Figure 2b). The right downward direction of the graph in Figure 2c, during the first semester of 2021, implies the existence of a positive relationship between Eurostoxx and RUB/USD for medium-frequency bands, with RUB/USD being the leading indicator. This interdependency seems to re-appear after the outbreak of the energy crisis and continues until August 2022. However, in the high bands, immediately before the beginning of the Ukraine war, a positive correlation was observed, with Eurostoxx being the leading indicator. Another important finding is presented in Figure 2d. More specifically, before the beginning of the Ukrainian war, we observed an in-phase correlation between Eurostoxx and S&P 500 in the medium to long term, with Eurostoxx as the leading indicator. However, this condition does not seem to exist after the beginning of the war, as S&P 500 takes the leading role in this in-phase correlation.

The results obtained from the second series of pictures suggest that no particular diversification effect exists between the variables examined, regardless of the type of crisis. The main differences mainly focus on the time impact, that is, whether the influence is extended to short-, medium- or long-term intervals. The relationship between Eurostoxx and Brent oil is similar to that between RTSI and Brent oil, as previously mentioned (Figure 1c). Moreover, the switching of the behavior between stock markets and Brent oil guides us to the outcome that the post-vaccination period provides markets with signs of

returning to normality, while the investment prospects seem to be reversed during the pre- and post-war period.

Finally, Figure 3 exhibits the wavelet coherence between S&P 500 and crude oil, whereas in the short and medium terms, a positive interdependency relationship between S&P 500 and crude oil is indicated, with the latter leading, and in low-frequency bands, an out-of-phase correlation can be observed, with crude oil leading the series. Moreover, in the medium term, after the outbreak of the energy crisis, there is a co-movement between the two series.

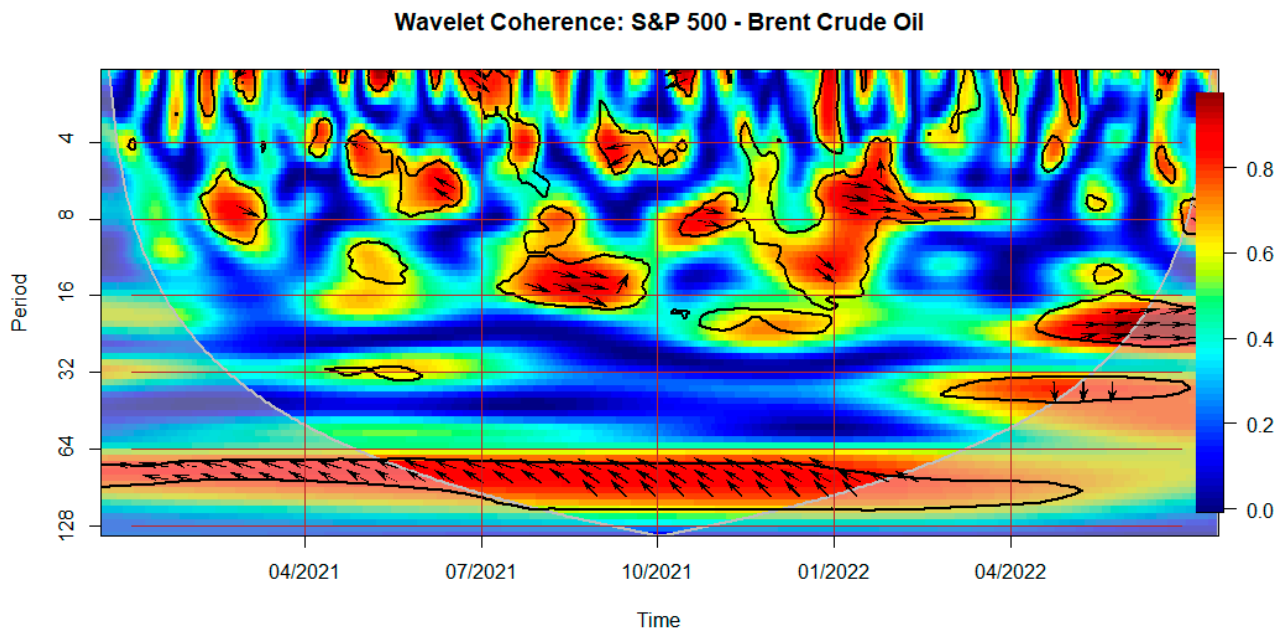


Figure 3. Wavelet coherence between S&P 500 and Brent crude oil.

In the interdependency relationship between S&P 500 and Brent crude oil, there is a clear diversification effect in the long run, making the S&P 500 Index a safe-haven investment during both the pandemic and war period, compared to Brent crude oil.

The above findings imply that the Russian Stock Exchange Index affects stocks in both Europe and US during the same period in a statistically significant way, following the same direction and to the same extent, which becomes more pronounced during the war and the energy crisis.

Moreover, RTSI seems to affect the Russian currency (RUB) compared to the other international strong reference currencies, such as EUR and USD, while it can be suggested that the EUR/USD exchange rate does not seem to be affected by RTSI. This may be due to the fact that the war affected both currencies intensively, at least during the beginning of the war and the outbreak of the energy crisis.

In addition, the observed co-movement between RTSI and Brent crude oil is possibly due to capital restrictions to the Russian stock market and increased demand for crude oil, as a result of the ongoing war and the retaliatory sanctions by Russia to NATO countries.

Furthermore, the existence of a negative correlation between the S&P 500 Index and Brent crude oil in the long run is conceivably due to the fact that low crude oil prices favor equity values and vice versa. However, after the beginning of the war and the energy crisis outbreak, tension associated with co-movement in the short- and medium-time intervals can be observed.

The wavelet coherence analysis was mainly applied in several scientific approaches during the pandemic period. However, these studies examine the impact of the pandemic from a different point of view and they suggest that investing in ESG during the COVID-19 period may lead to diversification [70,71]. Moreover, according to [53] investments in cryptocurrencies, gold and in the Shanghai Stock Exchange Index consist of safe-haven

assets. Similarly, Ref. [66] implies that investing in stock markets during the war in Ukraine can lead to hedging against market shocks and [1] verifies that during volatile periods, the causality between stock markets and Brent oil is more intense. The above findings are congruent with our case, as stock markets, in comparison with Brent oil, could be considered as alternative investments to diversify risks. More specifically, Eurostoxx at small to medium frequencies (8–16 days) and RTSI at medium to low frequencies (16–32 days) for the post-vaccination and pre-war period and S&P in low bands (64–128 days) during all the examined periods could represent alternative investments. The intense variability and the associated concerns related to the likelihood of a full recovery from the two crises have been verified by the studies of [2,3].

For robustness purposes, we also use the data of the S&P CBOE VIX Volatility Index, as the market fear proxy during the period under consideration, which represents both a normal and a volatile period (Figure 4). More specifically, the Chicago Board Options Exchange Volatility Index (VIX) provides the market's expectations for the upcoming price fluctuations of the S&P 500 Index.

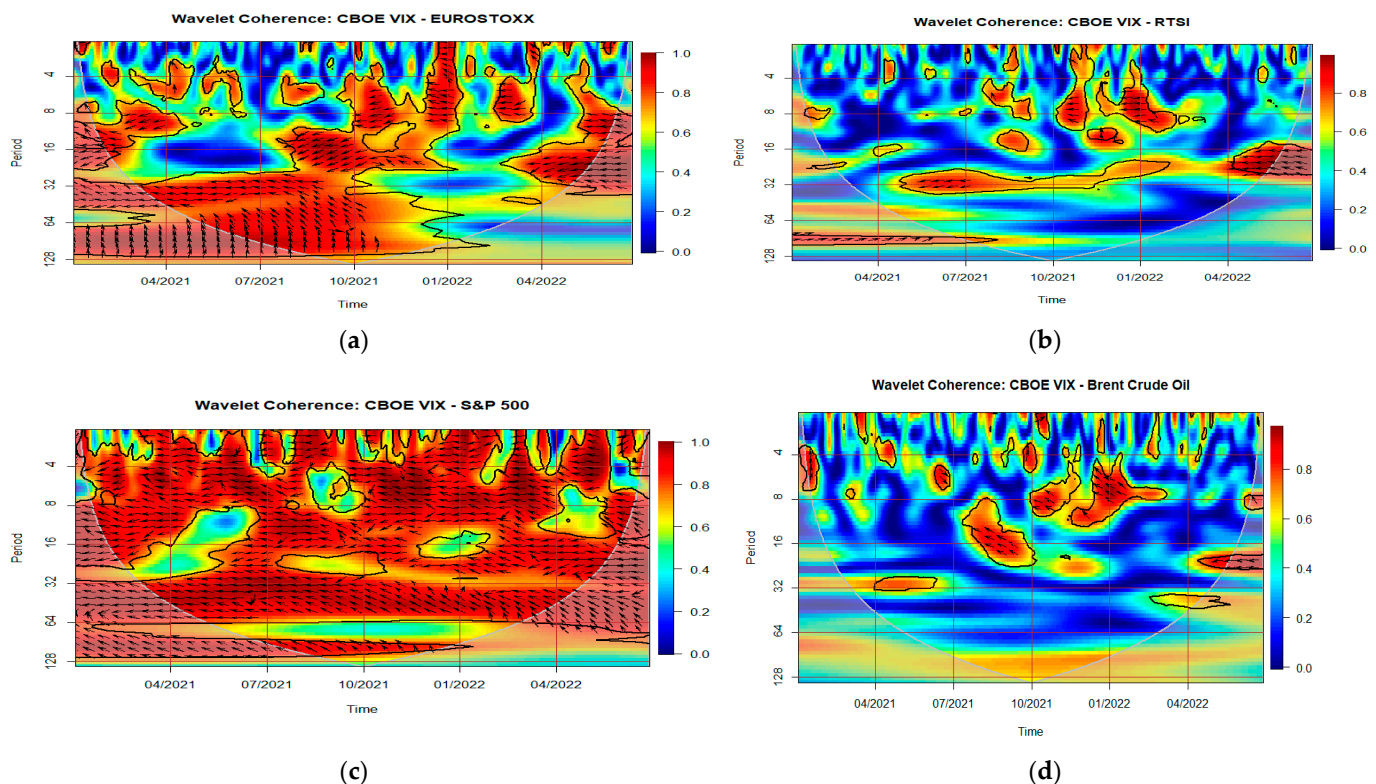


Figure 4. (a–d) Robustness tests for wavelet coherence between CBOE VIX and (a) Eurostoxx (b) RTSI, (c) S&P and (d) Brent crude oil.

The results of robustness test verify our findings, as a negative correlation between CBOE VIX and all the variables used can be observed, regardless of the time periods and frequencies (Figure 4a–d). More particularly, as the investors' fear increases, the fall in stock values could lead to more volatility. Thus, this situation reinforces oil market volatility.

This robust relationship is observed for the whole period under consideration for the S&P Index, regardless of the time period and frequency and for fewer time intervals for the Eurostoxx Index, while it is more intense during the pre- and post-war period in the case of Brent oil in small to medium bands. This is also the case for the relationship between the Brent oil prices and RTSI.

5. Conclusions

In this article, our analysis focuses on the existence of interdependencies between specific global stock market indices, such as Eurostoxx, S&P 500 and RTSI, exchange rates, such as EUR/USD and RUB/USD, and Brent crude oil prices. Our analysis covers the period from January 2021 to July 2022. This period is characterized by the start of vaccination against COVID-19, which signals the end of the lockdown period and the return to economic and social normality across the world. This covers the period up to July 2022, when the energy crisis reached its peak, due to the war in Ukraine, which started in February 2022. For the purpose of our study, we applied a wavelet coherence approach in order to capture the co-movements between time series both in the time domain and in the frequency domain.

The period we examined was characterized by long and intense instability, firstly due to the COVID-19 pandemic, followed by the war in Ukraine and the sanctions imposed both by NATO countries on Russia and by Russia on NATO countries that had a direct impact on the prices of energy sources. Our findings show different strong interdependencies and differences between the examined variables, for different frequencies, time periods and time extensions. The examined variables show the existence of high volatility due to the highly uncertain period. Furthermore, our results suggest that higher frequency bands exhibit a more persistent effect for all combinations of interdependencies, while also varying across different periods. Wavelet coherence at low frequencies exhibits slower changes, while demonstrating smoother and more reasonable behavior over time.

More specifically, the RTSI appears to affect the global stock market indices in the short and medium term, mainly at the start of the war and the energy crisis period, and the Russian currency throughout the period under review. In addition, co-movement between RTSI and crude oil is observed at high frequencies after the onset of war and the energy crisis, while a negative correlation at medium to low bands after COVID-19 and the pre-war period is observed. Similar findings apply to the interdependence between Eurostoxx and Brent oil, while in the long run, an out-of-phase relationship is observed between the S&P 500 Index and Brent crude oil for the entire period under consideration.

These findings can help policy makers, analysts, investors and portfolio managers to hedge their risks and make appropriate investment decisions during periods of global volatility. The findings of this study are also useful for policymakers in terms of creating an institutional and supervisory framework that will more easily identify systemic risks and mitigate them by implementing countercyclical policies.

During the pre-war period and the war period, the major stock indices and exchange rates appear to behave similarly to that of crude oil, as there is co-movement regardless of the time period and frequency. Therefore, they cannot be considered as suitable financial instruments to mitigate portfolio risks. In addition, the findings do not coincide with the pandemic and the war period, especially in relation to their scale, which should be taken into account by investors and policy makers. From their perspective, policy makers could take advantage of these findings by extending their analysis using qualitative criteria such as ESG indicators, which could also form the basis for future extension of the present study. Beyond the practical implications, this study can act as a beacon, shedding light on the development of research on issues during periods of high volatility and energy crises, using different methodologies and expanding the variables to cover ESG criteria, as well as other commodities of great importance, stock markets and exchange rates.

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