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Article

Crude oil price behavior and the adoption of sustainable measures in companies before and after COVID-19

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Abstract: The objectives achieved in the Paris Agreement to reduce greenhouse gas emissions and reduce dependence on fossil fuels have caused, in recent years, a growing importance on sustainability in companies in order to reduce Environmental, social and economic impacts. This study is focused on understanding how the variation in West Texas Intermediate crude oil prices affects the Dow Jones Sustainability Index, and therefore the companies included in it, and vice versa. The research aims to examine the statistical properties of both indices, using fractional integration methods, the fractional cointegration vector autoregressive (FCVAR) approach and the continuous wavelet transform (CWT) technique. The results warn of a change in trend, with the application of extraordinary measures being necessary to return to the original trend, while the analysis of cointegration and wavelet analysis measures reflect that an increase in those adopted based on sustainability by the different companies that make up the index imply a drop in the price of crude oil.

Keywords: oil prices; DOW jones sustainable index; fractional integration; FCVAR model; wavelet analysis

1. Introduction

The growing concern about climate change and sustainability has increased interest in sustainability indices, such as the Dow Jones Sustainability Index (DJSI) and its relationship with different economic spheres. Oil continues to be one of the most important raw materials in the global economy, being a significant source of income for companies and producing countries, the volatile price of crude oil can affect both the economy and the environment, especially after the Paris agreement, focused on reducing carbon emissions to address climate change, assuming a push towards greener energy sources (Steckel and Jakob, 2022).

Energy is one of the fundamental elements in sustainability, its production and consumption have a direct impact on the economy, the environment and society. Access to reliable and sustainable energy sources is of vital importance to achieve sustainable economic and social development.

Energy sustainability implies efficient management of energy resources by promoting the use of renewable energy and reducing energy consumption. Not only consumption affects the sustainability of companies, but price fluctuations also have an economic impact reflected in the financial sustainability of companies.

Various studies such as the one carried out by Gupta and Bhanja (2017), investigated the relationship between shocks in oil prices, the stock market, economic activity and sustainable development in a panel of Asian countries that are net oil importers, finding that shocks in oil prices have a negative impact on the

environmental dimension of sustainable development in the long term.

These results coincide with those reported by Uddin et al. (2020) the authors analyzed the effect of fluctuations in oil prices on sustainability, by analyzing the relationship between the DJSI and oil prices, among their conclusions they highlighted the negative impact on the sustainability index that occurs given the rise in oil prices, suggesting the need to reduce dependence on crude oil.

On a similar way, the article written by Nekhili et al. (2024) examines the evaluation between sustainability indices and oil and gold, obtaining results that show a high dependence between oil and DJSI assets, with Europe and the United States with greater dependence on oil in the long term, while Sha (2022) aims to analyze the link between the price of crude oil and economic performance in a pre-pandemic period.

The conclusions drawn by the literature make it necessary to delve deeper into the relationship between WTI oil prices and the DJSI sustainability index. The serious drop in economic activities caused by COVID-19 has caused an increase in oil prices in all over the world affecting global economic prospects, because they are the main inputs of economic production in addition to the essential factor of economic development (Nam, 2022).

From these conclusions, showing how the interaction between the price of crude oil and economic growth is essential for sustainability (Sha, 2022), the objectives to be discussed in this publication are drawn, studying how the companies included in the DJSI can be affected by the price of oil.

To the best of our knowledge, this is the first paper that analyzes the statistical properties of WTI crude oil prices and sustainable measures adopted by the companies in United States using methodologies based on fractional integration, fractional cointegration and Wavelet Analysis.

The focus of this research paper is to study how the variation in crude oil prices affects the sustainability index, and therefore the companies included in it. To do so, we analyze daily data from 2 January 2013 to 25 January 2023. Also, we take the COVID-19 as a structural break to analyze the behavior before and after this pandemic episode.

Our results can be summarized as follows: Using fractional integration methods, the results indicate that the DJSWI ($d = 0.95$) recovers before that the WTI crude oil prices ($d = 1.07$), which will need extraordinary measures to return to its original trend after COVID-19. In addition, according to the confidence interval we cannot reject the I(I) hypothesis, where the shock is expected to be permanent, causing a change in trend, which will need extraordinary measures to return to its original trend. To rule out possible spurious relationships, also we have calculated the VAR-based Granger-causality Test, finding that time series are related in both directions, whose results imply that the variation in any of the two indices will have a direct impact on the other, coinciding with the investigations carried out by other researchers such as Gupta and Bhanja (2017), Korkmaz and Akin (2018) and Uddin et al. (2020).

Finally, analyzing the long-term relationship of the time series using fractional cointegration vector autoregressive (FCVAR) model and Continuous Wavelet Transform (CWT), we find that an increase in the measures adopted based on sustainability by the different companies that make up the index implies a drop in the

price of crude oil. Specifically, the fall in the price of crude oil is around −17.463 according to the beta coefficient of the FCVAR model.

The rest of the paper is organized as follows. Section 2 reviews the literature. In the following sections the data source and the methodology applied in the paper are shown. Section 5 presents the main empirical results, while the final section shows the main conclusions of this research work.

2. Literature review

2.1. Dow jones sustainability index

Sustainability indexes have become increasingly important in recent years as companies and organizations seek to measure and improve their environmental, social and governance (ESG) performance. Research carried out by Bezerra et al. (2021) reviewed 68 articles on corporate sustainability rating models and found no consensus on what constitutes sustainability and how it should be measured. While the study from Oliveira et al. (2023) analyzed over a dozen relevant articles and reports on corporate sustainability and found a need for common proposals that could support corporate sustainability development on a larger scale.

Although investors start from a main objective, obtaining a high return on their investments, there is currently growing concern about climate change, social well-being and the sustainability of natural resources (Oliveira and Gebreyes, 2022), this has made that the integration of ESG factors and sustainability with investment is a highly relevant topic for investors. Investing in companies and projects that prioritize issues such as sustainability could lead to better financial performance (Soni et al., 2024).

The green economy is gaining increasing importance, sustainable investment receives great attention from investors, policymakers and society in general (Olanipekun et al., 2023). Sustainable investment is constantly encouraged, while investors show greater interest in incorporating companies that offer more sustainable products into their portfolios (Dutta et al., 2021).

For these reasons, research such as that carried out by Nguyen et al. (2022) states that companies' interest in ESG can make them appear more attractive to investors, resulting in higher stock markets.

The Dow Jones Sustainability index tracks the performance of the shares of companies considered world leaders in terms of a series of criteria, such as economic, environmental and social. The importance of this index is reflected in different investigations, such as the one carried out by Herzig and Schaltegger (2012), in which they provided an overview of the presentation of corporate sustainability reports, among which the DJSI stands out as one of the most relevant in the presentation of these reports.

Social ratings such as the DJSI index in measuring corporate social responsibility show that the inclusion of companies in this index has a positive correlation with the profitability and reputation of companies (Chatterji et al., 2009).

This index is based on the theory that companies with better performance in these areas are more attractive to investors and perform better in the long term since there is a positive relationship between the two (Friede et al., 2015; Scholtens and Dam, 2014).

Along the same lines, Lin et al. (2017) demonstrated that the inclusion of the DJSI index was associated with a positive impact due to higher profitability and lower volatility in share prices.

Khan et al. (2014) in their study confirmed that companies included in the DJSI index outperformed companies not included in long-term financial profitability. This conclusion coincides with the one shown by Kacperczyk and Hong (2013), where they analyzed the relationship between ethical values and the profitability of companies, concluding a higher profitability of the companies included in the index.

2.2. Dow jones sustainability index analysis

The DJSI index has been the subject of different analyzes in the literature using different techniques in order to study its behavior and trend in the face of different shocks such as the one suffered in 2008; Dincer et al. (2018) focused their study on analyzing the impact of the 2008 crisis on the DJSI index through the use of unit roots, analyzing the impact of economic fluctuations on the index's ability to measure the sustainability of companies.

Hadian et al. (2016) analyze the long-term relationship between the DJSI and the US stock index, using fractional cointegration techniques to determine whether a stable relationship exists, as well as whether sustainability can be used as a leading indicator of company performance.

The regression models were used by Kim and Ryu. (2019) to study the behavior of oil prices and the DJSI, demonstrating the negative effect of oil price shocks on the sustainability index.

One of the first investigations that uses the use of artificial neural networks (ANN) for the analysis of the DJSI is the one carried out by Korkmaz and Akin (2018), in their study they analyze the relationship between oil prices and the DJSI through the using neural networks, managing to predict changes in the DJSI from oil price data. In the same line of research Javed et al. (2019), make the prediction of the index using this type of algorithm, with an accuracy in their results greater than 85%.

2.3. West Texas intermediate analysis

Statistical characteristics of the prices of US oil is analyzed according to DJSI to understand the behavior of DJSI and WTI and how and how do they influence each other. (WTI) US oil prices, a measure of the degree of persistence using the fractional integration method (Monge et al., 2017a, 2017b; Monge and Gil-Alana, 2020). In addition, we analyze long-term relationships in time series using the Fractional Cointegration Vector Autoregressive (FCVAR) approach (Johansen and Nielsen, 2010, 2012). Finally, we use a wavelet transform-based method to examine possible structural changes induced by changes in exploration techniques in West Texas Intermediate (WTI) prices (Aguiar-Conraria and Soares, 2014).

Kaufman et al. (1994) assessed the feasibility of policies to encourage exploration and development by the petroleum industry and estimated a new model of US well completions that included expected price impacts from well data. Das et al. (2018) adds a new dimension to the relationship between oil prices and economic growth using the West Texas Intermediate (WTI) Index for a review of the relationship

between US economic growth and oil prices, taking into account the industrial production index and WTI spot prices.

2.4. Energy prices and sustainability

Focusing more on the subject matter of our analysis, there are numerous studies focused on the analysis of factors that affect the behavior between energy prices and sustainability. Research such as that carried out by Azhgaliyeva et al. (2022) investigated how the shocks produced in oil prices affected green bonds, the results suggested a high impact of these shocks, also finding a relationship between the volatility of oil prices with that of green bonds.

The relationship between oil prices and sustainable stock indices was analyzed by Alsharif et al. (2018), suggesting that the volatility of sustainable indices is influenced by oil prices. While the research by Liu et al. (2018) demonstrated an inverse relationship between energy prices and sustainability indices, indicating that companies with higher sustainability performance better cope with rising energy prices.

The variability of energy prices has a significant impact on the sustainability of companies, and consequently on their financial performance, with those companies included in the sustainable indices showing less exposure to energy price risk (Dragana et al., 2021).

Other research, such as the one carried out by Vasiljeva et al. (2022), focused on the relationship between the oil market and the sustainable development goals (SDGs), analyzing how the countries participating in the OPEC++ agreement, alliance which aims to reduce oil production and stabilize its prices, could balance its production and profitability objectives with the SDGs, proposing a gradual transition strategy towards a more sustainable economy and less dependent on oil.

In the study carried out by Haq et al. (2022) demonstrates a bidirectional transmission of volatility between sustainable financial markets and those of raw materials and rare commodities, which suggests a clear interconnection, so that volatility in some of them will be reflected in the others.

Oil prices have been related to sustainability in the most recent literature, authors such as Dehdashti and Mahani (2017) examine the relationship between oil prices and the sustainable performance of companies, suggesting that oil prices have a negative impact in sustainability. These results coincide with those obtained by Cunha et al. (2019) in their research, in which they analyzed this relationship by including the companies included in the DJSI index, the result also showed a negative impact of oil prices on the financial sustainability of these companies.

However, another line of literature focuses on the investigation of the impact of COVID-19 on crude oil prices (see for example Peng and Liang (2023)), showing a positive effect of inflation on prices. of oil, especially in the period of the pandemic. On the other hand, in a contrary approach, Sabour (2005) aims to quantify the external cost of consuming a barrel of oil in the context of sustainable development, concluding that, the total cost of consuming a barrel of oil now, which should be used in the calculation of the life cycle cost to design more sustainable products, is the sum of the price of oil and the external cost.

3. Data

One of the most well-known measures of business sustainability in the world is the Dow Jones Sustainability Index (DJSI). The goal of the index is to evaluate the performance of the most sustainable businesses in the world. It was developed by investment firm S&P Dow Jones Indices in collaboration with sustainability research firm RobecoSAM.

Investors looking to place money into businesses that have a strong emphasis on sustainability—from an environmental, social, and governance standpoint—have utilized the DJSI since its founding in 1999. Subject matter experts have assessed the index, which consists of top businesses in each of the categories that have proven their dedication to sustainability.

To carry out this study, daily data was collected for the DJSI and WTI indices from 2 January 2013 to 25 January 2023. To carry out this study, information was acquired from the Eikon Reuters database. The authors of this study ensured that the data had the same base year and that the information was unprocessed. Eikon is a privately accessible economic and financial database that provides industry-leading data, insights and exclusive, reliable news.

Results in **Table 1** show descriptive statistics of the variables. The results show that the mean values of DJSI and WTI have remained positive thought the period studied. However, DJSI experienced a high volatility rate as shown in the standard deviation of 314.4 against 22.7 for WTI.

Table 1. Main descriptive statistics.

DJSI		**WTI**	
Mean	1490.3	Mean	65,9
Std. Dev.	314.4	Std. Dev.	22,7
Min. Value	1017.4	Min. Value	−37
Max. Value	2242	Max. Value	123.6
Sample size	2527	Sample size	2527

4. Methodology

4.1. Unit roots

Unit roots can be tested in many different ways. To this research we use ADF test based on Dickey and Fuller (1979). There are many other tests available to calculate unit roots that have a greater power such as Phillips and Perron (1988) in which a non-parametric estimate of the spectral density of u_t at the zero frequency is used. Also, considering deterministic trends, we use the methodology based on Kwiatkowski et al. (1992) and Elliot et al. (1996), producing all essentially the same results.

4.2. ARFIMA (p, d, q) model

Following authors such as Diebold and Rudebusch (1991), Hassler and Wolters (1994), Lee and Schmidt (1996) and others, it is now a well stylized fact that all unit root methods have very low power if the true data generating process displays long

memory or if it is fractionally integrated. Thus, in what follows, fractional orders of differentiation are allowed.

For this reason, we use the ARFIMA (p, d, q) model where the mathematical notation is:

$$(1-L)^d x_t = u_t, t = 1,2 \tag{1}$$

In Equation (1), x_t refers to the time series that has an integrated process of order d $(x_t \approx I(d))$, d refers to any real value, L is the lag-operator $(Lx_t = x_{t-1})$ and u_t refers to I(0). The Akaike information criterion (Akaike, 1973) and Bayesian information criterion (Akaike, 1979) were used to select the appropriate AR and MA orders in the models.

The d parameter has been estimated considering all combinations of AR and MA terms $(p; q \leq 2)$ for the time-series and for the subsamples taking into account their confidence bands at 95%.

4.3. FCVAR model

Following Johansen and Nielsen (2012), we use their multivariate Fractional Cointegration Vector Autoregressive (FCVAR) model to check the relationship of the variables in the long term. The FCVAR model is notated in the next equation:

$$\Delta^d X_t = \alpha\beta' L_b \Delta^{d-b} X_t + \sum_{i=1}^{k} \Gamma_i \, \Delta^b L_b^i Y_t + \varepsilon_t \tag{2}$$

where ε_t is a term with mean zero and variance-covariance matrix Ω that is p-dimensional independent and identically distributed; α and β are $p \times r$ matrices where $0 \leq r \leq p$. The relationship in the long-term equilibria in terms of cointegration in the system is due to the matrix β. Controlling the short-term behavior of the variables is due to parameter Γ_i. Finally, the deviations from the equilibria and their speed in the adjustment is due to parameter α.

4.4. Continuous wavelet transform (CWT)

Time series are an aggregation of components operating on different frequencies. So, the most outstanding information is hidden in the frequency content of the signal. For this reason, this methodology makes a lot of sense.

Wavelet coherence and wavelet phase difference have been used to deepen this research in the time-frequency domain. This study allows to analyze the interaction of the time series in the time domain and revealing structural changes without the need for it to comply with the stationarity characteristic.

Based on the analysis carried out by Kyrtsou et al. (2009) on the energy markets and nonlinear dependencies, several authors have used nonlinear methods to analyze the impact of oil shocks using wavelet analysis. Other authors such as Aguiar-Conraria and Soares (2014) and Crowley and Mayes (2009) have used wavelets to test and to study business cycle synchronization.

To identify hidden patterns and/or information, we use the wavelet coherency plot that measure the correlation between the time series in the time-frequency domain. To get this result, we calculate the $WT_x(a, \tau)$ that is the wavelet transform of a time

series $x(t)$, projecting the mother wavelet ψ to map the original time series onto a function of τ and a:

$$WT_x(a,\tau) = \int_{-\infty}^{+\infty} x(t)\frac{1}{\sqrt{a}}\psi^*\left(\frac{t-\tau}{a}\right)dt \quad (3)$$

We choose Morlet wavelet as the mother wavelet because it is a complex sine wave within a Gaussian envelope, so we will be able to measure the synchronism between time series (see Following Aguiar-Conraria and Soares, 2014).

Taking into account the results that we get using Wavelet Transform, Wavelet Coherence helps us understand how one time series interacts with respect to the other. We can define this term as:

$$WCO_{xy} = \frac{SO\left(WT_x(a,\tau)WT_y(a,\tau)^*\right)}{\sqrt{SO(|WT_x(a,\tau)|^2)SO\left(\left|WT_y(a,\tau)\right|^2\right)}} \quad (4)$$

The SO parameter represents the smoothing operator in time, being relevant since if it were dispensed with, the wavelet coherence for all scales and times would be one (Aguiar-Conraria et al., 2008). It is possible to find the codes developed with MATLAB for the CWT solution on the Aguiar-Conraria website (Aguiar-Conraria and Joana Soares, n.d.).

5. Empirical results

5.1. Unit roots results

We start with the use of Unit Root tests (ADF, PP and KPSS) to determine whether a series is stationary I(0) or non-stationary I(1). In data analysis this is very important as it allows a more consistent interpretation of the model parameters. A trend or seasonal variation can distort the results and lead to erroneous conclusions about the underlying relationships in the data. The results are displayed in **Table 2**.

Table 2. Unit root tests for DOW jones sustainability world index.

	ADF			**PP**		**KPSS**	
	(i)	**(ii)**	**(iii)**	**(ii)**	**(iii)**	**(ii)**	**(iii)**
Dow Jones Sustainable World Index	Original Data						
	0.8799	−1.1311	−2.4601	−1.1377	−2.4987	22.8388	2.6557
	Before COVID-19						
	0.709	−1.6884	−2.287	−1.5806	−2.1365	10.6662	2.3517
	After COVID-19						
	0.5174	−1.5667	−1.558	−1.6396	−1.6645	7.446	1.8045
WTI crude oil prices	Original Data						
	−0.8077	−2.0348	−1.9355	−1.9152	−1.8035	4.5126	4.0371
	Before COVID-19						
	−1.1873	−1.2908	−1.1119	−1.3212	−1.1668	10.1888	3.6269
	After COVID-19						
	−0.2427	−1.5937	−2.4136	−1.4404	−2.2499	7.7384	1.5223

(i) No deterministic components; (ii) intercept, (iii) linear time trend. * Statistic significant at the 5% level.

The results suggest that the whole sample and the two subsamples, before and after COVID-19 for the Dow Jones Sustainable World Index and WTI crude oil prices, present a non-stationary behavior I(1). Therefore, the original series and the sub-samples present a trend that is not deterministic but stochastic. This means that deviations from the mean are not automatically corrected over time. Each future value depends on the previous value plus an error term, thus accumulating the impact of all past errors.

5.2. Long memory results

Following the results obtained in **Table 2** and due to the lower power of the unit root methods under fractional alternatives, we also employed ARFIMA (p, d, q) models to study the persistence of the global sustainability in the top 10% of the largest 2500 companies according to S&P Global BMI and based on long-term economic, environmental, and social criteria and the persistence of the crude oil prices.

The advantages of using the ARFIMA (p, d, q) model over any Unit Root tests are several: 1) They allow fractional values for d providing greater flexibility in how the series is modeled; 2) They capture long-term dependence; 3) They offer a complete framework for modeling and predicting time series.

Table 3 displays the fractional parameter d and the AR and MA terms obtained using Sowell's (1992) maximum likelihood estimator of various ARFIMA (p, d, q) specifications with all combinations of $p, q \leq 2$, for each time series.

Table 3. Results of long memory tests.

Data analyzed	Sample size (days)	Model Selected	*d*	Std. Error	Interval	I(*d*)
Dow Jones Sustainability World Index	Original Time Series					
	2527	ARFIMA (2, *d*, 2)	0.93	0.046	[0.86, 1.01]	I(1)
	Before COVID-19					
	1554	ARFIMA (0, *d*, 0)	1.08	0.023	[1.04, 1.12]	I(1)
	After COVID-19					
	973	ARFIMA (2, *d*, 1)	0.95	0.068	[0.84, 1.06]	I(1)
WTI crude oil prices	Original Time Series					
	2527	ARFIMA (0, *d*, 0)	0.85	0.013	[0.83, 0.87]	I(*d*)
	Before COVID-19					
	1554	ARFIMA (2, *d*, 2)	1.09	0.068	[0.98, 1.20]	I(1)
	After COVID-19					
	973	ARFIMA (2, *d*, 2)	1.07	0.126	[0.86, 1.22]	I(1)

We observe from **Table 3** that the estimates of d that we get focusing on the original time series of DJSWI and crude oil prices is lower that 1 in both cases ($d < 1$). We observe a high degree of persistence with all values in the confident bands in the interval $[0.5, 1)$ and showing nonstationary behavior. These results suggest that both time series are expected to be mean reverting and the shocks will be transitory, where sustainable behaviors in the companies ($d = 0.93$) will take longer recover the original trend than crude oil prices ($d = 0.85$). We cannot reject the I(1) hypothesis for the DJSWI.

If we focus on the period after the pandemic, we see that the index measuring sustainability in companies obtains a value of $d = 0.95$. This result suggests that the time series has high persistence and long memory, being on the borderline between stationary and non-stationarity. This suggests that shocks have long-lasting but slowly diminishing effects.

Related to the crude oil prices. where the value of d after COVID-19 is 1.07 indicates that not only is there an increasing trend in the price of oil, but that this trend is growing at a rate that implies significant cumulative effects of past shocks. This suggests that shocks to West Texas Intermediate will have long-lasting and increasingly pronounced effects over time.

After pandemic episode, in both time series, according to the confidence interval we cannot reject the I(1) hypothesis where the shock is expected to be permanent, causing a change in trend, which will need extraordinary measures to return to its original trend.

5.3. Granger causality VAR test results

Once we have studied the statistical properties of each time series, we use the Granger causality VAR test to examine the interactions between sustainable behaviors in the companies and crude oil prices movements in United States. Performing a bivariate causality analysis allows us to identify the influences that one variable or time series exerts on the other. Also, past values of the causal variable provide useful information that can be exploited to predict future values of the dependent variable.

The Granger causality VAR test results are displayed in **Table 4**. The results suggest that both time series are related in both directions. It means that not only does the variable "crude oil prices" help predict the variable "sustainable behaviors in the companies", but the variable "sustainable behaviors in the companies" also helps predict the variable "crude oil prices". This indicates a feedback relationship where both variables influence each other. In other words, each of the two variables provides useful information to predict the other.

Table 4. Results of granger causality test.

Direction of Causality	Lags (We have used Akaike Information Criterion to detect the number of lags.)	Prob.	Decision	Outcome
d_WTI → d_DJSI	46	0.0010	Reject Null	Crude oil prices cause sustainable behaviors in the companies
d_DJSI → d_WTI	46	0.0000	Reject Null	Sustainable behaviors in the companies cause crude oil prices movements.

5.4. Results of FCVAR

Once we have determined that the relationship exists between the two variables is not spurious (the relationship between the two variables is significant in both directions), we want to determine the long-run equilibrium relationships of the two variables jointly and their co-movements. To do so, we use the Fractional Cointegration VAR model (Johansen and Nielsen, 2012). The results are summarized in **Table 5**.

Table 5. Results of the FCVAR model.

	$d \neq b$	Cointegrating equation beta	
		DJSWI	**WTI**
	$d = 0.903\ (0.045)$ $b = 0.903\ (0.126)$	1.000	−17.463
Panel I: DJSWI vs. Crude oil prices "after COVID-19"	$\Delta^d \left(\begin{bmatrix} WTI \\ DJSWI \end{bmatrix} - \begin{bmatrix} 1471.013 \\ 56.972 \end{bmatrix} \right) = L_d \begin{bmatrix} 0.003 \\ 0.000 \end{bmatrix} \nu_t + \sum_{i=1}^{2} \hat{\Gamma}_i \Delta^d L_d^i (X_t - \mu) + \varepsilon_t$		

According to the results that we get using FCVAR model, we are going to focus in two terms. In the integrating and cointegrating part ($d \neq b$) and the beta term to analyze the behavior of the time series.

From Panel I, where we analyze the long-term relationship between crude oil prices and the sustainable behaviors in the companies, we observe that the order of integration of the individual series is 0.903 getting the same magnitude in the reduction in the degree of integration in the cointegrating regression. These results imply I(0) cointegrating errors. Therefore, the individual series apparently show I(0) behavior and also, with the results of our cointegration analysis we do not rule out the hypothesis that the effects of the shock disappear in the short-run.

On the other hand, we observe from the cointegrating equation beta that an increase in the sustainable policies in the companies related to the Dow Jones Index imply a decrease in the crude oil price behavior (cointegrating equation beta equal to −17.463).

5.5. Results of frequency causality test based on Breitung and Candelon (2016)

Since the original series are not stationary but according to the FCVAR model are cointegrated, it is possible that there is a long-run relationship that the Granger difference test may not capture.

For this reason, we use Breitung and Candelon Frequency Domain Causality Test Results (Breitung and Candelon, 2006).

We find different results using the frequency domain causality test for the full-time series. Focusing on the results of the Wald test statistics and the *p*-value (in parentheses) shown in **Table 6**, we find that the sustainable index causes long-run effects to U.S. crude oil prices for the original series as well as in the differenced series.

Table 6. Breitung and Candelon frequency domain causality test results.

Hypothesis	**Lag**	**Long Term($\omega = 0.05$)**	**Medium Term ($\omega = 1.5$)**	**Short Term($\omega = 2.5$)**
Original Time Series				
DJSI → WTI	4	18.52* (0.00)	10.65* (0.00)	0.49 (0.78)
WTI → DJSI		4.83 (0.09)	4.47 (0.11)	12.54* (0.00)
d_DJSI → d_WTI	3	16.86* (0.00)	10.96* (0.00)	0.54 (0.76)
d_WTI → d_DJSI		6.77 (0.34)	4.60 (0.10)	12.68* (0.00)

However, the crude oil price causes effects on sustainable firms and is statistically significant at 5% in the short run.

5.6. Continuous wavelet transform results

Finally, we use multivariate analysis based on the time-frequency domain to understand the correlation that exists between both variables, considering the COVID-19. Also, with this methodology we are able to detect structural changes in the whole sample.

In **Figure 1**, the image on the left represents wavelet coherence. The image on the right represents the result of the phase difference.

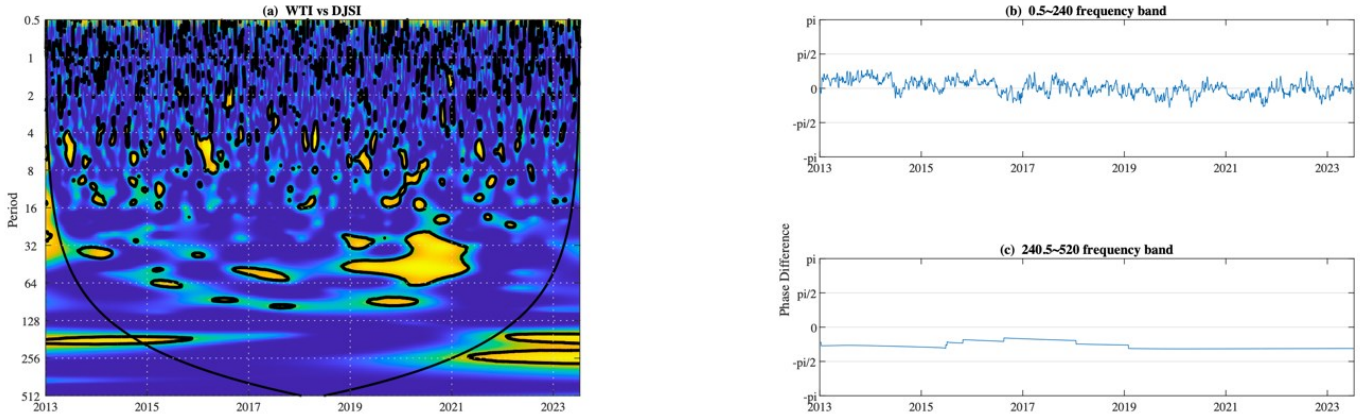

Figure 1. Wavelet coherency and phase-difference analysis.

From **Figure 1**, we can get several results. Wavelet Coherency is represented in section (a) of **Figure 1** and tell us when and at which frequencies the interrelations between time series occur and when they are the strongest, identifying the main regions with statistically significant coherency. To identify regions of high coherence we used Monte Carlo simulations (n = 1000). One region is located at cycles that correspond to 0.5–240 frequency band that is low frequency and correspond to short-term, measured in business days (from half day to the year). The other region is located at cycles that correspond to 240.5–520 frequency band that is high frequency and correspond to long-term, measured in business days (from one year to two years aprox.), starting both regions in 2013 in all the series.

Once we have identified the regions that corresponds to the high coherency (the most important results are around the coronavirus episode) located between 20–96 frequency band, we have to look the results obtained in section (b), that is the partial phase difference in the 0.5–240 frequency band. This result allows us to determine the impact and importance of the shock of one variable in relation to the other. On the results previously obtained at the 5% significance level, the phase difference is between $[0, -\frac{\pi}{2}]$.

At this frequency, this means that WTI crude oil prices are negatively correlated with DJSWI. Economically, this means that an increase in the measures adopted based on sustainability by the different companies that make up the index implies a drop in the price of crude oil. So, the adoption of sustainable policies in these companies have a direct impact on the price of crude oil.

6. Concluding remarks

Sustainability is becoming an increasingly important concern for companies around the world. Growing environmental, social, and economic risks are increasing scrutiny of business practices, and consumers are demanding greater transparency and accountability from companies. In addition, governments and regulators are increasingly imposing rules and regulations that require companies to adopt more sustainable practices.

The average consumption of barrels of crude oil in the United States exceeds 20 million barrels per day (mbpd). However, growing awareness of climate change has led to a notable expansion in the use of clean energy in recent years, reducing the market share of the most polluting traditional energy sources, such as petroleum.

It should be noted that sustainability has become an important issue for companies. 90% of executives now believe that sustainability is important to the long-term success of their organization (MIT Sloan Management Review, 2017). Similarly, 62% of investors consider sustainability an important factor in their investment decisions (Morgan Stanley, 2019). In addition, there is evidence that companies that adopt sustainable practices are more likely to be profitable and generate long-term economic returns (Eccles and Serafeim, 2013).

Our research has two purposes. First, we examine the statistical properties of the WTI and DJSI indices using fractional integration methods to determine the degree of persistence and long-term relationships in time series using FCVAR models. Next, we use a continuous wavelet transform technique to determine whether the relationship between the West Texas Intermediate (WTI) as a reference indicator of oil prices in the US and the Dow Jones Sustainability Index, a reference index in sustainability in the US.

We start by running several unit root methods, including ADF (Dickey and Fuller, 1979), KPSS (Kwiatkowski et al., 1992) and PP (Phillips and Perron, 1988). The results suggest that the time series present a non-stationary I(1). Using fractional integration methodologies based on ARFIMA (p, d, q) models, we observe that the DJSWI ($d = 0.95$) recovers before that the WTI crude oil prices ($d = 1.07$), which will need extraordinary measures to return to its original trend. In addition, according to the confidence interval we cannot reject the I(I) hypothesis, where the shock is expected to be permanent, causing a change in trend, which will need extraordinary measures to return to its original trend.

To rule out possible spurious relationships, also we have calculated the VAR-based Granger-causality Test, finding that time series are related in both directions, whose results imply that the variation in any of the two indices will have a direct impact on the other, coinciding with the investigations carried out by other researchers such as Gupta and Bhanja (2017), Korkmaz and Akin (2018) and Uddin et al. (2020).

Similar result to that obtained by Olasehinde-Williams et al. (2024), where they examined the risk of contagion between sustainable investment and crude oil prices, showing how a fall in the price of oil could lead to lower sustainable investment. while the increase in oil prices can provide an incentive for sustainable investment growth, and it is expected that the risks will be transmitted in oil price changes to sustainable investment returns.

Therefore, as long as investment decisions reflect the dynamics of the oil market, continuing to identify the dynamic connection between the two will be beneficial for investors. Furthermore, a detailed understanding of this relationship is valuable for designing policies that encourage investments in sustainable products.

Finally, from the cointegrating analysis and from CWT we find that an increase in the measures adopted based on sustainability by the different companies that make up the index implies a drop in the price of crude oil. Specifically, the drop in the price of crude oil is around 17.463 according to the beta coefficient of the FCVAR model.

These results are consistent with those obtained by Maraqa and Bein (2020), since their research found strong contagion effects between sustainability stock indices and international crude oil prices.

Our document offers relevant information for investors and portfolio managers. This finding may be useful to both individual and institutional investors seeking to maximize the long-term potential of sustainable stocks. Likewise, it is essential for investors focusing on sustainable stocks to consider the dynamic interrelationship between crude oil and sustainable stock markets, according to other relevant research (Nekhili et al., 2023). This interrelationship allows investors to identify the source of contagion and understand the market's vulnerability to external shocks. In our analysis, it is crucial to highlight that oil constitutes a significant source of disruption to sustainability markets.

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