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The long-run relationship between the prices of WTI and Brent crude oils – Periodogram based cointegration analyses

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ABSTRACT

The purpose of this article is to investigate the presence of a cointegrating relationship between the prices of the two most important crude oil price benchmarks, which are West Texas Intermediate and Brent, for June 1987-July 2021. We use the periodogram-based methodology. Our finding suggests a global long-run relationship between two major crude oil prices for the 1987:06-2010:03 period until the Deepwater Horizon oil spill took place at the Macondo Field, located in the Gulf of Mexico. After this accident, the relationship breaks down. We also find statistically significant closely 12-month common periodicities in both series for the pre-oil spill accident. We conclude that the cointegrating relationship between the two oil prices maintained up to 2010:03. This finding provides a practical implication that these two crude oil prices cannot be used for hedging purposes after this date.

Contribution/ Originality: This is the first study to examine the cointegration relationship between WTI and Brent using periodogram-based analyses. We also estimate common periodicities in both series when the presence of a cointegration relationship cannot be rejected.

1. INTRODUCTION

Under the assumption of the globalization of the oil market (Weiner, 1991) although the West Texas Intermediate (WTI) and Brent crude oil prices are globally benchmarked for spot and future crude oil markets, these two prices generally move together. It is worth noting that although the prices of WTI and Brent are quite close to each other in some periods, the spread between these two price series has increased remarkably, especially in the last decade.

The relationship between these prices is important to examine because of potential risks and arbitrage opportunities for crude oil traders and other oil market participants. Gülen (1998); Gulen (1999) and Fattouh (2011) explain the reasons for the (future) price spread between WTI and Brent by the differences in storage and logistic conditions and changes in macroeconomic conditions.[1] These findings present the standpoint which price spread between same quality crude oils moves closely together over time (stationary time process). However, some studies give evidence on the date(s) of structural break(s) at the price spread of WTI and Brent for the period after 2010 (non-

[1] Also, Ghoshray and Trifonova (2014) remark that the (future) price difference between WTI and Brent is not sourced from their quality differences.

stationary process). Chen, Huang, and Yi (2015) find one structural break in December 2010 and similarly, Scheitrum, Carter, and Revoredo-Giha (2018) detect one structural break which took place in January 2011. Buyuksahin, Lee, Moser, and Robe (2013) report that two structural breaks occur in the fall of 2008 and December 2010. Caporin, Fontini, and Talebbeydokhti (2019) provide evidence that there are two structural breaks in February 2011 and the second in October 2014. Ye and Karali (2016) claim that the first structural break took place in February 2005, the second in December 2010 and the third in April 2013.

The dates of structural breaks at the price spread of WTI and Brent correspond to important events that affect the crude oil market globally. The empirical evidence from Zhang, Yu, Wang, and Lai (2009); Charles and Darné (2014); Basistha and Kurov (2015) and Luong, Mizrach, and Otsubo (2019) reveal that changes in energy policies, unanticipated events in crude oil production process causing environmental disasters and geo-political and economic events significantly impact the price spread between WTI and Brent.

On the other hand, the structural breaks in crude oil markets mentioned above have increased the importance of examining the causality and cointegration relationship between the prices of WTI and Brent. Considering the structural breaks, the findings of these studies confirm that the causality and cointegration relationship between these series may have been affected by changing the relationship between WTI and Brent prices.

The structural breaks in the crude oil market also change the cointegration relationship between the prices of WTI and Brent. Sauer (1994) provides evidence that cointegration relations adjust with a time lag by using cointegration tests. Coronado, Fullerton, and Rojas (2017) show that WTI and Brent have co-movement by adopting a one-tailed non-parametric Granger causality test. Their findings reveal bi-directional feedback between WTI and Brent from 2013 to 2015. Also, the price spread between WTI and Brent is not stable over time, and it has significantly increased since the global financial crisis (GFC). Similarly, Liu, Ma, Yang, and Zhang (2018) study, covering the period from January 1994 to December 2016 and using the Structural Vector Autoregression (SVAR) method, suggests that volatility of the price spread between WTI and Brent increases beginning from the GFC. Moreover, Elder, Miao, and Ramchander (2014) for the 2007-2012 period and Liu, Schultz, and Swieringa (2015) for the 2008-2011 period find evidence that WTI has more price leading power than Brent has if WTI and Brent are cointegrated. Yang, Shao, Shao, and Song (2020) investigate the lead-lag price relationship between WTI and Brent from 1987 to 2017 with the non-parametric symmetric Thermal Optimal Path (TOP) method. Their evidence indicates that there is price leadership of WTI over Brent and claims that this lead-lag relationship is volatile and sensitive to extreme events.

In this paper, we examine the cointegration relationship between the prices of WTI and Brent. Unlike previous studies, this is the first study to examine the cointegration relationship between WTI and Brent using periodogram-based analyses employed by Akdi (1995) and Akdi and Dickey (1998). We also estimate common periodicities in both series when the presence of a cointegration relationship cannot be rejected.

The periodogram-based analysis that allows finding hidden periodicities in data has certain advantages. Brockwell and Davis (1987); Fuller (1996) and Wei (2006) summarize these advantages as: (i) The periodograms do not depend on any model specifications. (ii) The periodograms are invariant to the mean. (iii) The critical values of the distribution are independent of the sample size. (iv) Except for the variance of the white noise series, the periodogram-based analyses do not require parameter estimation. (v) Under the alternative hypothesis, the normalized periodogram is asymptotically distributed as chi-squares (χ^2) with 2 degrees of freedom; thus, the analytic power function of the test exists. (vi) The estimates are acknowledged as more robust if the data have periodic components.

Our study covers the period from June 1987 to July 2021 period. We repeat the analyses for the sub-periods that cover the dates when the increase in price spread of WTI and Brent correspond to events affecting the global crude oil market. The findings provided by the periodogram-based cointegration method suggest a cointegration relationship between the prices of WTI and Brent for the 1987:06-2010:03 sub-period. The sample ends with the oil-spill accident at the Deepwater Horizon oil spill took place at the Macondo Field, located in the Gulf of Mexico. We also find statistically significant common periodicities in both series for this period which is closely 12 months. Thus the cointegration relationship between WTI and Brent series can be related with the presence of common periodicities in both series for the pre-oil spill accident.

The remainder of this paper is organized as follows. In Section 2, we explain the methodology. Section 3 introduces the data set. Section 4 presents empirical evidence. Finally, in Section 5, we conclude.

2. METHODOLOGY

Our methodology comprises three stages. Firstly, we perform periodogram-based unit root tests developed by Akdi and Dickey (1998). Then, we examine the hidden periodicities in the data. Lastly, we estimate the cointegration relationship between the series using the periodogram-based cointegration test introduced by Akdi (1995).

2.1. Periodogram Based Unit Root Test

Given a time series $\{Y_1, Y_2, Y_3, \dots, Y_n\}$, the trigonometric transformation of the series can be shown as:

$$Y_t = \mu + R\cos(wt+\phi) + e_t\,,\ t=1,2,\dots,n, \quad (1)$$

Where μ is the expected value; R is the amplitude; ϕ is the phase; w is the frequency of the series; and e_t is the white noise sequence. We consider the properties of the cosine function, $a = R\cos(\phi)$ and $b = R\sin(\phi)$, the Equation 1 can also be written as:

$$Y_t = \mu + a\cos(w_k t) + b\sin(w_k t) + e_t,\ t=1,2,\dots,n. \quad (2)$$

Here, k is chosen to be the frequencies ($k = 1,2, \dots [n/2]$, and $[n/2]$ is the intiger part of $n/2$). When $w_k = 2\pi k/n$ is selected, the Ordinary Least Square (OLS) estimators of μ, a and b can be calculated as below:

$$\hat{\mu} = \overline{Y}_n, \quad (3)$$

$$a_k = \frac{2}{n}\sum_{t=1}^{n}(Y_t - \overline{Y}_n)\cos(w_k t) \quad (4)$$

and

$$b_k = \frac{2}{n}\sum_{t=1}^{n}(Y_t - \overline{Y}_n)\sin(w_k t) \quad (5)$$

Where a_k and b_k estimators are also known as Fourier coefficients (see: (Brockwell & Davis, 1987; Fuller, 1996)) and $\overline{Y}_n$ is the sample mean, then we can write:

$$\sum_{t=1}^{n}\cos(w_k t) = \sum_{t=1}^{n}\sin(w_k t) = 0 \quad (6)$$

And the periodogram ordinates are invariant to the mean. Therefore, Fourier coefficients can also be calculated as in Equations 7, 8, and 9, respectively:

$$\hat{\mu} = \overline{Y}_n, \quad (7)$$

$$a_k = \frac{2}{n}\sum_{t=1}^{n} Y_t\cos(w_k t) \quad (8)$$

and

$$b_k = \frac{2}{n}\sum_{t=1}^{n} Y_t\sin(w_k t). \quad (9)$$

From the model given in Equation 2, the periodogram ordinate at the frequency k is:

$$I_n(w_k) = \frac{n}{2}(a_k^2 + b_k^2). \quad (10)$$

Akdi and Dickey (1998) proposed a periodogram-based unit root test that is seasonally robust and free from selecting the lag lengths. In the test, the null hypothesis is that the series has a unit root. Akdi and Dickey (1998) show that for each fixed k the asymptotic distribution of $T_n(w_k)$ is distributed as a mixture of χ^2 given by:

$$T_n(w_k) = \frac{2(1-\cos(w_k))}{\hat{\sigma}_n^2} I_n(w_k) \xrightarrow{D} Z_1^2 + 3Z_2^2,\ n\to\infty \quad (11)$$

Where $T_n(w_k)$ is the test statistics, Z_1 and Z_2 denote independent standard normal random variables and $\hat{\sigma}_n^2$ is any consistent estimator of the error variance. Moreover $\xrightarrow{D}$ stands for convergence in distribution. α is the significance level, and if the value of $T_n(w_k)$ is smaller than the critical value c_α, then we reject the null hypothesis of a unit root. Provided that the series has a unit root, asymptotic distribution can be shown as:

$$T_n(w_k) \xrightarrow{D} \chi_1^2 + 3\chi_2^2,\ n \to \infty \ . \tag{12}$$

2.2. Periodicity

The hidden periodicities in data for a stationary time series can be examined by using periodograms. Under the null hypothesis that there is no periodic component, $P(V > c_\alpha) = m(1 - c_\alpha)^{m-1}$ where $m = (n-1)/2$, if n is odd and $m = (n/2)-1$ if n is even. If V is bigger than the critical values c_α for a given significance level α, then we reject the null hypothesis H_0: $a = b = 0$.[2] Thus, we can say that the model contains a periodic component.

Let $I_n(w_{(1)}) = \max\{I_n(w_k)\}$ for $k = 1,2,\ldots[n/2]$ where $[n/2]$ is the integer part of $n/2$ and define as:

$$V = I_n(w_{(1)})\left[\sum_{k=1}^{[n/2]} I_n(w_k)\right]^{-1}. \tag{13}$$

In order to examine another periodic component in the series, let $I_n(w_{(i)})$ be the i^{th} largest periodogram ordinate and define a test statistic as below:

$$V_i = \frac{I_n(w_{(i)})}{\sum_{k=1}^{[n/2]} I_n(w_k) - \sum_{k=1}^{i-1} I_n(w_{(k)})} \tag{14}$$

where V_i is the test statistics for the determination of a periodic component in series. If $V_i > c_\alpha$, then we reject the null hypothesis of no periodic component. Thus, the series has a periodic component at the corresponding frequency (Wei, 2006).

2.3. Periodogram Based Cointegration Test

The periodogram-based analysis estimates the cointegration vector for a multivariate time series (Akdi, 1995). Each component of a bivariate non-stationary time series can be written as a linear combination of two stationary and non-stationary series as:

$$X_{1,t} = \lambda_{11}U_t + \lambda_{12}S_t \tag{15}$$

$$X_{2,t} = \lambda_{21}U_t + \lambda_{22}S_t \tag{16}$$

Here, U_t and S_t represent unit root and stationary time series respectively. Since each component of the bivariate time series $(X_{1,t} \text{ and } X_{2,t})$ contains the non-stationary component of U_t. Both components are non-stationary. Note that:

$$Z_t = X_{2,t} - \left(\frac{\lambda_{21}}{\lambda_{11}}\right)X_{1,t} = \left(\lambda_{22} - \frac{\lambda_{21}\lambda_{12}}{\lambda_{11}}\right)S_t = cS_t. \tag{17}$$

Z_t is stationary and therefore the system is cointegrated with the cointegrating vector $(-\lambda_{21}/\lambda_{11}, 1)'$. Z_t also mimics the residuals from the regression of $X_{2,t}$ on $X_{1,t}$. Therefore, we have to estimate the $(\lambda_{21}/\lambda_{11})$ ratio. If the R_k is the real part of the cross periodogram ordinate of a bivariate non-stationary time series and P_k is the periodogram ordinate of one of the components of a bivariate series (say the first component), then R_k regressed on P_k as:

$$R_k = \alpha + \beta P_k + \eta_k,\ k = 1,2,3,\ldots,[T/2] \tag{18}$$

[2] We can test this hypothesis with Fisher's test based on the periodograms. Since the frequency of w_k is unknown, using a standard F statistic in not appropriate (Wei, 2006).

Where $[T/2]$ represents the integer part of $T/2$. From Equation 18, the OLS estimator of β is a consistent estimator for the ratio. That is, as $T \longrightarrow \infty$.

$$\hat{\beta}_T = \frac{\sum_{k=1}^{[T/2]}(R_k-\bar{R})(P_k-\bar{P})}{\sum_{k=1}^{[T/2]}(P_k-\bar{P})^2} \xrightarrow{P} \frac{\lambda_{21}}{\lambda_{11}} \tag{19}$$

Where $\bar{R}$ is the mean of R_k and $\bar{P}$ is the mean of P_k. Here, $\xrightarrow{P}$ represents converges in probability. Therefore, the cointegration vector can be identified as $\left(-\hat{\beta}_T, 1\right)$ (see for the critical values: (Akdi, Berument, & Cilasun, 2006; Berument, Akdi, & Atakan, 2005).

3. DATA

In this paper, we aim to examine the cointegration relationship between the prices of WTI and Brent and by using periodogram based cointegration analyses. We use the monthly data for the series from June 1987 to July 2021. Our data span covers 410 observations.

We use real price series. In order to calculate the real prices of WTI and Brent, we deflated these series by U.S. Consumer Price Index for All Urban Consumers (CPI). We gathered all data from St. Louis Federal Reserve Economic Data (FRED).

Figure 1 reports the time series plots of the real price spread between WTI and Brent. These series generally move together, but the real price spread between WTI and Brent has begun to increase after the first quarter of 2010. The real price of WTI was generally higher than the real price of Brent until April 2010 when the Deepwater Horizon oil spill taken place at the Macondo Field, located in the Gulf of Mexico and operated by British Petroleum (B.P.) After this accident, the reason of the real price of Brent was higher than the real price of WTI can be explained by the soaring insurance premium for off-shore drilling and thus and thus this affected the Brent prices. Moreover, in late 2015, the U.S. lifted the ban on the export of domestically produced crude oil, which had been in place since the 1970s. On the other hand, it is worth noting that since the COVID-19 pandemic epidemic, the price spread between WTI and Brent has begun to decrease again.

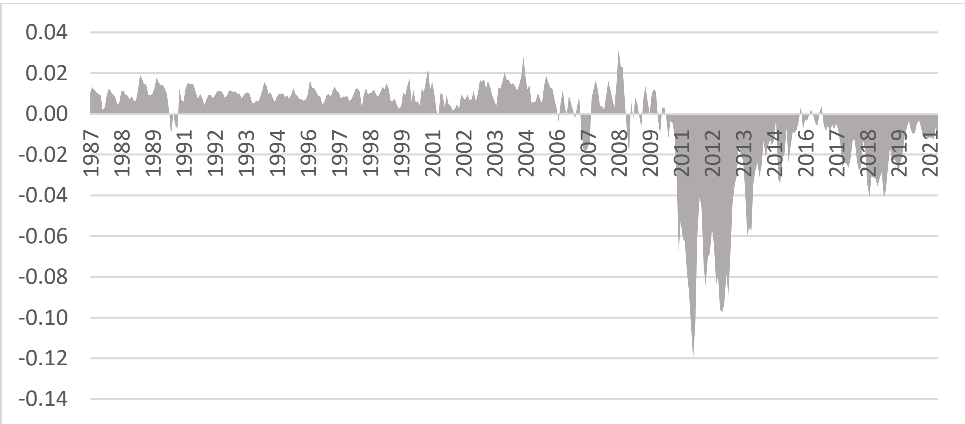

Figure 1. The real price spread between WTI and brent.

Source: FRED economic data, federal reserve bank of St. Louis.

Considering the increase in the price spread between WTI and Brent, we repeated our analyses for four sub-periods. These periods are 1987:06-2010:03 for the period before the oil-spill accident at Mexico Gulf; 2010:05-2020:02 for the period from the oil-spill accident at Mexico Gulf until to COVID-19 Pandemic Epidemic; 2010:05-2021:07 for the period after the oil-spill accident at Mexico Gulf; and 2016:01 2021:07 for the period after the U.S. lifted the export ban on the domestically produced crude oil.

4. EMPIRICAL EVIDENCE

We adopt the periodogram-based cointegration method that Akdi (1995) introduced to determine the existence of a cointegration relationship between the real prices of WTI and Brent for 1987:06-2021:07 and its various sub-periods. Firstly we report the periodogram-based unit root tests Table 1 employed by Akdi and Dickey (1998). Table 1 reveals that the test statistics for the WTI and Brent values are less than the critical value at the 5% level (0.178) for all periods. Thus, we cannot reject the null of a unit root, and then we conclude that both series have unit-roots.

Table 1. Test statistics for periodogram-based unit root test with intercept.

Period	Variable	$I_n(w_1)$	$\hat{\sigma}_n^2$	$t_n(w_1)$	Decision
1987:06-2021:07	WTI	3.321	0.000	2.321	Fail to reject the null hypothesis.
	Brent	4.365	0.000	2.563	Fail to reject the null hypothesis.
1987:06-2010:03	WTI	1.427	0.000	2.428	Fail to reject the null hypothesis.
	Brent	1.458	0.000	2.268	Fail to reject the null hypothesis.
2010:05-2020:02	WTI	0.927	0.000	6.101	Fail to reject the null hypothesis.
	Brent	1.387	0.000	8.278	Fail to reject the null hypothesis.
2010:05-2021:07	WTI	0.969	0.000	4.536	Fail to reject the null hypothesis.
	Brent	1.372	0.000	5.816	Fail to reject the null hypothesis.
2016:01-2021:07	WTI	0.039	0.000	0.902	Fail to reject the null hypothesis.
	Brent	0.068	0.000	1.326	Fail to reject the null hypothesis.

Note: The 5% critical value is 0.178.

Table 2 reports the test statistics of periodogram-based cointegration analyses. Our results suggest no global long-run relationship between two major oil blends for the whole period. However, the values of the periodogram-based tests are bigger than the critical values at 5% (for all periods except for the 1987:06-2010:03). Thereby, even if this relationship exists until the Deepwater Horizon oil spill, the relationship breaks down after this incident. One explanation is that since Brent is produced at off-shore platforms, the insurance premium of extracting and producing oil increased considerably after the incidence at Mexican Gulf, which affected the Brent prices. Note that most oil prices are traded indexing to one of these two oil blends and the Oman-Dubai blend. Thus, one may need to consider this differential when they price/trade the other oil contracts.

Table 2. Results for periodogram-based cointegration.

Period	Dependent variable	$\hat{\beta}_i$	$\hat{\tau}_a$	Decision
1987:06-2021:07	WTI	1.140	-2.35	Fails to reject the null hypothesis of no cointegration.
	Brent	0.869	-2.45	Fails to reject the null hypothesis of no cointegration.
1987:06-2010:03	WTI	1.012	-7.44	Reject the null hypothesis of no cointegration.
	Brent	0.987	-7.44	Reject the null hypothesis of no cointegration.
2010:05-2020:02	WTI	1.218	-3.19	Fails to reject the null hypothesis of no cointegration.
	Brent	0.817	-3.19	Fails to reject the null hypothesis of no cointegration.
2010:05-2021:07	WTI	1.192	-3.40	Fails to reject the null hypothesis of no cointegration.
	Brent	0.831	-3.40	Fails to reject the null hypothesis of no cointegration.
2016:01-2021:07	WTI	0.792	-0.26	Fails to reject the null hypothesis of no cointegration.
	Brent	1.173	-0.83	Fails to reject the null hypothesis of no cointegration.

Note: The 5% critical value is -3.43564.

We also offer empirical evidence of whether there are common periodicities between WTI and Brent prices or not. The statistics presented in Table 3 suggest that WTI and Brent series have statistically significant common periods of 11.87 months for the 1987:06-2010:03 but whole periods and other sub-periods have not. Thus, our results suggest that the cointegration relationship between WTI and Brent series can be related with the presence of common periodicities in both series.

Table 3. Periodogram values and their corresponding values of V statistics.

Period	WTI			Brent			5% Critical value for V_i.
	$I_n(w_{(i)})$	V_i	# Of cycle	$I_n(w_{(i)})$	V_i	# Of cycle	
1987:06-2021:07	0.007	0.041	10.487*	0.006	0.035	10.687	0.040
1987:06-2010:03	0.005	0.055	11.870*	0.006	0.058	11.870*	0.055
2010:05-2020:02	0.004	0.074	9.750	0.005	0.084	9.750	0.114
2010:05-2021:07	0.004	0.066	5.583	0.006	0.079	5.583	0.103
2016:01-2021:07	0.004	0.161	5.583	0.006	0.177	8.375	0.183

Note: * Is for the statistically significant for 5% critical value for Vi for the first difference series.

5. CONCLUSION

The WTI and Brent crude oil prices are global benchmarks for spot and future crude oil markets. Historically, WTI and Brent prices are generally move together. However, especially within the last decade, the price spread between these major crude oils has increased remarkably. The price of WTI was generally higher than the price of Brent until the Deepwater Horizon oil spill accident took place at the Gulf of Mexico in April 2010, after this accident, the exact opposite became true. The other important events that affected the price spread between WTI and Brent are that the U.S. lifted the ban on exporting domestically produced crude oil in late 2015 and the COVID-19 pandemic. Thus, the empirical findings from the literature about structural break(s) verify that these events affect the global crude oil market.

In this study, we investigate a long-run relationship between the prices of WTI and Brent by using periodogram-based cointegration method, which allows to find hidden periodicities in the stationary data set, introduced by Akdi (1995) for the periods of 1987:06-2021:07. We repeat our analyses for different sub-periods by considering that these events affected the price spread between WTI and Brent.

Our results summarized in Table 4 suggest that the whole period and sub-periods except for the 1987:06-2010:03 period do not have the cointegration relationship between the prices of two major crude oils. These statistics suggest that the cointegration relationship existed until the Deepwater Horizon oil spill in April 2010. The reason why the cointegration relationship has broken down after the accident at the Mexican Gulf can be explained by the insurance premium of extracting and producing oil increased considerably. This affected the prices of Brent, which is produced on off-shore platforms. Our finding coincides with studies that found structural break date(s) in the price spread between WTI and Brent.

Table 4. A summary of periodogram based analyses.

No.	Period	Unit root test	Cointegration	No. of cycles
1	1987:06-2021:07	Fail to reject the null of unit root.	No cointegration between WTI and Brent.	WTI has periods of 10.487 month, but Brent does not.
2	1987:06-2010:03	Fail to reject the null of unit root.	Cointegration between WTI and Brent.	WTI and Brent have statistically significant common periods of 11.87 months.
3	2010:05-2020:02	Fail to reject the null of unit root.	No cointegration between WTI and Brent.	WTI and Brent have not a statistically significant common periodic component.
4	2010:05-2021:07	Fail to reject the null of unit root.	No cointegration between WTI and Brent.	WTI and Brent have not a statistically significant common periodic component.
5	2016:01-2021:07	Fail to reject the null of unit root.	No cointegration between WTI and Brent.	WTI and Brent have not a statistically significant common periodic component.

We also examine whether these series include common periodicities. When the cointegration relationship for the 1987:06-2010:03 period cannot be rejected, we estimate a statistically significant common periodicity in both series, which is approximately 12 months. However, whole periods and other sub-periods have not statistically significant common periodicities. Thus, unlike previous literature, our other important contribution is that the cointegration relationship between WTI and Brent series can be related with the presence of common periodicities in both series.

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REFERENCES

Akdi, Y. (1995). *Periodogram analysis for unit roots*. Unpublished Ph.D. Dissertation, North Carolina State University, USA.

Akdi, Y., Berument, H., & Cilasun, S. M. (2006). The relationship between different price indices: Evidence from Turkey. *Physica A: Statistical Mechanics and its Applications, 360*(2), 483-492. https://doi.org/10.1016/j.physa.2005.05.037

Akdi, Y., & Dickey, D. A. (1998). Pfriodograms of unit root time series: Distributions and tests. *Communications in Statistics-Theory and Methods, 27*(1), 69-87. https://doi.org/10.1080/03610929808832651

Basistha, A., & Kurov, A. (2015). The impact of monetary policy surprises on energy prices. *Journal of Futures Markets, 35*(1), 87-103.

Berument, H., Akdi, Y., & Atakan, C. (2005). An empirical analysis of Istanbul stock exchange sub-indexes. *Studies in Nonlinear Dynamics & Econometrics, 9*(3), 1–12. https://doi.org/10.2202/1558-3708.1229

Brockwell, P. J., & Davis, R. A. (1987). *Time series: Theory and methods*. New York: Springer Science & Business Media.

Buyuksahin, B., Lee, T., Moser, J., & Robe, M. (2013). Physical markets, paper markets and the WTI–Brent spread. *Energy Journal, 34*(3), 129-151. https://doi.org/10.5547/01956574.34.3.7

Caporin, M., Fontini, F., & Talebbeydokhti, E. (2019). Testing persistence of WTI and Brent long-run relationship after the shale oil supply shock. *Energy Economics, 79*, 21-31. https://doi.org/10.1016/j.eneco.2018.08.022

Charles, A., & Darné, O. (2014). Volatility persistence in crude oil markets. *Energy Policy, 65*, 729-742. https://doi.org/10.1016/j.enpol.2013.10.042

Chen, W., Huang, Z., & Yi, Y. (2015). Is there a structural change in the persistence of WTI–Brent oil price spreads in the post-2010 period? *Economic Modelling, 50*, 64-71. https://doi.org/10.1016/j.econmod.2015.06.007

Coronado, S., Fullerton, J. T. M., & Rojas, O. (2017). Causality patterns for brent, WTI, and argus oil prices. *Applied Economics Letters, 24*(14), 982-986. https://doi.org/10.1080/13504851.2016.1245830

Elder, J., Miao, H., & Ramchander, S. (2014). Price discovery in crude oil futures. *Energy Economics, 46*, S18-S27. https://doi.org/10.1016/j.eneco.2014.09.012

Fattouh, B. (2011). *An anatomy of the crude oil pricing system*. Retrieved from Oxford Institute for Energy Studies, OIES Paper WPM, No. 40.

Fuller, W. A. (1996). *Introduction to statistical time series* (2nd ed.). New York: John Willey.

Ghoshray, A., & Trifonova, T. (2014). Dynamic adjustment of crude oil price spreads. *Energy Journal, 35*(1), 119-136. https://doi.org/10.5547/01956574.35.1.7

Gulen, S. G. (1999). Regionalization in the world crude oil market: Further evidence. *The Energy Journal, 20*(1), 125-126. https://doi.org/10.5547/issn0195-6574-ej-vol20-no1-7

Gülen, S. G. (1998). Efficiency in the crude oil futures market. *Journal of Energy Finance & Development, 3*(1), 13-21. https://doi.org/10.1016/s1085-7443(99)80065-9

Liu, J., Ma, F., Yang, K., & Zhang, Y. (2018). Forecasting the oil futures price volatility: Large jumps and small jumps. *Energy Economics, 72*, 321-330. https://doi.org/10.1016/j.eneco.2018.04.023

Liu, W. M., Schultz, E., & Swieringa, J. (2015). Price dynamics in global crude oil markets. *Journal of Futures Markets, 35*(2), 148-162. https://doi.org/10.1002/fut.21658

Luong, P. V., Mizrach, B., & Otsubo, Y. (2019). Location basis differentials in crude oil prices. *The Energy Journal, 40*(2), 41-59. https://doi.org/10.5547/01956574.40.si2.pluo

Sauer, D. G. (1994). Measuring economic markets for imported crude oil. *The Energy Journal*, *15*(2), 107-124. https://doi.org/10.5547/issn0195-6574-ej-vol15-no2-6

Scheitrum, D. P., Carter, C. A., & Revoredo-Giha, C. (2018). WTI and brent futures pricing structure. *Energy Economics*, *72*, 462-469. https://doi.org/10.1016/j.eneco.2018.04.039

Wei, W. W. S. (2006). *Time series analysis, univariate and multivariate methods* (2nd ed.). USA: Addison Wesley.

Weiner, R. J. (1991). Is the world oil market "one great pool"? *The Energy Journal*, *12*(3), 95-108. https://doi.org/10.5547/issn0195-6574-ej-vol12-no3-7

Yang, Y., Shao, Y., Shao, H., & Song, X. (2020). The time-dependent lead-lag relationship between WTI and brent crude oil spot markets. *Frontiers in Physics*, *8*(132), 1–6. https://doi.org/10.3389/fphy.2020.00132

Ye, S., & Karali, B. (2016). *Estimating relative price impact: The case of brent and WTI. No 235728*. Paper presented at the 2016 Annual Meeting, July 31–August 2. Boston, MA: Agricultural and Applied Economics Association.

Zhang, X., Yu, L., Wang, S., & Lai, K. K. (2009). Estimating the impact of extreme events on crude oil price: An EMD-based event analysis method. *Energy Economics*, *31*(5), 768-778. https://doi.org/10.1016/j.eneco.2009.04.003