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Strength in Transition: Resilience of Sustainable Energy vs. Fossil Energy

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Abstract: *Promoting clean energy sources necessitates global cooperation through cross-border collaboration, knowledge sharing, and resource allocation. A global imperative exists to transition towards a cleaner, sustainable energy mix to combat climate change and maintain environmental equilibrium. This study assesses the influence of fossil energy prices (Brent Crude Spot, WTI, FTSE 350 Oil, Gas & Coal, EURO STOXX Oil & Gas) on sustainable energy prices (Geothermal Index, Solar Energy Index, NASDAQ OMX Bio Clean Fuels Index, Wind Energy Index, WilderHill Clean Energy Index) in both stable and turbulent market conditions. This study suggests that sustainability and innovation in green energy significantly impact fossil fuel-related indexes. During challenging periods, sustainable energy markets gain prominence, while "dirty" energy indexes exhibit varying degrees of influence. Remarkably, the WilderHill Clean Energy Index plays a central role in shaping both fossil fuel and sustainable energy indexes. These findings underscore the growing trend towards greener and more sustainable investments, emphasizing sustainability's substantial sway over financial markets.*

1. INTRODUCTION

Concerns about oil shortages and climate change are driving tremendous growth in the renewable energy industry. Government support is increasing demand for experienced expertise in the design, installation, and maintenance of renewable energy systems (Duraiappah, 2018). Clean energy innovation can bring about significant social and economic developments, such as job creation in local communities and economic growth in underserved areas, in addition to environmental advantages. As a result, those engaging in clean energy initiatives, whether entrepreneurs or inventors, must emphasize not only profit but also the promotion of beneficial social change (Dias, Alexandre, et al., 2023; Dias, Horta, et al., 2023; Dias, Teixeira, et al., 2023).

This study adds to the existing literature in a variety of ways. For starters, it goes beyond the earlier study, which focused on the relationship between crude oil markets and sustainable energy. Unlike prior assessments, this one considers the interactions between renewable energy sources and other fossil fuels such as natural gas and diesel. This study looks at how dirty and clean energy markets interact. It employs a broader data set, including numerous fossil fuel markets, namely Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP); and specific sustainable energy subsectors: Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy, and WilderHill Index (ECO). Second, this study is groundbreaking in its examination of how important events in 2020 and 2022 influenced structural dynamics and linkages across dirty and clean energy markets. Although earlier studies have investigated the impact of the 2020 pandemic on energy prices and

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market indexes, there is still much to learn about how these events influence energy price formation as well as the impact of fossil fuel costs on sustainable energy prices. Third, this study is notable for using a time-frequency perspective to strengthen the interconnectedness of dirty and clean energy markets. The data collection is separated into two distinct subperiods: "Tranquil", which spans the period from May 17 to December 31, 2019, and "Stress", which spans the period from January 1, 2020, to April 28, 2023, and includes occurrences from 2020 and 2022. This method enables a dynamic investigation of the changing link between clean and dirty energy markets, capturing changes in market dynamics and correlations over time and thus providing significant value to research.

The manuscript is organized as follows: in Section 2, we discuss the relevant literature. Section 3 presents the data in detail and describes the econometric methodologies used in the study. Section 4 illustrates the empirical findings and related discussion. Section 5 presents the study's primary findings as well as future directions.

2. LITERATURE REVIEW

In recent years, there has been a surge of interest in the fields of innovation and sustainability, with a changing narrative centered on determining the price movements of conventional and sustainable energy sources. This exploitation has gained momentum in recent years, fueled in part by key events like the global COVID-19 pandemic in 2020 and the turmoil in energy markets caused by Russia's invasion of Ukraine in 2022.

The importance of renewable energy options in addressing energy and climate concerns has been emphasized. However, the traditional prices of fossil fuels continue to influence renewable energy progress. It is consequently critical to strengthen the synergies between these opposing energy paradigms. This study is a critical component in propelling renewable energy forward, ultimately leading to the achievement of sustainable energy targets.

Several studies have explored the relationships between energy markets, renewable energies, and economic variables in terms of sustainability. According to Vrînceanu et al. (2020), there is no strong link between oil markets and renewable energy markets, implying that oil price shocks have less impact on the development of renewable energy companies. Ren and Lucey (2021), on the other hand, investigated the association between clean energy stock indexes and cryptocurrencies based on their energy consumption levels. The authors discovered that in times of uncertainty, clean energy tended to function as a safe haven for "dirty" cryptocurrencies rather than "clean" crypto. He et al. (2021) explored how changes in oil prices, gold prices, and financial stress affect clean energy returns in the US and European economies. Long-term results show that financial stress has a major detrimental impact on US and European clean energy stock indexes in less optimistic market conditions. Furthermore, gold prices have a negative impact on clean energy stocks in Europe when the market is up and in the US under varied market conditions. In addition, during the COVID-19 epidemic, Ghabri et al. (2021) investigated the influence of fossil energy market shocks on clean energy stock indexes. Following the collapse of crude oil prices, they detected major shocks in clean energy. However, the proclamation of COVID-19 as a global pandemic caused natural gas and renewable energy prices to rise after initially falling.

Hoque and Batabyal (2022), Attarzadeh and Balcilar (2022), and Shakhabiddinovich et al. (2022) provide insights into the behavior of carbon futures, clean energy stocks, and their relationships with market conditions and political uncertainties. According to Hoque and Batabyal (2022), carbon futures provide a strong safe haven based on market conditions and levels of uncertainty, whereas clean energy equities provide limited covering capacity and a robust haven during high market phases. In addition, the authors Attarzadeh and Balcilar (2022) investigate the effects of volatility on the renewable energy, oil, and technology stock markets over 16 years, highlighting the two-way effects of volatility on the oil and clean energy markets, with the oil market absorbing the majority of the volatility. Shakhabiddinovich et al. (2022) contribute to a better understanding of renewable and clean energy shocks and their impact on green economy stock prices. Their study, which spans the years December 2010 to July 2021, highlights the prevalence of negative shocks in renewable and clean energy production as well as the nuanced relationship between renewable production prices and green economy share prices, which can be both positive and negative.

In more recent studies, Farid et al. (2023) examined a variety of energy sources, including crude oil, heating oil, diesel, gasoline, natural gas, and clean energy represented by indexes. Their analyses revealed a few shocks between clean energy stocks and dirty energy indexes, highlighting a significant distinction between both markets. This discrepancy was prominent during the pandemic, emphasizing the benefits of diversifying investment portfolios in the clean and dirty energy markets. Furthermore, Lu et al. (2023) investigated the interplay between profitability and volatility in green financial markets, including green bonds, clean energy, and socially responsible acts, with a particular focus on the influence of the COVID-19 pandemic. The authors identified specific indexes as net transmitters of volatility effects. This research provides useful insights for both investors and regulators, boosting understanding of the mechanics of sustainable financial markets.

It became obvious in the recent years of 2020 and 2022 that it is critical to focus on the relationship between clean and dirty energy share indexes in the context of sustainable energy and innovation. According to studies, the short-term connections between these energy categories are minimal, but significant changes emerge over longer periods. Furthermore, disturbances in fossil energy markets can have a considerable impact on clean energy stock indexes, emphasizing the significance of understanding these linkages. In short, recognizing that there is a link between clean and dirty energy is critical for improving renewable energy solutions and reaching sustainable energy goals. In the face of global concerns such as climate change and pandemics, this becomes critical since it directs the creation of new sustainable energy and resilience solutions in an ever-changing global setting.

3. DATA AND METHODOLOGY

3.1. Data

The daily price indexes have been used in this study. The sample includes 4 dirty energy indexes (fossil fuels): Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP), as well as 4 sustainable energy subsectors: Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy Index, and WilderHill Index (ECO). Examine the subsectors of sustainable energy that have significant importance from the point of view of sustainability and innovation. These subsectors collectively represent the diverse scenario of sustainable energy solutions, and their research contributes to several critical aspects, including innovation catalysts, diversification, resource optimization, market insights, environmental impact, policy alignment, and technological convergence. The period under consideration ranges from May 17, 2018, to April 28, 2023. To increase the robustness of the results, the sample was divided into two subperiods: a quiet period of apparent stability in international financial markets, which lasted from May 2018 to December 2019. The stress period runs from January 2020 to April 2023, and it includes high-complexity events in the global economy, such as the global pandemic of COVID-19, followed by an oil price war between OPEC members (Russia and Saudi Arabia) and, starting in 2022, an armed conflict between Russia and Ukraine. The data obtained via the Thomson Reuters Eikon platform is in US dollars.

3.2. Methodology

The research will be conducted in multiple stages. In the first stage of sample characterization, descriptive statistical metrics are used. Additionally, the Jarque and Bera (1980) adherence test is conducted to assess the normality of the data based on the null hypothesis. To assess the stationarity of the time series, particularly with regard to its adherence to a white noise process characterized by a mean of 0 and constant variance, panel unit-root tests are employed. The tests employed in this study consist of the Dickey and Fuller (1981) method, which incorporates Fisher's Qui-square transformation, as well as Choi (2001) unit root tests. Both tests assume the null hypothesis of a unit root. To validate the evidence, we employ the Hadri (2000) test, which tests the null hypothesis of stationarity. The convergence of these tests enhances the reliability of the determination concerning the stationarity of the time series. The Augmented Dickey-Fuller (ADF) test is a commonly used method in the examination of financial time series. It encompasses different versions, including the ADF Fisher Qui-Square test and the ADF Choi Z-stat test. The first strategy used test statistics that were derived from the discrepancy between the estimated coefficients and the hypothetical coefficients in the regression model. On the other hand, the second approach employed an alternate methodology by utilizing estimates of maximal verisimilitude from the autoregressive model. Both versions evaluate if there is a unit root present or absent in the time series. Moreover, the Hadri (2000) test relies on estimating the regression coefficient between variations in series and a certain set of instrumental variables. The variables are employed for the purpose of identifying deterministic trends within time series data. Furthermore, stability analyses were conducted on the waste generated by the clean and dirty energy stock indexes. The objective of these stability tests is to identify fluctuations in variance, particularly substantial changes in variance throughout the sample period while considering occurrences in 2020 and 2022. To comprehensively address the study question, we will utilize the Granger Vector Autoregressive Causality Econometric Model (VAR). This paradigm enables the examination of causal interactions among variables within the framework of time series multivariate data. Granger's causality, a fundamental concept in the field of vector autoregressive (VAR), is predicated on the notion that the historical values of a certain variable enhance the prediction capacity of another variable. Therefore, if the initial variable contributes to the enhancement of predictions for the second variable, it is regarded as the Granger causality of the latter. The notion of causality, sometimes referred to as Granger's causality, enables us to evaluate not only the existence but also the orientation and magnitude of causal connections among variables.

4. RESULTS AND DISCUSSION

Figure 1 shows the evolution, in daily returns, of the Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP), as well as sustainable energy subsectors including the Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy Index, and WilderHill Index (ECO). The observed period spans from May 17, 2018, to April 28, 2023. Through visual analysis, it can be shown that the mean return exhibits a certain degree of stability, as indicated by the values being near zero. Nevertheless, the time series exhibits noteworthy fluctuations, indicating the inherent instability experienced by these markets, particularly during the initial months of 2020, coinciding with the repercussions of the COVID-19 pandemic on the global economy.

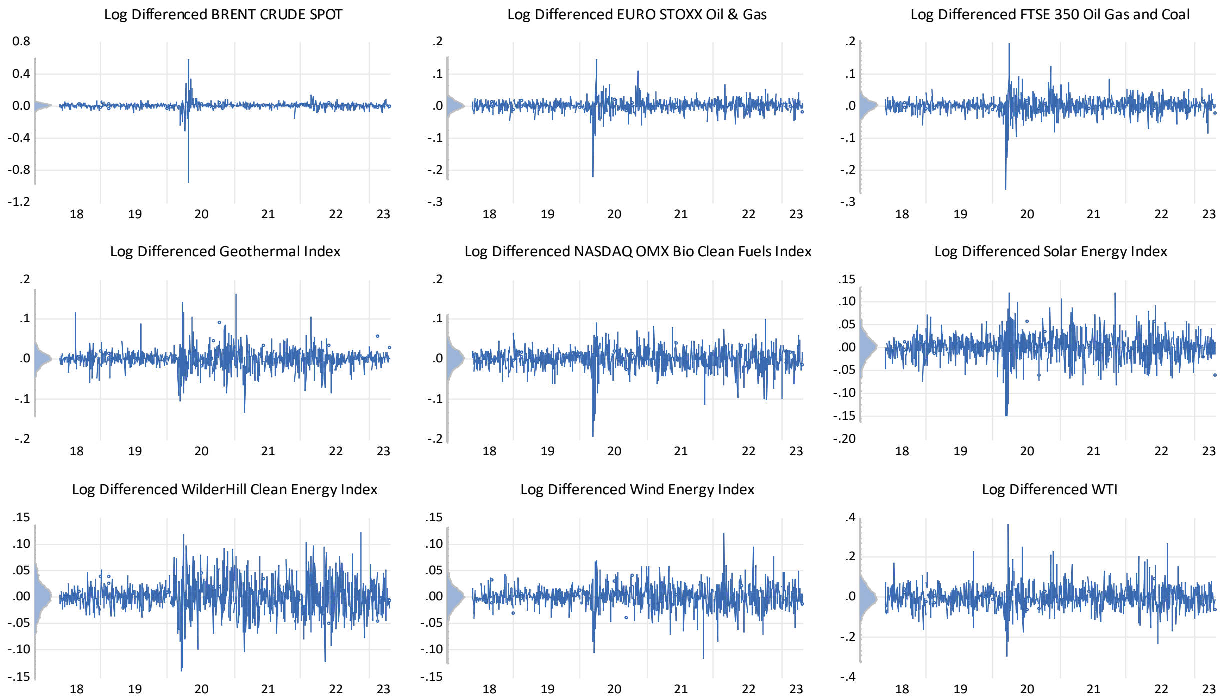

Figure 1. The evolution, in returns, of the dirty and clean energy stock indexes, from May 17, 2018, to April 28, 2023

Source: Own research

Table 1 presents the statistical summary metrics, which reveal that the average returns exhibit a positive trend, except for the ECO (-0.000263) and the WTI index (-0.000346). Notably, the ECO demonstrates the highest standard deviation (0.027018) among the stock indexes analyzed. To ascertain the presence of Gaussian distributions, it is observed that the asymmetries exhibit non-zero values, and it is noted that the BRENT distribution (-1.182660) displays the highest magnitude among these values. Furthermore, all stock indexes have kurtosis values exceeding 3, with particular significance placed on the GRNBIO stock index, which stands at 10.46391. To validate the findings, the Jarque and Bera (1980) adherence test additionally indicates the rejection of the null hypothesis at a significance level of 1%. The anticipated outcomes can be attributed to the existence of fat tails, namely extreme values, arising from the occurrences in 2020 and 2022.

Table 1. Table summary of the core statistics metrics, in returns, relating to the clean energy stock indexes under analysis, from May 17, 2018, to April 28, 2023

	GRNGEO	GRNBIO	SOLAR ENERGY	ECO	WIND ENERGY
Mean	0.000169	0.000266	0.000963	-0.000263	0.000242
Std. Dev.	0.022783	0.024585	0.026279	0.027018	0.019379
Skewness	0.147747	-1.182660	-0.661870	-0.127951	0.047109
Kurtosis	9.613298	10.46391	8.942274	5.483255	7.285361
Jarque-Bera	1659.797	2321.916	1403.758	236.0386	695.8847
Probability	0.000000	0.000000	0.000000	0.000000	0.000000
Observations	909	909	909	909	909

Source: Own elaboration

Table 2 shows the descriptive statistics of the "dirty" energy stock indexes, and we can see that the mean returns are positive, except for WTI (-0.000346). BRENT has the highest standard deviation (0.054528), asymmetry (-8.335251), and kurtosis (220.5009), suggesting that it is the riskiest market. The other markets likewise illustrate that we are dealing with non-Gaussian distributions, as they have values different from 0 (asymmetry) and 3 (kurtosis). The Jarque and Bera (1980) adherence test was used to confirm that we are dealing with deviations from normal distributions.

Table 2. Table summary of the core statistics metrics, in returns, relating to the dirty energy stock indexes under analysis, from May 17, 2018, to April 28, 2023

	BRENT	SXEP	FTSE 350 OG & COAL	WTI
Mean	0.000796	1.83E-05	0.000133	-0.000346
Std. Dev.	0.054528	0.017505	0.023261	0.051376
Skewness	-8.335251	-0.466404	-0.516129	0.304305
Kurtosis	220.5009	20.67552	19.22784	7.918369
Jarque-Bera	1802265.	11866.02	10014.47	930.2389
Probability	0.000000	0.000000	0.000000	0.000000
Observations	909	909	909	909

Source: Own elaboration

To assess the assumption of stationarity for various stock indexes, including Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP), as well as subsectors of sustainable energies such Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy, and WilderHill Index (ECO), we conducted unit root tests. Specifically, we employed the Dickey and Fuller (1981) - Fisher Chi-square and Choi Z-stat tests, along with the Hadri (2000) test. This analysis was conducted for the period from May 17, 2018, to April 28, 2023. The robustness of the intersection of the tests with contradictory null hypotheses allows for the measurement of the level of lag of each time series until it achieves equilibrium, characterized by an average of 0 and a variance of 1. The findings indicate that the time series exhibits unit roots when estimating the original price series. To achieve stationarity, a logarithmic transformation was applied to the first differences. This transformation facilitated the rejection of the null hypothesis in the Dickey and Fuller (1981) test, specifically through the Fisher Chi-square and Choi Z-statistic. About the Hadri (2000) test, it is seen that the null hypothesis is not rejected, thereby confirming the basic assumptions for the estimation of VAR models (see **Tables 3** and **4**).

Table 3. Dickey and Fuller (1981) panel unit root test, in returns, relating to the stock indexes under analysis, for the period from May 17, 2018, to April 28, 2023

Null Hypothesis: Unit root (individual unit root process)		
Method	Statistic	Prob.
ADF - Fisher Chi-square	2245.91	0.0000
ADF - Choi Z-stat	-46.4970	0.0000

Source: Own elaboration

Table 4. Hadri (2000) panel unit root test, in returns, relating to the stock indexes under analysis, for the period from May 17, 2018, to April 28, 2023

Null Hypothesis: Stationarity		
Method	Statistic	Prob.
Hadri Z-stat	-0.18385	0.5729
Heteroscedastic Consistent Z-stat	-0.07167	0.5286

Note: High autocorrelation leads to severe size distortion in Hadri test, leading to over-rejection of the null.

Source: Own elaboration

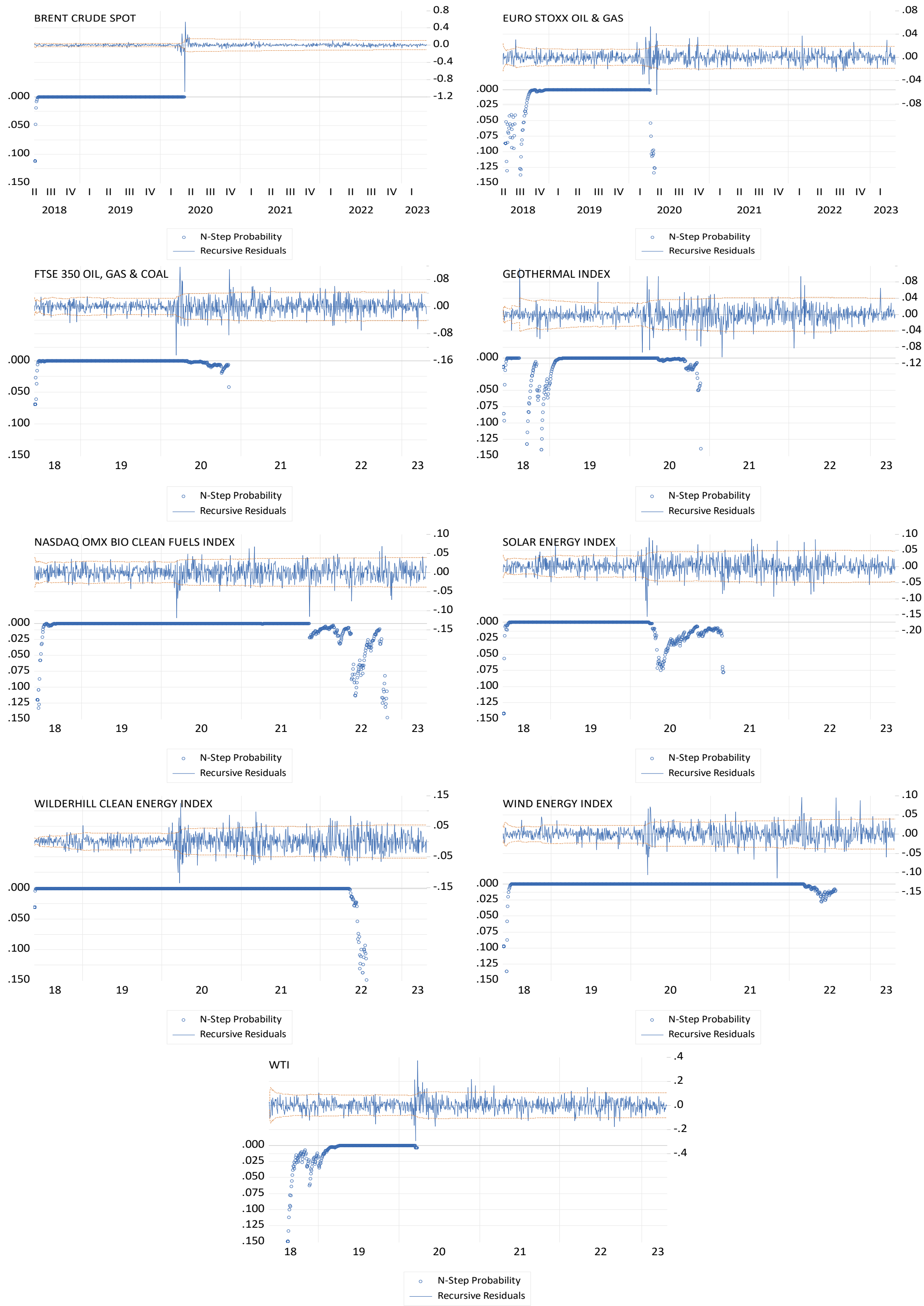

Figure 2. Stability tests for residues, in returns, relating to the stock indexes under analysis, for the period from May 17, 2018, to April 28, 2023

Source: Own research

Figure 2 depicts residue stability charts based on the stock indexes Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP), as well as sustainable energy subsectors Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy, and WilderHill Index

(ECO). We may examine the presence of disturbances in the variance of the residues using the graphical analysis of the stability charts in Figure 3. Furthermore, violations of the 95% confidence limits demonstrate the presence of unstable behavior in the time series. These findings suggest that the stock indexes studied are vulnerable to fluctuating and unpredictable patterns, emphasizing the need to take these elements into account when making investment decisions.

In this study, we intended to see if fossil fuels influenced the establishment of prices for sustainable energy, especially during times of global economic instability, in particular during the events of 2020 and 2022. We looked at the clean energy stock indexes, specifically the subsectors Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy, and WilderHill Index (ECO), as well as the price indexes Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP). To increase robustness, we divide the sample into two subperiods: Tranquil (the period from May 17, 2018, to December 31, 2019) and Stress (the period from January 2020 to April 2023).

Upon comparing the two subperiods, it becomes evident that there was a substantial rise in the number of influential movements between the Tranquil and Stress subperiods, with the count rising from 18 to 49 moves. The GRNGEO, Solar Energy Index, GRNBIO, and Wind Energy Index are examples of sustainable energy subsectors that did not have an impact on the prices of fossil fuels and sustainable energy pairs during the Tranquil Period. Upon analyzing the Stress subperiod, it became evident that the GRNGEO and Wind Energy Index subsectors have begun to exert an influence on the price development of BRENT and WTI. The Solar Energy Index has a significant impact on the prices of Brent, WTI, Wind Energy, and ECO. Similarly, the GRNBIO has a notable influence on the prices of BRENT, WTI, SXEP, the ECO index, as well as the subsectors of the Solar Energy and Wind Energy Index. During a period of relative stability, the ECO had a significant impact on the prices of most comparable indexes, except for BRENT. However, during a period of heightened stress, the ECO index influenced the development of prices across all energy markets, including both fossil fuels and sustainable energy.

When we started examining “dirty” energy markets during the Tranquil period, we discovered that WTI (6) was the most significant emitter, followed by BRENT (4), FTSE 350 OG & Coal (1), and finally the SXEP, which did not influence the formation of any index’s prices. When we analyze the Stress period, we observe that the SXEP influences the prices of all its peers (8 out of 8 possibilities), and the BRENT influences the prices of their peers, except the Wind Energy Index. Similarly, the WTI has an impact on its peers, except for the GRNGEO, whilst the FTSE 350 OG & Coal has an impact on the WTI, GRNGEO, Solar Energy Index, and ECO.

Table 5. Summary table of short-term shocks in relation to the stock indexes under analysis during the Tranquil and Stress subperiods

Market	Tranquil Subperiod	Stress Subperiod	Evolution
GRNGEO	0 / 8 possibilities	2 / 8 possibilities	↑
SOLAR ENERGY	0 / 8 possibilities	4 / 8 possibilities	↑
GRNBIO	0 / 8 possibilities	6 / 8 possibilities	↑
WIND ENERGY	0 / 8 possibilities	2 / 8 possibilities	↑
ECO	7 / 8 possibilities	8 / 8 possibilities	↑
BRENT	4 / 8 possibilities	7 / 8 possibilities	↑
FTSE 350 OG. & COAL	1 / 8 possibilities	5 / 8 possibilities	↑
SXEP	0 / 8 possibilities	8 / 8 possibilities	↑
WTI	6 / 8 possibilities	7 / 8 possibilities	↑

Source: Own elaboration

In summary, the dynamic relationship between sustainability and innovation in the realm of green energy is significantly influencing indexes related to fossil fuels. During periods of adversity, there is an increased importance placed on sustainable energy subsectors, while indexes associated with "dirty" energy exhibit differing levels of influence. The WilderHill Clean Energy Index (ECO) plays a key role in shaping the price formation of fossil fuels and sustainable energy indexes.

5. CONCLUSION

The objective of this study is to examine the impact of fossil fuels on the development of sustainable energy prices in the context of global economic instability, specifically focusing on the occurrences of 2020 and 2022. A comprehensive study was conducted on various clean energy indexes, namely Geothermal Index (GRNGEO), Solar Energy Index, NASDAQ OMX Bio Clean Fuels (GRNBIO), Wind Energy, and WilderHill Index (ECO). Additionally, the prices of Brent Crude Spot (BRENT) WTI, FTSE 350 Oil, Gas & Coal (FTSE 350 OG & Coal, and EURO STOXX Oil & Gas (SXEP) were included in the analysis. In order to enhance the reliability of our results, we partitioned the sample into two distinct periods: Tranquil (May 17, 2018, to December 31, 2019) and Stress (January 2020 to April 2023). The research indicated a notable rise in the occurrence of influence movements across these indexes, increasing from 18 to 49 during the transition from the Tranquil to Stress subperiods. During a time characterized by relative stability, the subsectors associated with sustainable energy exhibited a constrained impact on the pricing dynamics of fossil fuels and durable energy sources. Nevertheless, during the stress subperiod, a notable change occurs as the GRNGEO subsector and Wind Energy Index begin to exert influence on the formulation of BRENT and WTI prices. The emergence of Solar Energy and the GRNBIO has had a notable impact on many price indexes, such as BRENT, WTI, SXEP, ECO, Solar Energy Index, and Wind Energy Index. In summary, this research emphasizes the significant effects of sustainability and innovation in the field of green energy on the dynamics of influence pertaining to indexes related to fossil fuels. During periods characterized by economic tension, there is an increased importance of sustainable energy subsectors, but the influence of "dirty" energy indexes exhibits various degrees. The WilderHill Clean Energy Index (ECO) holds significant influence in affecting the formation of fossil fuels and sustainable energy indexes. These findings not only draw attention to the continuous trend towards investments that are both environmentally benign and economically sustainable but also underscore the increasing significance of sustainability within the domain of financial markets. With the growing global consciousness regarding the pressing necessity to tackle climate change and encourage ethical industry practices, there is an escalating recognition among investors of the enduring advantages associated with integrating sustainability into their investment plans. The results shed light on the fact that sustainability has transcended its status as a mere buzzword or a niche market. The impact of this aspect on the performance and stability of financial markets has gained substantial importance.

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