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Energy Security in Danger? A Comparative Analysis of Oil and Copper Supply

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Abstract: This study aims to examine energy security in terms of crude oil and copper supply. While oil remains the leading energy commodity globally, copper is crucial for many new technologies, foremost for RES. Therefore, both oil and copper are extremely important for current and future energy security. This article contains a bivariate methodological approach to a comparative analysis of oil and copper supply: determining supply security with an Index of security of supply, and examines price stability with generalized autoregressive conditional heteroscedasticity (GARCH) models. This research provides evidence that there are many differences but also significant similarities between these two completely different commodities in terms of both supply security and price stability. Facing the future for RES, significant demand may cause a threat to energy security on a previously unknown scale. Therefore this instability, both supply- and price-related, appears to be the main threat to future energy security.

Keywords: copper; crude oil; energy security; renewable energy sources (RES); GARCH

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1. Introduction

Throughout the years, energy security has remained one of the most important topics for analysis and discussion [1]. Great attention has been paid to this notion in many different fields, such as politics [2], national energy policies [3], international relations [4], and national security [5]. Initially, due to two oil shocks in the 1970s and 1980s, energy security was mostly perceived as energy supply [6,7]. Thus, free access to fossil fuels, namely crude oil, coal, and natural gas, played a significant role. Nowadays, environmental issues are also becoming increasingly important [8,9], and hence, renewable energy sources (RES) are developing intensively.

In the light of contemporary theoretical research on the energy security concept, several hundred or more papers deal with this issue, and they have delivered dozens of different definitions of what is meant by energy security (see for example [10,11]). Despite the huge popularity of the energy security area, difficulties have been encountered in developing a clear and precise concept of this notion [12–15]. However, the most common definitions still refer to "the uninterrupted availability of energy sources at an affordable price" [16,17]. Hence, the continuity of energy supplies at an acceptable price still might be perceived as being at the core of a vast majority of the existing definitions of this concept. On the other hand, there are also other elements of this concept that depend in turn on the context of the considerations [18–23]. For example, currently, due to serious concerns about environmental issues like global warming [24], climate change [25,26], CO_2 and greenhouse gas emissions, heavy-metal emissions, water contamination [27], air pollution [28], acidic rain [29], and indoor suffocation [30], these environmental needs are often accented as well.

Due to the lack of an unambiguous concept of energy security, there are many different methods for assessing this issue in practice. These indicators might be grouped depending on the purpose of the analysis. On the one hand, there are measures regarding the degree of concentration in imports. These are based on the commonly proclaimed thesis that diversification of supply and suppliers is the right solution for ensuring energy security [31,32].

The scale of diversification of imports can be evaluated by using an import concentration index (e.g., the Herfindahl-Hirschman index (HHI): [20,33–36] or a dispersion index (e.g., the Shannon–Weiner dispersion index: [37,38]. On the other hand, there are indicators based on the analysis of the costs of interruptions in energy supply [39–43]. However, these are often referred to as supply cost estimates rather than energy security measures. These methods allow for a quantitative analysis of supply shocks and their impact on the economy. Additionally, few other indicators are based on measuring energy security through the prism of its complexity. Research on this issue is based on advanced measures of energy security. These measures comprise many elements relating to such issues as domestic fuel resources, reliability of transmission infrastructure, or the dependence of the importing country on foreign supplies of energy resources [22,44–50]. They are published by international organizations such as the International Energy Agency (Model of Short-Term Energy Security), the World Energy Council (Energy Trillema Index), and the American Chamber of Commerce in cooperation with the Global Energy Institute (Energy Security Index).

Although much has been said about energy security, an extensive review of the literature reveals that there are still some areas very little explored, especially in terms of empirical assessment. For example, although studies and reports point to the problem of significant future demand for many different raw materials, to the best of the author’s knowledge, there are no analogous comparative studies for such materials as crude oil and copper in terms of energy security. In general, comparative analysis is narrowly used in the energy security area, which is especially obvious when it comes to the case of completely different groups of commodities: energy and non-energy. However, it should be noted that energy production is currently more and more substitutable, i.e., electricity can be produced by burning coal, oil, or gas, and also comes from wind and solar farms. Hence, the comparative method in the energy security field is strongly justified.

While fossil fuels are still dominant today and one-third of energy still comes from oil [51], the shift towards RES is greatly expected in the future. As energy transitions accelerate globally, clean energy implies a significant increase in demand for minerals essential for solar panels, batteries, wind turbines, and electric networks, led by copper. Until the mid-2010s, the energy sector’s share in total demand for minerals was small. However, clean energy technologies and RES are becoming the fastest-growing demand segment as energy transitions gather pace. In a scenario that meets the Paris Agreement goals, the demand for clean energy technologies will rise significantly over the next two decades to over 40% in the case of copper and rare earth elements, 60–70% for nickel and cobalt, and almost 90% for lithium [52]. The ambitious plans regarding solar panels, wind turbines, and electric cars might be threatened by the scarcity of necessary resources for RES, including but not limited to copper. In contrast, fossil fuels and crude oil continue to be essential. Therefore, there is a need to assess the price volatility and supply security of both crude oil and copper in a comparative manner [40].

This article aims to examine the state of energy security for both copper and oil in terms of their price stability and security of supply. The reason for this case study analysis is that oil is still the world’s dominant energy commodity [39], while copper is the most widely used mineral in clean energy technologies due to its thermal and electrical conductivity [53]. Hence, both oil and copper are fundamental for the energy sector now and in the future.

On the other hand, there are significant differences between these two groups of raw materials and their use in the energy sector. For example, a shortage or spike in the price of copper only directly affects the price of new electric vehicles (EV) or solar plants, while an increase in oil prices causes the fuel price dynamic, and there is a follow-on impact concerning energy security. Moreover, oil combustion means a new supply is essential for energy production (a non-renewable resource). By contrast, copper, as a component of infrastructure, has the potential to be recovered and recycled [54].

This paper is organized as follows. Section 2 firstly contains the bivariate methodology of quantitative measurement of energy security: supply security (Section 2.2) and price stability (Section 2.3). Section 3 presents the research results based on both the security of supply index (Section 3.1) and GARCH models for price volatility (Section 3.2). Section 4 contains a discussion. Section 5 provides conclusions and prospects for further research.

2. Methodology

2.1. Energy Security Dimensions in the Case of Oil and Copper Supply

Due to both core elements of this energy security concept, a bivariate methodological approach is taken in further analysis: a comparison of the global supply of crude oil and copper (Section 2.2) and their price stability (Section 2.3)—see Figure 1.

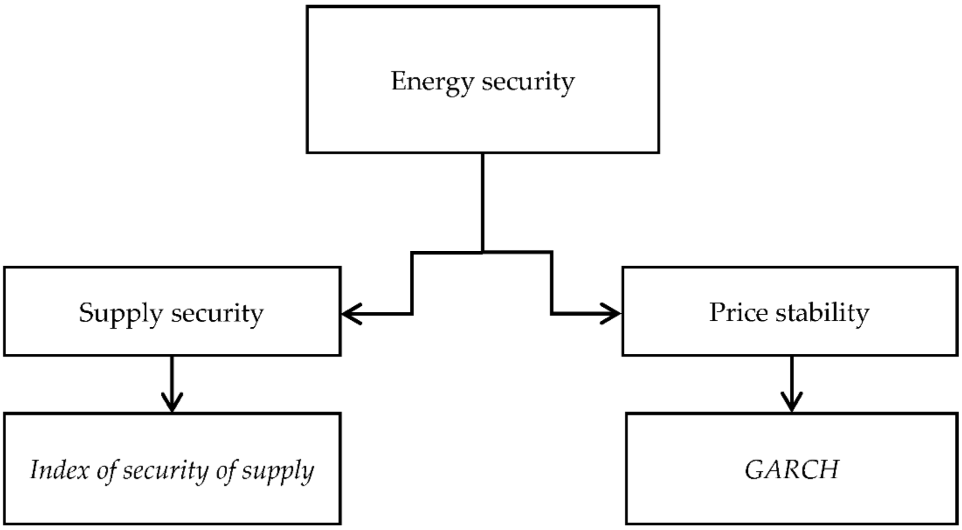

Figure 1. Energy security components: methodological approach.

2.2. The Security of Global Oil and Copper Supply

Energy security in terms of supply security might be achieved using different approaches. However, most of this analysis concerns fossil fuels only. In this field, the quantitative measures are based on the commonly proclaimed thesis that supply diversification is the right solution for ensuring energy security [31,32]. Therefore, the scale of diversification of import might be evaluated by using an import concentration index (e.g., the Herfindahl-Hirschman index (HHI); [33–36]) or a dispersion index (e.g., the Shannon–Weiner dispersion index; [37,38]). Moreover, for a more thorough analysis, many other parameters might also be included, for example, political stability of the supplier or share in the total world production by the exporter (see, e.g., [34]). As this article relates to the holistic approach to the global risk of both oil and copper supply, the indicator takes the form described below:

$$\text{Index of security of supply} = \sum(HHI_i \times PSI_i), \quad (1)$$

where:

HHI_i—the Herfindahl-Hirschman index of world oil or copper producer;

PSI_i—political stability of the supplier (World Bank’s Political Stability Index (Political stability index (−2.5 weak; 2.5 strong), 2019—Country rankings: The average for 194 countries was −0.06 points)).

Herfindahl-Hirschman Index (HHI) measures the concentration level in a given industry and the level of competition in a given market [55]. In this article, the formula relates to copper and oil production, and is as follows:

$$\text{HHI} = S_1^2 + S_2^2 + \ldots S_n^2, \quad (2)$$

where:

S_n—represents the market share of each producer/supplier, and n represents the total number of producers/suppliers (see Table 1).

Table 1. Herfindahl-Hirschman index and levels of market concentration.

Market *	USA	EU
Not concentrated—a lot of competition in the market	<1000	<1000
Moderately concentrated—further development in the case of entities that are dominant in this market may threaten the existing competition	1000–1800	1000–2000
Highly concentrated—further development in the case of parent entities has a harmful effect on competition	>1800	>2000

Notes: * the higher values of the Herfindahl-Hirschman index. There is a higher level of concentration of a given market (the risk to competitiveness of supplies increases).

2.3. The Price Stability of the Copper and Oil

Generally, regarding price conditions of the oil and copper supply, it is difficult to precisely define the affordability level for all importer countries. This always depends on the counterparty of the transaction. Moreover, that parameter is not stable over time. However, it is commonly assumed that an affordable price should be characterized by certain stability [9] and predictability. Therefore, price volatility is considered crucial for risk management in terms of energy security. In this context, many methods for assessing volatility and making forecasts in literature are applied, e.g., econometric models and soft computing models (see for example [56–58]) or artificial intelligence and machine learning [59–61]. However, like generalized autoregressive conditional heteroscedasticity (GARCH) models, and the variations of these, such econometric models are still in use in the case of time-series analysis. In this model, the variances from previous periods make it possible to assess the current variability of the process dependent on its entire past in a sparingly parameterized manner. These econometric models have been applied in plenty of studies regarding energy commodities, particularly crude oil (e.g., [62–71]) or natural gas (e.g., [64,66,72]). Also, metals (including copper) are well examined regarding volatility persistence using autoregressive time-series and GARCH models as well (e.g., [73–81]). Surprisingly, the results for non-energy and energy commodities are very rarely compared. Therefore, in this article, the GARCH model is also used as a standard tool for measuring volatility.

Firstly, the ARIMA (p,d,q) (auto-regressive integrated moving average) model was applied to forecast both the oil and copper time-series in-sample. However, as the specification of the ARIMA model indicated the canceling values of the coefficients for both oil and copper (see Appendix A), the GARCH models are employed on logarithmic returns. The GARCH (p,q) model (introduced by Bollerslev [82]) is applied to describe the time-varying variance. This model assumes that ε_t is the innovation process which can be presented as:

$$\varepsilon_t | \psi_{t-1} \sim N(0,\ h_t), \tag{3}$$

where h_t is the conditional variance, ψ_{t-1} is the set of all information available at time $t-1$, N is the conditional normal distribution.

$$h_t = \alpha_0 + \sum_{i=1}^{q} \alpha_i \varepsilon_{t-i}^2 + \sum_{j=1}^{p} \beta_j h_{t-j}, \tag{4}$$

where $\alpha_0 > 0$, $\alpha_i \geq 0$, $\beta_j \geq 0$ for $i = 1, 2, \ldots, q$; $j = 1, 2, \ldots, p$.

Prior research shows that in practice, the most frequently used model in financial time-series modeling is the GARCH (1,1) model. However, in individual cases and for a longer time series, the GARCH (1,2) and GARCH (2,1) models sometimes describe volatility better than the GARCH (1,1) model (see for example [83,84]). The choice of the sparingly parameterized form of the GARCH model is made based on the Akaike criterion (AIC), Schwarz criterion (SIC), and Hannan-Quinn (HQC); here, AIC is the main information criterion, while SIC and HQC are treated as auxiliary criteria. From among the various forms of the model, the one for which the value of the information criterion is lowest is selected.

3. Results

3.1. Geographical Concentration of Oil and Copper Production

The degree of concentration of production is still fundamental for analyzing energy security. Thus, there is an assumption that high dispersion together with political stability of the suppliers favors the security of both crude oil and copper supply.

Given its unmatched thermal and electrical conductivity, copper has wide application in various industries such as machine manufacturing, automobile manufacturing, agriculture, electronic components, household appliances, and finally, RES [85–88]. As it is commonly believed, copper's attributes make it almost irreplaceable. Hence, world production of copper has a large impact on the future of clean energy technologies [89,90]. While oil has remained the leading energy commodity globally over the years [51], the demand for copper for clean energy technologies remains one of the highest both by weight and monetary value [53]. Copper is the third most consumed industrial metal (after iron and aluminum) [91,92].

In the case of copper, Chile and Peru are the world's main suppliers, with production accounting for 28% (HHI 783.69) and 12% (141.07), respectively [93]—see Figure 2, Table 2. China, Congo, D.R., the United States, and Australia are the other major producing countries, though their individual share in total world production is less than 10%. Copper supply has been expanding rapidly over the past decades due to demand generated by strong economic growth in emerging and developing economies. More than 250 mines currently operate in nearly 40 countries, producing around 21 million tons of copper. This level of production is 30% greater than ten years ago. Nevertheless, the current production in major copper mines has already peaked or is expected to peak in the early 2020s due to declining ore quality and exhaustion of reserves [53]. Total copper production is moderately concentrated on a global scale (HHI 1175.27), and its further development in the case of entities dominant in this market may threaten the existing competition. Moreover, the largest production is still realized in politically unstable countries. This determines the threats to the stability of the copper supply. The threats arise in areas such as government effectiveness of the exporters' countries, regulatory quality in these countries, the rule of law, control of corruption, or probability of occurrence of violence or terrorist attacks (see, for example, the World Bank's Political Stability Index [94]).

In the case of crude oil, production concentration is not as high: HHI 763.70, which suggests competition in the market. While the United States is the main crude oil producer in the world, with production accounting for 16.70% (HHI 278.90), the Russian Federation and Saudi Arabia are also significant suppliers, with shares of approximately 12.80% (HHI 163.96) and 12.43% (HHI 154.48), respectively [51]—see Figure 3; Table 3. However, the shape of the crude oil market is also significantly influenced by OPEC (The Organization of the Petroleum Exporting Countries), with nearly 80% of the world's proven oil reserves [95]. Furthermore, supply security is determined by certain political and economic turmoil, such as in Venezuela (still retaining the world's biggest crude reserves) or other factors such as sanctions on Iranian oil.

Comparing copper and oil production, in the case of the 15 largest copper producers, the index of security of supply is at 691.541, while 15 of the world's major oil producers have 183.551 of this index. This is because there are low values (negative Political Stability Index) in many major producers. Therefore, oil production seems to be 3.77 times less stable than copper. This means that top oil producing countries are politically unstable states, and hence there is a greater risk of intermittent supply than in the case of copper. On the other hand, in the case of copper, the Total-15 concentration is even higher than oil, at around 89.40% vs. 81.34%, which ultimately demonstrates a higher market concentration.

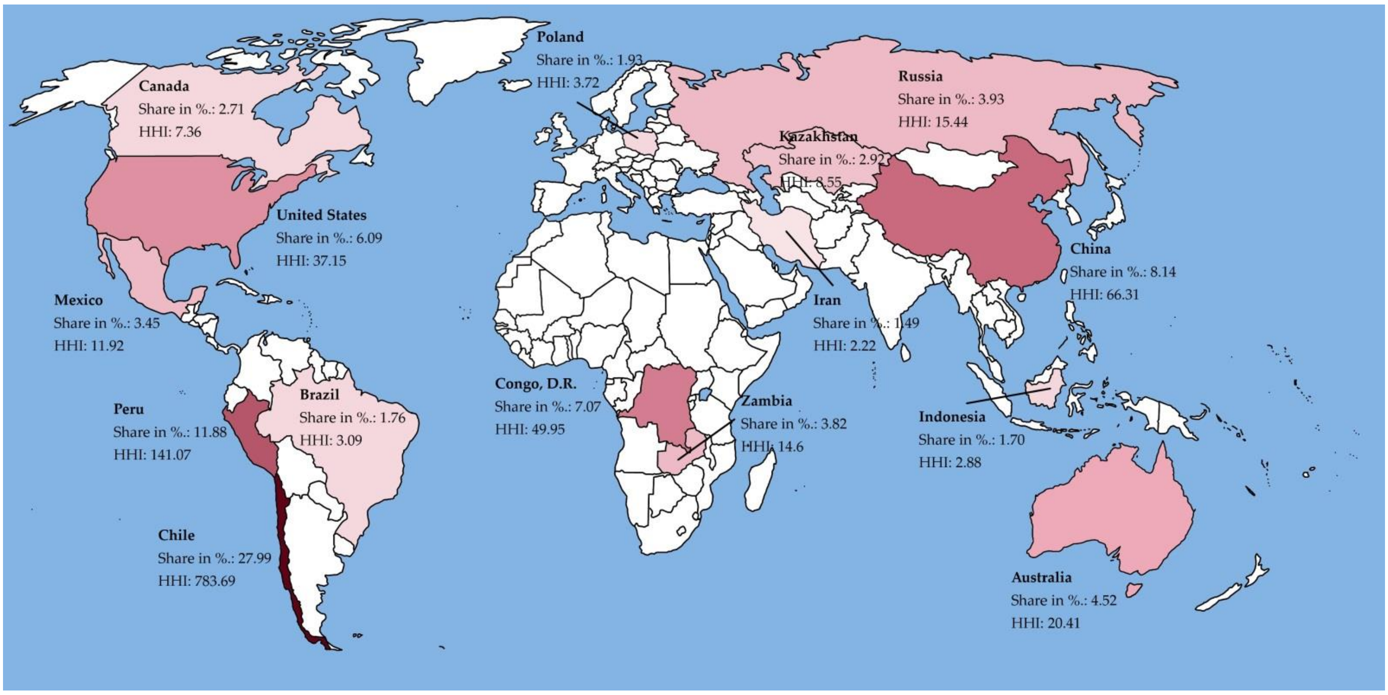

Figure 2. Herfindahl-Hirschman index (HHI) and copper production in 2020.

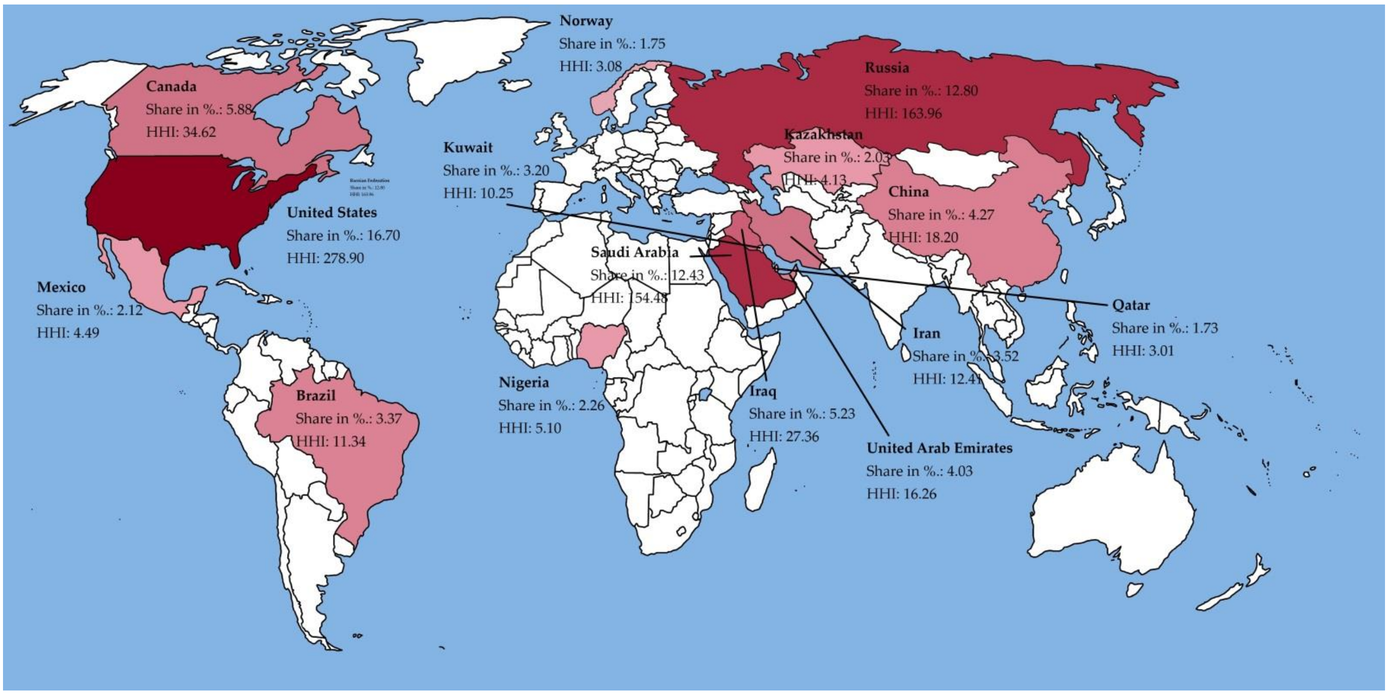

Figure 3. Herfindahl-Hirschman index (HHI) and crude oil production in 2020.

Table 2. Herfindahl-Hirschman index, index of security of supply and copper production in 2020.

Rank	Country	Production (Tones)	Share in %	HHI	Political Stability Index	Index of Security of Supply
1	Chile	5,787,400	27.99	783.69	0.945	740.932
2	Peru	2,455,440	11.88	141.07	−0.049	−6.912
3	China	1,683,450	8.14	66.31	−0.363	−24.063
4	Congo, D.R.	1,461,124	7.07	49.95	−1.606	−80.220
5	United States	1,260,000	6.09	37.15	1.129	41.944
6	Australia	934,055	4.52	20.41	1.565	31.950
7	Russia	812,400	3.93	15.44	−0.580	−8.953
8	Zambia	789,942	3.82	14.6	−0.453	−6.619
9	Mexico	713,704	3.45	11.92	−0.371	−4.428
10	Kazakhstan	604,470	2.92	8.55	−0.298	−2.546
11	Canada	560,800	2.71	7.36	1.578	11.613
12	Poland	398,900	1.93	3.72	0.648	2.412
13	Brazil	363,268	1.76	3.09	−0.180	−0.557
14	Indonesia	351,080	1.70	2.88	−0.166	−0.479
15	Iran	308,270	1.49	2.22	−1.140	−2.532
-	Total-15	18,484,303	89.40	1168.36	0.659	691.541
-	World	20,673,358	100.00	1175.27	-	-

Table 3. Herfindahl-Hirschman index, index of security of supply and crude oil production in 2020.

Rank	Country	Production (Tones)	Share in %	HHI	Political Stability Index	Index of Security of Supply
1	United States	747,843,230	16.70	278.90	1.129	314.892
2	Russian Federation	573,388,845	12.80	163.96	−0.580	−95.074
3	Saudi Arabia	556,564,010	12.43	154.48	−0.227	−35.104
4	Canada	263,462,162	5.88	34.62	1.578	54.618
5	Iraq	234,220,106	5.23	27.36	−1.514	−41.427
6	China	191,014,000	4.27	18.20	−0.363	−6.603
7	United Arab Emirates	180,544,180	4.03	16.26	0.647	10.524
8	Iran	157,764,822	3.52	12.41	−1.140	−14.155
9	Brazil	150,774,423	3.37	11.34	−0.180	−2.043
10	Kuwait	143,379,896	3.20	10.25	−0.045	−0.458
11	Nigeria	101,139,828	2.26	5.10	−1.048	−5.348
12	Mexico	94,918,412	2.12	4.49	−0.371	−1.669
13	Kazakhstan	91,043,885	2.03	4.13	−0.298	−1.231
14	Norway	78,545,297	1.75	3.08	1.766	5.434
15	Qatar	77,684,138	1.73	3.01	0.397	1.195
-	Total-15	3,642,287,234	81.34	747.58	−0.250	183.551
-	World	4,477,987,878	100.00	763.70	-	-

3.2. Oil and Copper Price Volatility

Apart from the stability of supply and suppliers, the definition of energy security also includes the affordable price component. As the World Energy Council has stated, volatility of energy prices has a critical uncertainty for the future economy [96]. Hence, price stability is highly desirable.

Table 4 shows the descriptive statistics of both variables: copper and oil prices (also with their daily logarithmic returns). Financial data have been sourced from the Shanghai Metals Market (SMM) for copper (Copper 99.95 Spot Price Daily), and from the NY Mercantile Exchange for oil (Brent Forties and Oseberg Dated FOB Northsea Crude daily), both via Reuters. The time-series span is from the beginning of June 2012 to the end of August 2021 (The time limitation of the study is due to the availability of data: SMM quoted copper from June 2012). These variables are on different price levels: the mean price for copper is around USD 7 577.4 per ton, while the mean for oil is USD 69.329 per barrel. However, the findings suggest that crude oil is twice as volatile as copper. This is evidenced by the corresponding standard deviations in relation to their mean values: 36.34% vs. 17.29%. Both time-series returns for oil and copper are negatively skewed. Both have excess kurtosis, and their distributions are leptokurtic. In the case of both, the null of normality is strongly rejected according to the Jarque-Bera test (Table 4).

Table 4. Statistic of time-series.

Variable	Mean	Median	Minimum	Maximum	Std. Dev.	Ex. Kurtosis.	Jarque-Bera Test	Skewness
copper	7577.4	7425.8	5167.8	11,986	1310.3	0.27231	123.093	0.55806
copper—returns	0.000082	0.000038	−0.10565	0.07544	0.01066	10.108	9387.42	−0.47259
oil	69.329	63.520	9.1200	118.90	25.195	−0.88626	167.526	0.47855
oil—returns	−0.000178	0.000522	−0.48037	0.31743	0.02878	53.382	260518	−1.6297

The time-series of both oil and copper prices are not stationary, and this has been confirmed by the Augmented Dickey-Fuller (ADF) test [97] and Phillips-Perron test [98] (Table 5). Therefore, logarithmic returns were used (realization of both time-series are shown in Figure 4)

Table 5. Unit root tests.

Variable	Augmented Dickey-Fuller Test	Phillips-Perron Test
copper	−0.602	-0.699
copper—returns	−31.317	−45.976
oil	−1.516	−1.556
oil—returns	−32.268	−47.672

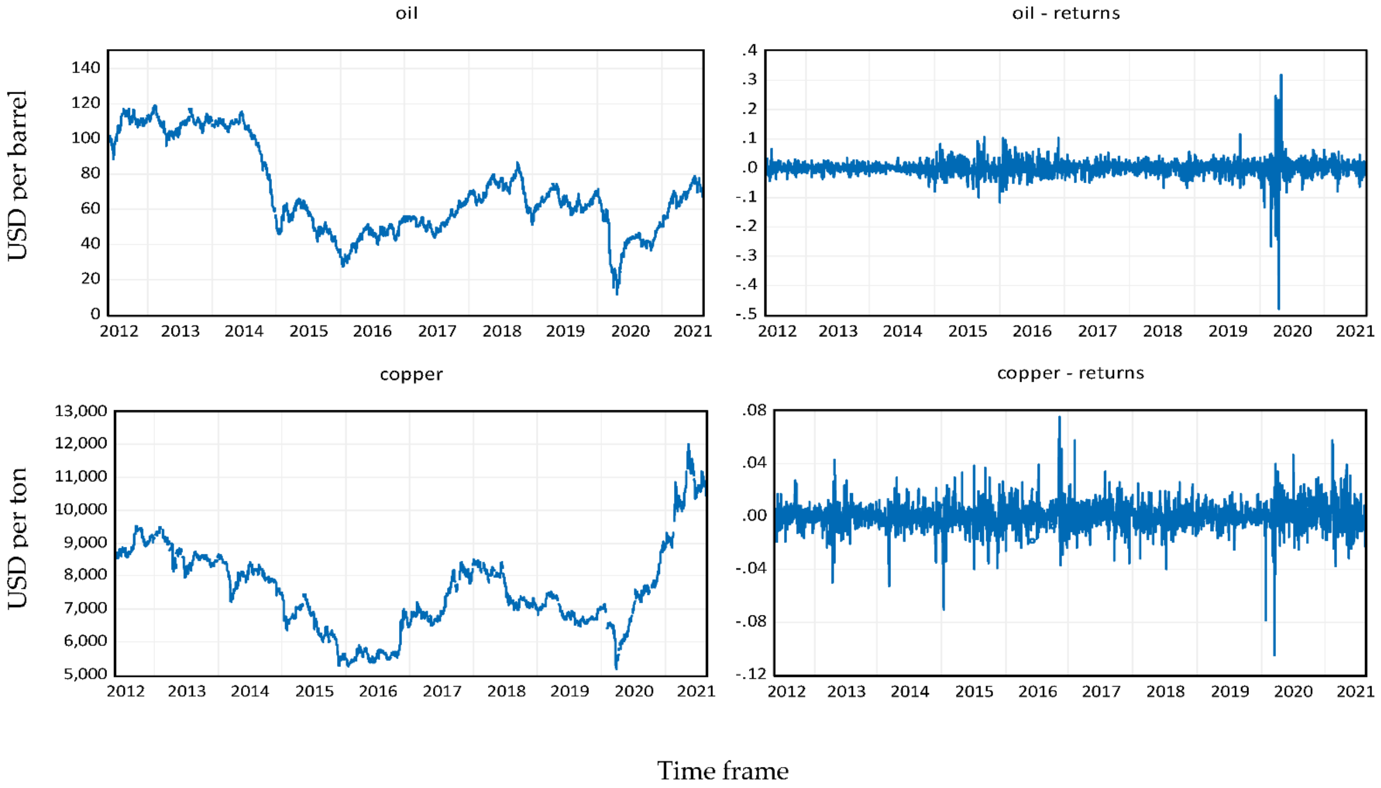

Figure 4. Time-series of crude oil and copper prices.

Moreover, the presented graphs of logarithmic rates of return on crude oil and cooper indicate variance grouping effects, namely volatility clustering (periods of increased volatility and relatively stable periods occurring consecutively). Therefore, the traditional

ARCH/GARCH test confirms there are ARCH effects; the test statistic for oil is LM: 151.021, while for copper, it is LM: 56.2352 (Table 6).

Table 6. ARCH/GARCH tests.

Variable	F-Statistic	Decision
copper	56.2352 ***	ARCH effects exist
oil	151.021 ***	ARCH effects exist

Notes: The null hypothesis is H0: There is no ARCH effect. *** Indicates that the likelihood ratio test is statistically significant at 1%.

The GARCH (1,1) for oil and GARCH (2,1) for copper are applied based on the AIC (Appendix B: Tables A3 and A4). In both cases, the value of coefficients is less than but close to unity. In this context, the greater the sum of the evaluation of the parameters $\alpha_1 + \alpha_2 + \ldots + \alpha_q + \beta_1 + \beta_2 + \ldots + \ldots + \beta_p = 1$ in the GARCH model, the longer the impact of shock phenomena on the variance of the analyzed process [83]. Therefore, this indicates that volatility shocks are quite persistent and cluster. In the case of copper, the sum of the β coefficient in the GARCH model is 2.6 times greater than α, while in the case of oil, this ratio is approximately 7.6, which suggests higher unexpected volatility. Forecasts for the conditional variance (in-sample) generated by the models for both oil and copper are presented in Figure 5.

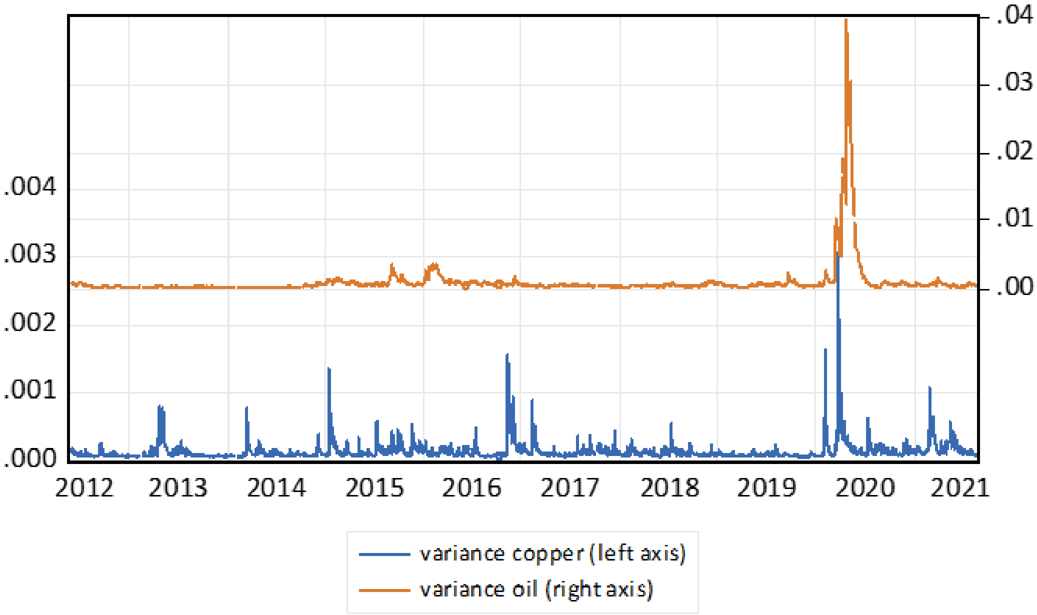

Figure 5. Forecasts for the conditional variance (in-sample) of crude oil and copper.

4. Discussion

This study examined energy security in the case of both crude oil and copper supply. It found that the price of crude oil is twice as volatile as the price of copper in the research period. This is evidenced by the corresponding standard deviations in relation to their mean values. Moreover, the relation of the β coefficients to α is higher in the case of oil than copper, which means the state will experience higher unexpected oil price volatility than copper. On the other hand, copper has a higher concentration level in the Total-15 producer group. This ultimately suggests a higher concentration of the market. In turn, by analyzing the security of the supply index, there is strong evidence that both copper and oil are at serious risk of supply discontinuity. However, oil production seems to be 3.77 times less stable than copper. The source of these threats may be insufficient government effectiveness of the producing countries, low regulatory quality in these countries, or even unsatisfactory control of corruption (these factors are included in the Political Stability Index).

Finally, the study results show that the expected dynamics of demand for oil and copper, amid relatively limited supplies and conditions of low competitiveness among suppliers, may mean that their price will not be determined solely by the market mechanism. These fears are compounded by the relatively high political instability of the main exporters of these materials, as well as the socio-economic problems in these countries [99].

Looking deeply into the problem in light of the existing studies, there are many factors determining price changes of oil and copper. The most frequent determinants in the case of oil price equations cover economic factors such as demand and supply levels (amount of consumption and production [100–103]); business cycle (global GDP growth) or global financial market liquidity [103]; political factors such as OPEC production amounts [100–105]; or the political risk of exporters (e.g., measured by the International Country Political Risk Guide [103]); infrastructure factors like production capacity [106] or crude oil stocks [100,102,105]; and other factors such as the ratio of futures contracts trading in relation to physical deliveries, and the number of terrorist attacks or number of soldiers stationed in the Middle East.

In the case of copper, per analogiam, the current level of demand and supply strongly determine the price as well. These are crucial because the copper market is relatively transparent, which means that a change in supply or demand is reflected in the price, while an excess of production over consumption results in higher stock levels. On the other hand, a production deficit relative to consumption results in lower stock levels. Also, recessions result in reduced demand. Additionally, supply can be delayed by long lead times for the construction of new facilities [107] (growth rate in industrial production) (see, e.g., [108]). Moreover, there are also financial factors [108–111]. Thus, the impact of various hedge funds that focus, or at least partially focus on commodities, also affects copper prices (the financialization of commodity markets) [109,112]. This obviously has a real-world link. Such funds can increase instability in copper prices, especially in the short term. In the past, prices tended to change more gradually, but there are more spikes, both high and low, in the current marketplace.

Furthermore, for both these commodities, unexpected events also have a major effect on the price. For example, oil and copper prices spiked during the first half of 2020. This might be explained by, among other things, the ongoing COVID-19 pandemic, and it can be assumed that this is not merely a one-off event. The prolonged effect of the pandemic, and any additional repercussions the pandemic might cause, could determine potential future market turmoil.

5. Conclusions and Prospects for Further Research

Extending the obtained conclusions from the analysis of the entire group of clean energy metals (e.g., silver, vanadium, titanium, molybdenum, zinc, nickel, lithium, lead, indium, cobalt, chromium, or aluminum), it is assumed that possible disruptions combined with already unstable prices, accounting for significant future demand for RES, may present a threat to energy security on a previously unknown scale. This instability, both price-related and political (affecting the continuity of supplies), appears to be the main threat to future energy security. Therefore, the implementation of new solutions as the basis for reducing dependence on metals such as copper (e.g., the use of substitutes) due to the strong concentration of production is of key importance. Moreover, the long-term supply of clean energy metals will also depend on developing efficient recycling systems. Therefore, recycling will be a key element influencing the state of energy security of the future.

Undoubtedly, an extremely important area of future research in light of energy security will be even greater analysis of the determinants of non-energy commodity prices, especially those essential for RES. This type of research might provide new insights into the rapidly changing world energy picture. As has been proved, comparative analysis has great value; hence further development is postulated.

Additionally, further analyses and forecasts are extremely necessary in order to better manage risk and ensure energy security in the future. Hence, the price volatility of non-energy commodities should be an indispensable part of energy security research.

From the methodological point of view, it is still problematic to find the most appropriate models and tools to measure both the stability of supplies and prices more accurately. Possible further research into energy security could be performed by applying other GARCH model modifications such as EGARCH, IGARCH (In this research, the sum of coefficients nearly unity for GARCH (1,1) in the case of crude oil suggest that the Integrated GARCH model could be used as a peculiar case of the IGARCH process, GARCH-M, GARCH GJR, or APARCH for better prediction of clean energy metal price volatility (not only copper).

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Appendix A

Table A1. Statistic of time-series.

	Coefficient	Coefficient	Std. Error	z	*p*-Value
copper_price ARIMA (2,1,2)	phi_1	1.07808	0.132760	8.120	<0.0001 ***
	phi_2	−0.752266	0.0423458	−17.76	<0.0001 ***
	theta_1	−1.08824	0.122010	−8.919	<0.0001 ***
	theta_2	0.786759	0.0381243	20.64	<0.0001 ***
oil_price ARIMA (1,1,1)	phi_1	−0.769229	0.0395812	−19.43	<0.0001 ***
	theta_1	0.792901	0.0376070	21.08	<0.0001 ***

Notes: *** 1% level significant.

Table A2. Statistic of time-series.

Statistics	ME	RMSE	MAE	MPE	MAPE
copper_price ARIMA (2,1,2)	0.95534	84.094	54.885	0.0038776	0.72846
oil_price ARIMA (1,1,1)	−0.010504	1.2807	0.93484	−0.058535	1.6369

Appendix B

Table A3. Parameters and statistics of GARCH models in the case of copper.

Model	Parameter	Coefficient	Std. Error	z	*p*-Value	Schwarz Criterion	Akaike Criterion	Hannan-Quinn
GARCH(1,1)	alpha(0)	0.00001	0.00000	4.943	<0.0001 ***	−13,894.18	−13,916.94	−13,908.62
	alpha(1)	0.17681	0.02778	6.364	<0.0001 ***			
	beta(1)	0.72767	0.03937	18.480	<0.0001 ***			
GARCH(1,2)	alpha(0)	0.00001	0.00000	3.468	0.0005 ***	−13,885.74	−13,914.19	−13,903.79
	alpha(1)	0.15560	0.03545	4.390	<0.0001 ***			
	alpha(2)	0.00000	0.04841	0.000	1			
	beta(1)	0.74521	0.05644	13.200	<0.0001 ***			

Table A3. *Cont.*

Model	Parameter	Coefficient	Std. Error	z	*p*-Value	Schwarz Criterion	Akaike Criterion	Hannan-Quinn
GARCH(1,3)	alpha(0)	0.00001	0.00000	3.331	0.0009 ***	−13,878.05	−13,912.19	−13,899.71
	alpha(1)	0.15845	0.03584	4.421	<0.0001 ***			
	alpha(2)	0.00000	0.05095	0.000	1			
	alpha(3)	0.01288	0.04277	0.301	0.7634			
	beta(1)	0.73274	0.06865	10.670	<0.0001 ***			
GARCH(2,1) ***	alpha(0)	0.00001	0.00000	4.987	<0.0001 ***	−13,899.77	−13,928.22	−13,917.82
	alpha(1)	0.25220	0.03501	7.204	<0.0001 ***			
	beta(1)	0.21564	0.05896	3.657	0.0003 ***			
	beta(2)	0.44103	0.06397	6.894	<0.0001 ***			
GARCH(3,1)	alpha(0)	0.00001	0.00000	4.921	<0.0001 ***	−13,892.36	−13,926.50	−13,914.02
	alpha(1)	0.26043	0.03847	6.770	<0.0001 ***			
	beta(1)	0.17843	0.08661	2.060	0.0394 **			
	beta(2)	0.43279	0.06612	6.546	<0.0001 ***			
	beta(3)	0.03796	0.06939	0.547	0.5843			
GARCH(2,2)	alpha(0)	0.00001	0.00000	3.729	0.0002 ***	−13,891.72	−13,925.86	−13,913.38
	alpha(1)	0.23565	0.03603	6.541	<0.0001 ***			
	alpha(2)	0.00000	0.04507	0.000	1			
	beta(1)	0.24630	0.13290	1.853	0.0638 *			
	beta(2)	0.42435	0.09627	4.408	<0.0001 ***			
GARCH(2,3)	alpha(0)	0.00001	0.00000	2.571	0.0102 **	−13,882.79	−13,922.62	−13,908.06
	alpha(1)	0.21461	0.03975	5.399	<0.0001 ***			
	alpha(2)	0.00000	0.03964	0.000	1			
	alpha(3)	0.00002	0.06246	0.000	0.9998			
	beta(1)	0.23965	0.11909	2.012	0.0442 **			
	beta(2)	0.46793	0.12417	3.769	0.0002 ***			

Notes: Selected model based on AIC criteria. * 10% level of significant; ** 5% level significant; *** 1% level significant.

Table A4. Parameters and statistics the GARCH models in case of crude oil.

Model	Parameter	Coefficient	Std. Error	z	*p*-Value	Schwarz Criterion	Akaike Criterion	Hannan-Quinn
GARCH(1,1) ***	alpha(0)	0.000006	0.0000018	3.241	0.0012 ***	−10,714.08	−10,736.84	−10,728.52
	alpha(1)	0.116227	0.0126919	9.158	<0.0001 ***			
	beta(1)	0.883214	0.0115181	76.68	<0.0001 ***			
GARCH(1,2)	alpha(0)	0.000013	0.0000049	2.609	0.0091 ***	−10,689.03	−10,717.48	−10,707.08
	alpha(1)	0.172150	0.0315393	5.458	<0.0001 ***			
	alpha(2)	0.000000	0.0379168	0.000	1			
	beta(1)	0.825979	0.0313808	26.32	<0.0001 ***			
GARCH(2,1)	alpha(0)	0.000007	0.0000023	3.01	0.0026 ***	−10,708.03	−10,736.48	−10,726.08
	alpha(1)	0.138277	0.0220650	6.267	<0.0001 ***			
	beta(1)	0.651605	0.1803880	3.612	0.0003 ***			
	beta(2)	0.209163	0.1635130	1.279	0.2008			

Notes: Selected model based on AIC criteria. *** 1% level significant.

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