CESifo WORKING PAPERS

11017
2024

March 2024

Informational Efficiency of World Oil Markets: One Great Pool, but with Varying Depth

Marc Gronwald, Sania Wadud, Kingsley Dogah

CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp
An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
· from the RePEc website: www.RePEc.org
· from the CESifo website: https://www.cesifo.org/en/wp

CESifo *Working Paper No. 11017*

Informational Efficiency of World Oil Markets: One Great Pool, but with Varying Depth

Abstract

This paper investigates the informational efficiency of global crude oil markets using a recently introduced quantitative measure for market inefficiency. The methodology assesses the deviation of observed oil price behavior from the Random Walk benchmark, representing an efficient market. The main findings of the analysis are as follows: firstly, the degree of crude oil market inefficiency demonstrates temporal variations. Secondly, there are marked increases in the degree of inefficiency during extreme episodes, such as the price downturns experienced in 2008, 2014, and early 2020. Thirdly, the degree of inefficiency exhibits substantial variations across regional crude oil markets before 2006 but converges thereafter. Since this discovery is grounded in the observation of more similar price behavior across markets post-2006, the paper establishes a connection between the literature on oil market integration and that focusing on the informational efficiency of oil prices.

JEL-Codes: C220, E300, G140, Q020, Q310.

Keywords: world oil markets, efficient market hypothesis, market integration, fractional integration.

Marc Gronwald
International Business School Suzhou
Xi'an Jiaotong-Liverpool University / China
marc.gronwald@xjtlu.edu.cn

Sania Wadud
Leeds University Business School
University of Leeds / United Kingdom
s.wadud@leeds.ac.uk

Kingsley Dogah
Department of Finance, Accounting and Economics, University of Nottingham
Ningbo / China
Kingsley.Dogah@nottingham.ecu.cn

March 2024

1 Introduction

Adelman (1984) famously asserted that the world crude oil markets are just one great pool, just like the world ocean is. This declaration serves as the genesis of a body of literature examining oil market integration, essentially probing whether the global oil market tends towards globalization or regionalization. The predominant methodologies employed in this literature primarily revolve around empirically assessing the law-of-one-price hypothesis, utilizing approaches such as cointegration methods. In essence, contributions to this literature hinge on empirical analyses of crude oil price dynamics. Among the latest additions to this field, Gronwald and Jin (2024), aligns with this tradition while simultaneously expanding the methodological toolkit employed in such studies. Notably absent in the existing literature is an exploration of potential differences in informational inefficiency across different crude markets. Consequently, this paper introduces a novel research dimension: investigating whether global oil markets also exhibit variations in levels of informational (in-)efficiency.

The empirical approach used in this paper is the quantitative measure for market inefficiency recently proposed by Duan, Li, Urquhart, and Ye (2021). The key idea of this approach is to measure the degree of market inefficiency through the extent to which the observed price behaviour deviates from the Random Walk benchmark. Duan et al. (2021) are similar in essence to Kristoufek and Vosvrda (2013, 2014) and Sattarhoff and Gronwald (2022). While the former base their measure on Hurst exponents, Sattarhoff and Gronwald (2022) use a multifractal approach. Duan et al.'s (2021) measure for market efficiency is based on the novel interpretation of fractional integration. In that approach, the order of integration d of a time series can be a fractional number between 0 and 1. This paper employs the so-called Feasible Exact Local Whittle estimator to estimate d. Duan et al. (2021) gauge the degree of inefficiency of a market using the absolute difference between the estimate of d and 1: $D = |1 - d|$. To measure dynamic efficiency, i.e. how efficiency is varying over time, this paper uses a rolling window approach.

This paper's key results can be summarised as follows: First, the degree of inefficiency of global crude oil markets varies over time, but there is no systematic decline in the degree of inefficiency due to e.g. markets which mature. The degree of inefficiency of the WTI market, for example, is higher prior to 2006, but varies over time to a much lesser degree. Post 2006, there is a considerable degree of variation. Second, abrupt increases in the degree of inefficiency post 2006 occur during extreme oil price episodes: the oil price downturns witnessed in 2008, 2014, and 2020, respectively. Third, the degree of inefficiency varies considerably across regional crude oil markets pre-2006, but converges afterwards. As this finding is based on a more similar price behaviour across the markets post 2006, this paper links the literature on oil market integration with that on informational efficiency of oil prices. These are the two streams of literature this paper contributes to. Within the literature on empirically testing the Efficient Market Hypothesis (EMH), there is the tendency to use quantitative rather than qualitative procedures to test the EMH. The method used in this paper has been proposed by Duan et al. (2021). The main motivation for this procedure is that market efficiency is not an absolute concept but a market characteristics that evolves dynamically over time and varies across markets (Rösch, Subrahmanyam, & Van Dijk, 2017). This approach is also used in Ren, Xiao, Duan, and Urquhart (2024) who analyse inefficiency of fossil as well as green energy markets. The idea to measure the degree of market efficiency also features prominently in Lo's (2004) Adaptive Market Hypothesis (AMH). Among the most recent contributions to the literature on integration of world oil markets are Plante and Strickler (2021) as well as Bravo Caro, Golpe, Iglesias, and Vides (2020). These two papers reflect the two main approaches used in this literature: While Plante and Strickler (2021) use so-called differentials between different crude oil price series, Bravo Caro et al. (2020) apply cointegration-type approaches in order to analyse the relationship between two crude oil prices. Plante and Strickler (2021), to summarise just one of those recent papers, find that there are fewer structural breaks in oil price differentials. Thus, the global oil market became more integrated in recent years.

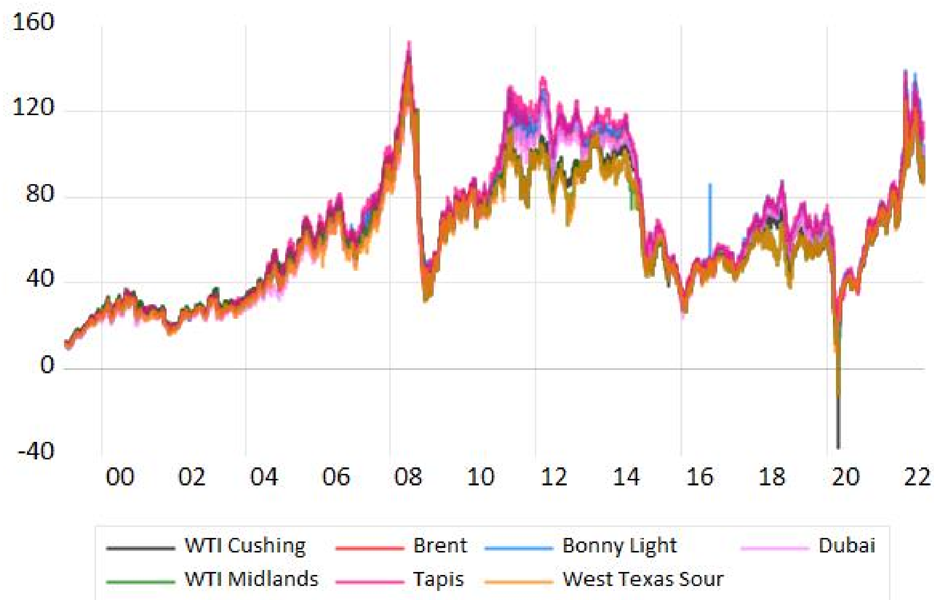

Figure 1: Crude oil price series used in this paper.

The remainder of the paper is organised as follows: Sections 2 discusses data and methods used in this paper. Section 3 presents the results obtained from the application of the inefficiency measure. Section 4 offers concluding remarks.

2 Data and Method

Figure 1 visually presents the dataset utilized in this paper, comprising prices for seven distinct crude oil types (WTI Cushing, WTI Midlands, West Texas Sour, Brent, Bonny Light, Dubai, and Tapis).[1] The data is observed at daily frequency over the period from January 2, 1997, to September 2,

[1]Detailed data sources: Cushing OK WTI Spot Price (USCRWTIC, Bloomberg), WTI Midland (USCRWTIM, Bloomberg), West Texas Sour (USCRWTSM, Bloomberg), Tapis FOB Malaysia (APCRTAPI, Bloomberg), W.Africa Bonny Light FOB (OILMSBD, Refinitiv), Europe Brent Spot FOB (EUCRBRDT, Bloomberg), Crude Oil Dubai 1Mth FOB Asia (OLDUB1M, Refinitiv)

2022. The figure distinctly illustrates a high degree of co-movement among the crude oil price series considered in this study. Identifying significant differences is virtually impossible during the relentless price surge leading up to 2008. Moreover, the collapse of prices in 2008 and 2009, followed by a period of price stabilization in 2010, appears synchronized across all markets. However, noteworthy differences emerge between 2010 and 2014, with prices exhibiting substantial divergence. This period marks the emergence of the WTI-Brent spread, indicating that WTI Cushing prices, along with the other two U.S. price series, are considerably lower than Brent and other regional series. In 2014, during another oil price collapse, the price series converge once more, moving in tandem until 2017 when another spread between the price series occurs. Importantly, this later spread is smaller in magnitude and shorter-lived compared to the 2010-2014 period. The onset of the Covid-19 pandemic in early 2020 is associated with yet another price collapse. Notably, the U.S. price series WTI Cushing, WTI Midlands, and West Texas Sour briefly become negative, a phenomenon not observed in the other series. The recovery of price levels appears to be a synchronized movement, as are the disturbances associated with the Russian invasion of Ukraine in early 2022.

Having described the price series used in this paper, now the focus is shifted to the empirical approach. Processes characterised by fractional integration $I(d)$ have garnered increasing interest among empirical researchers in the fields of economics and finance. This is because $I(d)$ processes can effectively capture specific long-term features within economic and financial data (for details, see Zaffaroni and Henry (2003)). This paper employs the methodology introduced by Duan et al. (2021), which utilises a framework based on fractional integration, particularly using Shimotsu's (2010) semiparametric Feasible Exact Local Whittle (FELW) estimator. Shimotsu (2010) introduce a modified (two-step) ELW estimator, tailored for economic data analysis, to account for an unspecified mean (which needs to be estimated) and a polynomial time trend. This estimation approach complements the fully extended local Whittle estimator introduced by Abadir, Distaso, and Giraitis (2007), which uses a fully extended discrete Fourier transform. A fully extended local Whittle is based on the Type I process, whereas FELW is founded on the Type II process.[2] This framework is employed to investigate the efficiency of the WTI crude oil market.

Table 1: Memory properties of a given price series (y_t) with different d values.

d **Value**	**Persistence of shocks**	**Market efficiency**	**Information transmission**	**The close degree to an efficient market**
$d > 1$	Expansionary memory, explosive over time	Inefficiency	Excessive transmission	-
$d = 1$	Permanent memory	Efficiency	Complete transmission	Efficient Market
$0.5 \leq d < 1$	Long memory	Inefficiency	Partial transmission	High degree
$0 < d < 0.5$	Long memory	Inefficiency	Partial transmission	Lower degree
$d = 0$	Short memory	Inefficiency	None	Zero degree
$d < 0$	Long memory	Inefficiency	Reverse transmission	-

Note: This table provides information on the memory properties of a given price series (y_t) across different integration orders (d) and outlines their corresponding effects on market efficiency. Adapted from "Dynamic efficiency and arbitrage potential in Bitcoin: A long-memory approach," by K. Duan, Z. Li, A. Urquhart, and J. Ye, 2021, *International Review of Financial Analysis*, 75, p. 4, (`https://doi.org/10.1016/j.irfa.2021.101725`). Copyright 2021 by Elsevier Inc.

Duan et al. (2021) follows Hamilton (1994) to explain different forms of "memory" within a given time series to identify potentially existing fractional integration order that is a crucial metric for quantifying the level of market informational efficiency.[3] Moreover, this accommodates the fractional integration order by incorporating the concept of "long-memory" within the model system.

The empirical analysis is initiated by estimating d-value i.e. fractional

[2]See Shimotsu and Phillips (2006) for further details on the Type I and Type II process.

[3]Later, they adopt the Fractionally Cointegrated Vector Autoregressive (FCVAR) model introduced by Johansen (2008) and Johansen and Nielsen (2012) that accounts for both short-run error corrections and long-term links among the target variables. For the details of the model see Section 3.1 of Duan et al. (2021)

integration order of crude oil price series (y_t) by using the Feasible Exact Local Whittle estimator (FELW) introduced by Shimotsu (2010). Considering that overly high or low bandwidths can result in a reduced or increased number of valid observations utilised in the estimation of d using the FELW methods (Shimotsu, 2010), causing unstable outcomes, a moderate bandwidth of 0.6 is chosen to generate the time series for d. Later, the d-value is used to gauge the degree of market efficiency. Table 1 (Duan et al., 2021) show the statistical (memory) properties of y_t at varying values of d, along with the corresponding indications of market efficiency.

To examine how the informational efficiency of the WTI crude oil market evolves over time, market efficiency is assessed by using a self-derived index D in this study. This D index is created by computing the absolute difference between 1 and the fractional integration order that provides insights into the oil market's evolving nature of efficiency.

$$D_t = |1 - d_t|$$

where d_t is the estimated fractional integration order at time t. In particular, a 4-year rolling window is used to estimate the d-value; results for a shorter 2-year window and a longer 10-year window are also reported. The index D, determined by the disparity between d values and 1, inversely signifies the level of market efficiency. In other words, a higher D indicates a larger absolute gap, reflecting a more inefficient market and a lower degree of market efficiency. Hence, D can also be seen as a representation of the degree of market inefficiency.

This approach is directly comparable to the analysis of market efficiency using Hurst exponents, proposed by Hurst (1951). The Hurst exponent, (H), quantifies whether a time series is uncorrelated (H $=$ 0.5), persistent (H $>$ 0.5), or anti-persistent (H $<$ 0.5). Loosely speaking, Hurst exponents measure the long-run memory of time series. Although the seminal work of Hurst (1951) first appeared in hydrology study, there has since been numerous applications into the financial markets specifically in the area of EMH of indices including commodities (Kristoufek, 2019; Tiwari, Umar, & Alqahtani, 2021); cryptocurrencies (Dimitrova, Fernández-Martínez, Sánchez-Granero, & Trinidad Segovia, 2019; Kristoufek & Vosvrda, 2019); stocks (Di Matteo, Aste, & Dacorogna, 2005; Matos, Gama, Ruskin, Al Sharkasi, & Crane, 2008). The connection between EMH and Hurst exponent is deduced when the exponent of a series, H=0.5, which implies a random walk without long memory. This is consistent with the EMH which asserts that markets are unpredictable due to the random walk behaviour of prices. Thus, series with H higher than 0.5 indicates long-run memory with a higher predictability level (see Horta, Lagoa, & Martins, 2014). Duan et al. (2021) point out that the Feasible Exact Local Whittle estimator (Shimotsu, 2010) mitigates the weaknesses of this traditional method.

3 Results

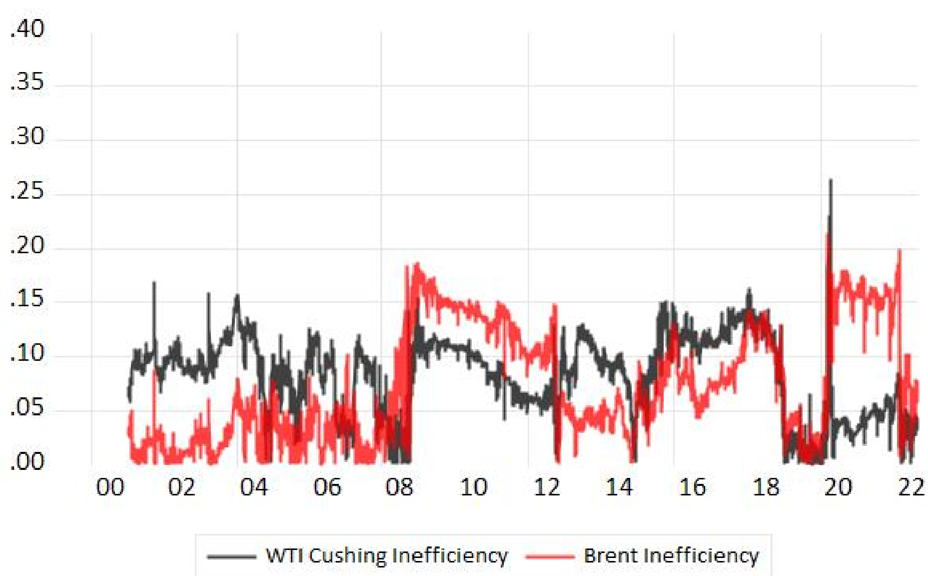

Figure 2: Degree of inefficiency of WTI Cushing and Brent Oil Prices - 4 year rolling window.

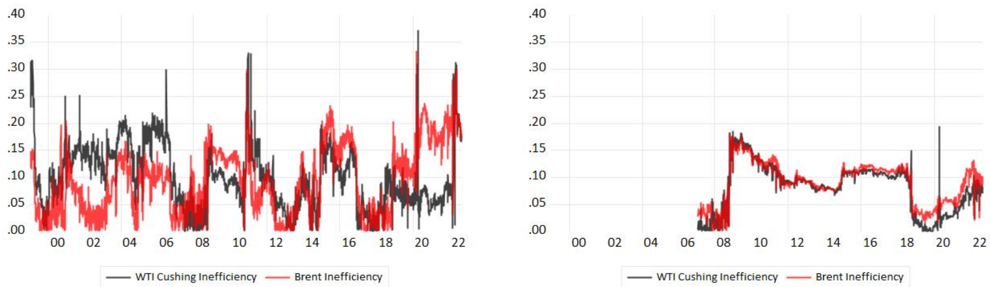

Figure 3: Degree of inefficiency of WTI Cushing and Brent Oil Prices - 2 and 10 year rolling windows

As elucidated earlier, Duan et al. (2021) propose interpreting the absolute distance between d and 1 as a measure of the degree of market inefficiency: $D = |1 - d|$. Figure 2 illustrates the inefficiency measure D (4-year rolling window) for two globally recognized benchmark markets: WTI Cushing and Brent. For both markets, D fluctuates primarily between 0 and 0.2. Notably, there is no discernible long-term trend in this measure, indicating that the degree of inefficiency does not exhibit systematic reduction over time due to market maturation. Despite not revealing significant differences in price levels between 2000 and 2008, the degree of inefficiency of the two markets demonstrates remarkable divergence. Prior to 2006, the WTI market is notably more inefficient than the Brent market. Between 2009 and 2017, the relative positions shift twice, influenced by the 2008 decline; excluding this period from the rolling window results in a considerable change in the D estimate. Given the 4-year estimation window and the influence of the 2008 episodes, drawing definitive conclusions about potential differences in the degree of inefficiency during the 2010-2014 spread is challenging. Only in 2008 and 2018-2020 is the degree of inefficiency found to be similarly low for both markets. This summary demonstrates a key advantage of the method used in this paper: the ability to compare the degree of inefficiency across markets. The dynamic nature of this measure also facilitates the examination of the degree of inefficiency's evolution over time. Both markets exhibit more significant fluctuations in the degree of inefficiency prior to

2008, with notable shifts post-2008, albeit with reduced overall fluctuation. These shifts are attributed to dramatic oil price episodes. Additionally, it is noteworthy that the degree of inefficiency sharply increases during oil price downturns, such as those witnessed in 2008, 2014, and 2020.[4] Post-2020, a substantial difference in the degree of inefficiency is observed, attributed to the negative values assumed by WTI Cushing in 2020. It needs to be emphasized that the estimation of the fractional integration parameter d is sensitive to such extreme movements.

The adoption of a shorter 2-year window facilitates the capture of short-term fluctuations in the degree of inefficiency, as illustrated in the left panel of Figure 3. However, one trade-off of this approach is the reduction in estimation precision due to a smaller number of observations in each window. Despite this drawback, it serves as a valuable robustness check, reaffirming the primary findings outlined earlier. Notably, specific oil price episodes exert a more pronounced influence in this case, with the degree of inefficiency for both markets exhibiting more significant fluctuations prior to 2006 than in the subsequent period. The observed sharp increases in the degree of inefficiency during oil price collapses are accentuated, as is the discovery of very low degrees of the degree of inefficiency before the peak in 2008 and between 2016 and 2018. Regarding the 2010-2014 spread, the shorter window enables a more precise statement: between 2010 and 2013, the inefficiency measures for the two markets display divergent movements, whereas between in the remaining time between 2008 and 2018, they exhibit more comparable patterns. Overall, the inefficiency measures range between 0 and 0.2, but the frequency of surpassing the latter value is higher than observed in the 4-year window.

Concerning the longer 10-year window (depicted in the right panel of Figure 3), it is evident that the estimation results exhibit greater stability owing to the larger number of observations. The D estimates consistently remain below 0.2. The finding of an increase in the degree of inefficiency during oil price declines is also discernible here, particularly in 2008 and

[4]Gronwald, Wadud, and Dogah (2024) thoroughly discuss the underlying economic reasons for these downturns and also provide a detailed interpretation of this finding.

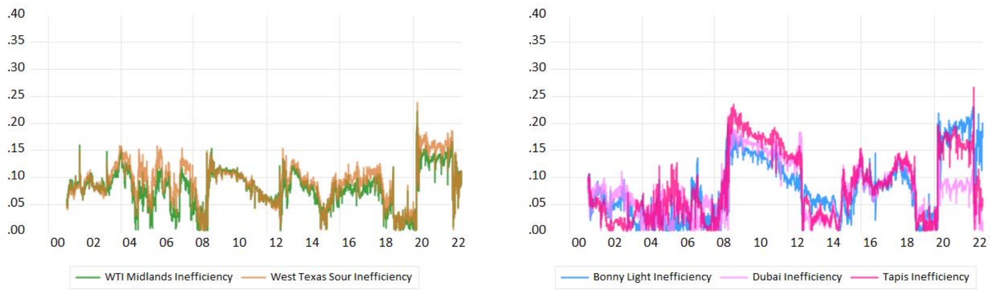

Figure 4: Degree of inefficiency of WTI Midlands and West Texas Sour Prices (upper panel), Bonny Light, Dubai and Tapis Prices (lower panel)- 4 year rolling window.

2014. Post-2018, a notable divergence in inefficiency levels is observed, attributed to the oil price episode in 2020. However, this does not lead to a sharp increase in the level of inefficiency. Therefore, when the number of observations in the window is sufficiently large, the impact of individual observations becomes proportionally smaller, even in the case of extreme oil price movements such as the one witnessed in early 2020. Given the longer window and the observation period commencing in 2000, definitive conclusions regarding differences in the degree of inefficiency before 2008 are challenging.

After delving into the detailed results for globally recognized benchmark price series, attention is now directed towards the degree of inefficiency of markets with more regional relevance, beginning with two regional U.S. markets: the ones for WTI Midlands and West Texas Sour. The upper panel of Figure 4 illustrates the results for the 4-year rolling window. Notably, the difference in degrees of inefficiency between these two markets is generally much lower than that observed for the WTI Cushing and Brent markets. This observation allows one to conclude that the price behavior for these crude types is more similar than that of the benchmark series; thus, the empirical approach employed in this paper facilitates assertions about the integration of world oil markets. The overarching results discussed earlier resurface, including a larger extent of fluctuation over time prior to 2006

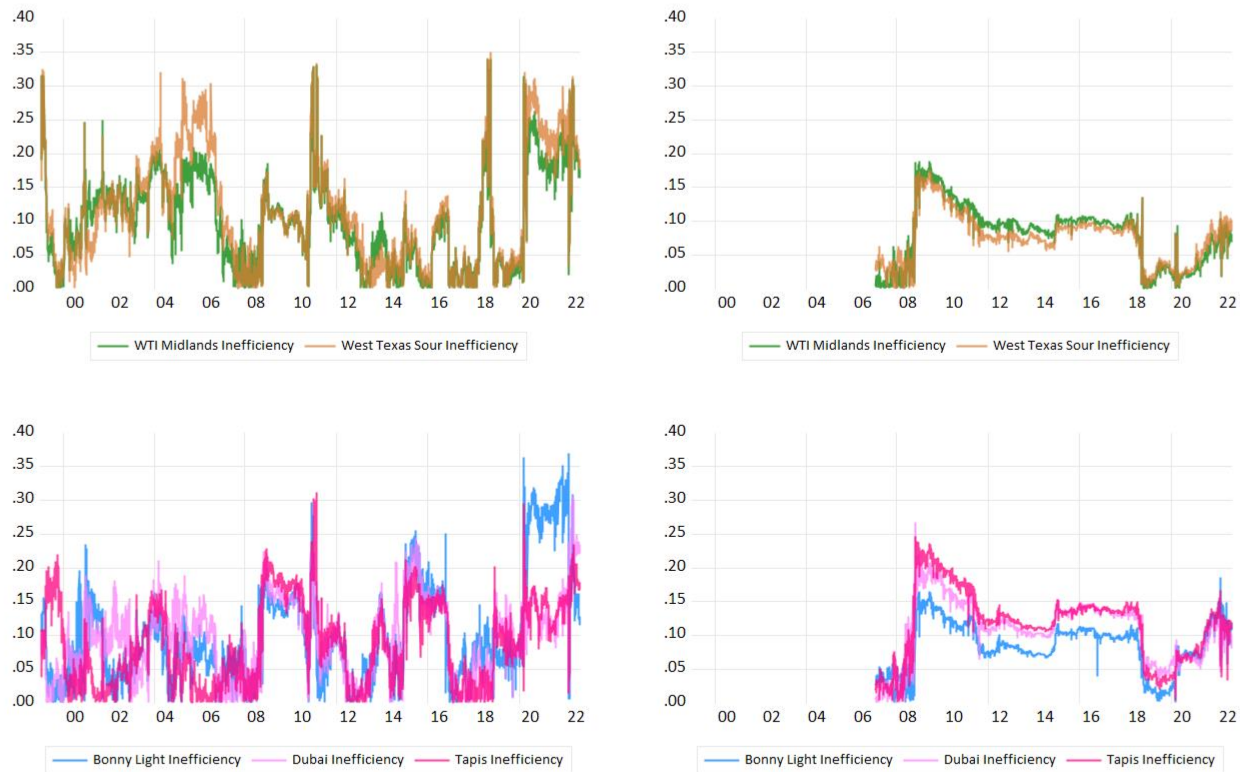

Figure 5: Degree of inefficiency of WTI Midlands and West Texas Sour Prices (upper panels), Bonny Light, Dubai and Tapis Prices (lower panels)- 2 and 10 year rolling windows.

and a pronounced increase in market inefficiency during oil price declines.

The robustness analysis, as depicted in the upper panels of Figure 5, reinforces all the previously discussed results. The 2-year window reveals that the degree of inefficiency of regional U.S. markets fluctuates to a larger extent before 2006. This refined analysis even discerns slight differences in the degree of inefficiency, indicating that, even for these closely related regional markets, greater similarity in price movements is found post-2008—indicating an increased degree of market integration. Between 2008 and 2020, the degrees of inefficiency closely follow each other, much more closely than observed for the WTI Cushing-Brent pair. As for the 10-year window, the results are consistent with the other pair, showing much less fluctuation over time. Relative differences are also similar, with a particularly small disparity in the level of inefficiency post-2018.

Shifting focus to the degree of inefficiency of regional oil price series from around the world—Bonny Light, Dubai, and Tapis—the results for the 4-year rolling window are presented in Figure 4. Despite the extensive set of results already discussed, notable insights emerge. The differences in the development over time of the degree of inefficiencies prior to 2008 become particularly apparent, emphasizing the growing similarity between 2008 and 2012, and 2014 and 2020, respectively. A noteworthy finding is that, for Bonny Light, there is no abrupt drop in the degree of inefficiency in 2012 when the 2008 oil price episode is no longer included in the rolling window. This observation substantiates the earlier assertion that price behavior—fundamental to market efficiency—is becoming more similar across the markets post-2008. The robustness checks, illustrated in the lower panel of Figure 5, confirm these findings. The heterogeneity prior to 2008 becomes even more apparent, while post-2008, the movement of the degree of inefficiency over time appears very similar for these three markets, despite representing geographically distinct locations. Additionally, for the 10-year window, the behavior over time exhibits striking similarities, with differences in level primarily stemming from the 2008 oil price episode.

4 Conclusions

Fama (1970) famously stated "a market in which prices always 'fully reflect' all available information is called 'efficient'." Empirically testing the Efficient Market Hypothesis (EMH) is the subject of an extensive literature, particularly focusing on the weak form of the EMH through evaluations of the random walk hypothesis. This paper employs a recently proposed quantitative measure for market inefficiency, leveraging a novel interpretation of the fractional integration parameter, denoted as d. This approach not only facilitates an analysis of whether a specific market is efficient or not, but also provides insights into the degree of efficiency or inefficiency. Furthermore, it enables the examination of how the degree of inefficiency of a market evolves over time and allows for comparisons across different markets.

The global crude oil market is an ideal subject for the application of this method for several reasons. Notably, crude oil is perceived as a homogeneous product, suggesting that its price should remain consistent across the markets where it is traded. The paper considers seven important crude oil price series: WTI Cushing, WTI Midlands, West Texas Sour, Brent, Bonny Light, Dubai, and Tapis, representing significant oil-producing regions, including North America, the North Sea, West Africa, the Persian Gulf, and Asia Pacific. Despite certain quality differences among these crude streams, the overall determination of crude oil prices is influenced by global demand and supply dynamics. Some markets, such as WTI and Brent, hold global benchmark status, while others primarily cater to regional demand. Additionally, crude oil holds high geopolitical relevance, being a fossil resource intertwined with climate change. The dominance of OPEC, a resilient cartel, and the vast oil extraction and processing industry further underscore the complexity of the crude oil market.

Key findings from the analysis include variations in the degree crude oil market inefficiency over time, abrupt increases in the degree of inefficiency during extreme episodes like the price downturns in 2008, 2014, and early 2020, and a notable convergence of inefficiency levels across regional crude oil markets post-2006.

Ultimately, the analysis of world oil market integration draws upon the statistical properties of price series from various markets. Traditional methods such as cointegration-based approaches, structural break testing, but also innovative approaches like measuring world oil market integration with a Thick Pen (Gronwald & Jin, 2024) are employed. Fractional integration, while just another data property, is showcased in this paper to reveal that overall price behavior has become more similar across world oil markets since 2008. This paper establishes a connection between two strands of literature: EMH testing and the measurement of world oil market integration. In summary, the paper concludes that the world oil market is indeed one great pool, but one with varying depths.

References

Abadir, K. M., Distaso, W., & Giraitis, L. (2007). Nonstationarity-extended local whittle estimation. *Journal of econometrics*, *141*(2), 1353–1384.

Adelman, M. A. (1984). International Oil Agreements. *The Energy Journal*, *5*(3), 1–9. doi: 10.1080/03050718.1977.9985485

Bravo Caro, J. M., Golpe, A. A., Iglesias, J., & Vides, J. C. (2020). A new way of measuring the WTI – Brent spread. Globalization, shock persistence and common trends. *Energy Economics*, *85*, 104546. Retrieved from `https://doi.org/10.1016/j.eneco.2019.104546` doi: 10.1016/j.eneco.2019.104546

Di Matteo, T., Aste, T., & Dacorogna, M. M. (2005). Long-term memories of developed and emerging markets: Using the scaling analysis to characterize their stage of development. *Journal of banking & finance*, *29*(4), 827–851.

Dimitrova, V., Fernández-Martínez, M., Sánchez-Granero, M., & Trinidad Segovia, J. (2019). Some comments on bitcoin market (in) efficiency. *PloS one*, *14*(7), e0219243.

Duan, K., Li, Z., Urquhart, A., & Ye, J. (2021). Dynamic efficiency and arbitrage potential in Bitcoin: A long-memory approach. *International Review of Financial Analysis*, *75*, 1–47. doi: 10.1016/j.irfa.2021.101725

Fama, E. F. (1970). Efficient capital markets: A review of theory and empirical work. *The Journal of Finance*, *25*(2), 383–417.

Gronwald, M., & Jin, X. (2024). Measuring world oil market integration with a Thick Pen. *Energy Economics*, *130*, 107315. Retrieved from `https://doi.org/10.1016/j.eneco.2024.107315` doi: 10.1016/j.eneco.2024.107315

Gronwald, M., Wadud, S., & Dogah, K. (2024). *Oil Market Efficiency, Quantity of Information, and Oil Market Turbulence.* (CESifo Working Paper 10995)

Hamilton, J. D. (1994). Time series analysis, vol. 2 princeton university press. *Princeton, NJ*.

Horta, P., Lagoa, S., & Martins, L. (2014). The impact of the 2008 and 2010 financial crises on the hurst exponents of international stock markets: Implications for efficiency and contagion. *International Review of Financial Analysis*, *35*, 140–153.

Johansen, S. (2008). A representation theory for a class of vector autoregressive models for fractional processes. *Econometric Theory*, *24*(3), 651–676.

Johansen, S., & Nielsen, M. Ø. (2012). Likelihood inference for a fractionally cointegrated vector autoregressive model. *Econometrica*, *80*(6), 2667–2732.

Kristoufek, L. (2019). Are the crude oil markets really becoming more efficient over time? some new evidence. *Energy Economics*, *82*, 253–263.

Kristoufek, L., & Vosvrda, M. (2013). Measuring capital market efficiency: Global and local correlations structure. *Physica A: Statistical Mechanics and its Applications*, *392*(1), 184–193. Retrieved from `http://dx.doi.org/10.1016/j.physa.2012.08.003` doi: 10.1016/j.physa.2012.08.003

Kristoufek, L., & Vosvrda, M. (2014). Commodity futures and market efficiency. *Energy Economics*, *42*, 50–57. doi: 10.1016/j.eneco.2013.12.001

Kristoufek, L., & Vosvrda, M. (2019). Cryptocurrencies market efficiency ranking: Not so straightforward. *Physica A: Statistical Mechanics and its Applications*, *531*, 120853.

Lo, A. W. (2004). The adaptive markets hypothesis: market efficiency from an evolutionary perspective. *Journal of Portfolio Management*, *30*, 15–29.

Matos, J. A., Gama, S. M., Ruskin, H. J., Al Sharkasi, A., & Crane, M. (2008). Time and scale hurst exponent analysis for financial markets. *Physica A: Statistical Mechanics and its Applications*, *387*(15), 3910–3915.

Plante, M., & Strickler, G. (2021). Closer to one great pool? evidence from structural breaks in oil price differentials. *Energy Journal*, *42*(2), 1–30. doi: 10.5547/01956574.42.2.MPLA

Ren, X., Xiao, Y., Duan, K., & Urquhart, A. (2024). Spillover effects between fossil energy and green markets: Evidence from informational inefficiency. *Energy Economics*, *131*(December 2023), 107317. Retrieved from `https://doi.org/10.1016/j.eneco.2024.107317` doi: 10.1016/j.eneco.2024.107317

Rösch, D. M., Subrahmanyam, A., & Van Dijk, M. A. (2017). The dynamics of market efficiency. *Review of Financial Studies*, *30*(4), 1151–1187. doi: 10.1093/rfs/hhw085

Sattarhoff, C., & Gronwald, M. (2022). Measuring informational efficiency of the European carbon market — A quantitative evaluation of higher order dependence. *International Review of Financial Analysis*, *84*(October), 102403. Retrieved from `https://doi.org/10.1016/j.irfa.2022.102403` doi: 10.1016/j.irfa.2022.102403

Shimotsu, K. (2010). Exact local whittle estimation of fractional integration with unknown mean and time trend. *Econometric Theory*, *26*(2), 501–540.

Shimotsu, K., & Phillips, P. C. (2006). Local whittle estimation of fractional integration and some of its variants. *Journal of Econometrics*, *130*(2), 209–233.

Tiwari, A. K., Umar, Z., & Alqahtani, F. (2021). Existence of long memory in crude oil and petroleum products: Generalised hurst exponent ap-

proach. *Research in International Business and Finance*, *57*, 101403.
Zaffaroni, P., & Henry, M. (2003). The long range dependence paradigm for macroeconomics and finance. In Doukhan, Oppenheim, & Taqqu (Eds.), *Theory and applications of long-range dependence.* Birkhauser.