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# Persistence in International Energy Prices 1960-2023

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## Abstract
This paper examines the persistence of energy prices in international markets and its implications for market participants and policymakers. Using the ARFIMA model and log-periodogram regression technique, we estimate the long memory parameter in energy price indices. Our findings confirm the persistence in energy prices, indicating that past price movements have a lasting impact on future prices. For market participants, understanding the persistence of energy prices is crucial for developing effective trading strategies and risk management measures. The long-lasting effects of past price movements suggest the need for preparedness in the face of extended periods of price volatility. Policymakers can also benefit from this knowledge by implementing measures to stabilize energy markets and mitigate the impacts of price shocks. Furthermore, our study highlights the importance of incorporating the persistence of shocks in energy price forecasting models. By accounting for the long-lasting effects of past price movements, these models can improve the accuracy of price forecasts and aid in decision-making for market participants. While our study provides valuable insights into the persistence of energy prices, further research is needed to investigate the root causes of persistence and its implications in a rapidly changing global economic environment. Additionally, exploring the individual factors that influence energy price indices can enhance our understanding of their dynamics and improve prediction accuracy. Overall, our findings contribute to the existing literature by confirming the presence of persistence in energy prices and providing valuable insights for market participants and policymakers. Further research in this area can offer more pragmatic advice and enhance decision-making in the energy markets.

## Keywords
List the keywords covered in your paper. These keywords will also be used by the publisher to produce a keyword index.

## Introduction

The persistence of energy prices has been a subject of extensive research, with scholars seeking to understand the factors that influence long-term memory actions in price indicators. This knowledge is crucial for stakeholders in energy markets, including traders, energy corporations, and policymakers, as it can inform trading strategies, risk management measures, and policy decisions. However, despite the existing literature on energy price persistence, there is still a need for further investigation to delve into the root causes of such actions and their implications in a rapidly changing global economic environment.

Early investigations in energy price persistence focused on the interplay between supply and demand as the primary driver of energy prices. Hotelling's seminal work in 1931 emphasized that a scarcity of resources would inevitably result in escalating resource costs (Baffes, 2010). However, subsequent research revealed that this principle needs to be more adequately accounted for technological advancements, alternative resources, and market competition, which could mitigate the impact of scarcity (Krautkraemer, 1998),

The oil shocks of the 1970s brought attention to the significant influence of geopolitical events on energy prices, leading to the study of energy price volatility (Barros et al., 2013). These occurrences could generate sudden and drastic fluctuations, thereby initiating the exploration of the persistence of energy price movements (Wang et al., 2022; Qian et al., 2023; Skare et al., 2023). Understanding the persistence of energy prices is crucial for stakeholders, as it can help them prepare for unexpected price fluctuations and craft effective policies to stabilize prices (Mahasneh, 2003; Martin-Valmayor et al., 2023; Gil-Alana and Monge, 2021).

To analyze the persistence of energy prices, researchers have employed various methodologies. In this study, the authors adopt the ARFIMA(p, d, q) model, which incorporates fractional differencing to capture long-term memory in time series data (Geweke and Porter-Hudak, 1983). The degree of long-term memory is determined by the fractional differentiation parameter d, where positive values indicate positive long-term memory and negative values indicate negative long-term memory.

The findings from previous studies on energy price persistence have provided valuable insights. For example, research by Barros et al. (2013) suggests that natural gas prices in the United States exhibit the most substantial persistence. This indicates that past price movements continue influencing current prices, highlighting the long-lasting impact of shocks in the natural gas market. Similarly, Dias and Ramos (2014) found evidence of persistence in energy prices, suggesting that they tend to remain within the same range for an extended period, indicating the possibility of regime-switching dynamics.

Contrary to the common belief that real energy prices have consistently risen over time, studies by Fouquet (2011) and Fouquet and Pearson (2003) challenge this assumption. Their research reveals significant declines in energy prices over the past five centuries, indicating that energy markets are not immune to fluctuations and can experience periods of downward trends.

These findings have important implications for stakeholders in energy markets. Traders and energy companies need to consider the persistence of energy prices in their analysis and decision-making processes, as unexpected price fluctuations can have a prolonged impact on their earnings and trading strategies. Policymakers also need to consider the enduring effects of price shocks when crafting energy policies, emphasizing the need for measures to increase market liquidity and competition to improve the market's resilience to shocks.

In conclusion, the persistence of energy prices is a crucial aspect to consider in understanding the dynamics of energy markets. The existing literature provides valuable insights into long-term memory actions in price indicators. It highlights the need for further research to explore the root causes of such actions and their implications in a rapidly changing global economic environment. By gaining a deeper understanding of energy price persistence, stakeholders can make more informed decisions, develop more accurate predictive models, and implement effective risk management strategies and policy interventions.

The paper is divided into several sections that contribute to a comprehensive analysis of the persistence of international energy prices. The introduction section sets the stage by providing an overview of the topic and its significance while highlighting the need for further research. The literature review section examines previous studies on energy price persistence, discussing various theories and factors that influence price fluctuations. The methodology section explains the ARFIMA model used in the research and provides a clear framework for estimating and analyzing long memory time series models. The results section presents the empirical findings, showcasing the increasing trend of persistence over time in both energy and non-energy price indices. The discussion section delves into the implications of these findings for stakeholders in energy markets, emphasizing the importance of understanding the differences between energy and non-energy markets. The conclusion section summarizes the main findings and suggests avenues for future research.

## Persistence in Energy Prices - a Review

Extensive research has been conducted on the persistence of energy prices, albeit yielding vastly disparate conclusions. In the literature, multiple theories have been posited describing diverse facets of this phenomenon, including temporal and geographical characteristics. This literature review aims to analyze the principal contributions made in this field to comprehensively comprehend the factors that influence the persistence of energy prices.

Early investigations have demonstrated that the pricing of energy sources was predominantly reliant on the interplay between supply and demand. (Hotelling, 1931) seminal work underscored that a shortage of resources would inevitably result in escalating resource costs. However, subsequent research revealed that Hotelling's principle inadequately accounted for technological advancements, alternative resources, and market competition, which could mitigate the impact of scarcity (Krautkraemer, 1998)

During the 1970s, in the aftermath of the oil shocks (Pindyck, 1978) and others highlighted the substantial influence of geopolitical events on energy prices. These occurrences could generate sudden and drastic fluctuations, thereby initiating the study of energy price volatility.

The research investigated how financial markets affected energy prices during the early 2000s. Research conducted by (Fattouh et al., 2013) and other scholars have demonstrated a strong linkage between financial markets and energy prices. These studies suggest that the behavior of investors and speculation may induce persistence in energy prices.

Kilian and Murphy (2014) argue that global macroeconomic conditions significantly influence energy prices. They assert that economic expansion results in higher demand for energy and, consequently, higher prices. This phenomenon elucidates a portion of the persistence observed in energy prices, as global economic conditions exhibit a certain degree of inertia.

The emergence of the concept of persistence in energy prices occurred in the 1990s as a result of the seminal work of (Engle and Bollerslev, 1986) on volatility clustering in economic data. This work opened up a discussion on the persistence of energy prices, revealing that large and small changes follow large changes.

Hamilton (2009) provided a more detailed explanation of the concept, highlighting that energy price fluctuations typically endure because of a range of structural factors. These factors consist of prolonged disparities between supply and demand, geopolitical hazards, limitations in infrastructure, and governmental regulations.

Table 1 summarizes previous studies and findings on the persistence of energy prices.

*Tab. 1. Review on persistence in energy prices findings*

| Authors | Date | Findings |
|---|---|---|
| Roger Fouquet | 2011 | An upward trend in average energy prices before the Industrial Revolution and a decline afterward. Dangers of focusing on the cost of energy rather than energy services |
| John Baffes | 2010 | The pass-through of energy price changes to the non-energy commodity index is 0.28 Fertilizer index has the largest pass-through (0.55) |
| Istemi Berk, Hakan Yetkiner | 2014 | Energy prices harm economic growth. Increasing renewable energy sources can improve welfare. |
| Marc Joëts | 2012 | Energy price co-movements increase during extreme fluctuations. Energy market causalities are stronger during bear markets. |
| Mohammad Zahid Hasan, Selim Akhter, Fazle Rabbi | 2013 | Coal volatility exhibits strong mean reversion. Shocks in crude oil volatility are persistent. |
| Carlos Pestana Barros, L. A. Gil-Alana, James E. Payne | 2014 | Energy prices exhibit long memory and persistence. Breaks in data were found in 1973 and 1945. |
| Jenny Morel | 1980 | Real prices of oil and coal increased by 50% since 1973. Gas prices returned to 1973 levels. |
| Mohammad Ashraful Ferdous Chowdhury, Muhammad Saeed Meo, Ajim Uddin, Md. Mahmudul Haque | 2020 | Energy prices have a higher and long-lasting effect on agriculture commodity prices. Wheat and corn prices lead to energy price volatility. |
| Shokri Ghanem, Rezki Lounnas, Garry Brennand | 2000 | Stable oil prices in the low 20s lead to annual oil demand growth of 1.5 million barrels per day. High prices above $30/b lead to lower oil demand and a strong response in non-OPEC production. |
| Quhafah Mahasneh | 200 | Days of cheap oil prices are gone. Oil prices will surge higher to unbearable levels |
| Roger Fouquet | 2011 | The long-run trend in energy prices stable/downward Divergence between energy prices and energy services |

| | | |
|---|---|---|
| I. Bashmakov | 2016 | Energy prices and costs have cyclical patterns. Energy affordability thresholds and price elasticities are important factors |
| Roger Fouquet, Peter J. G. Pearson | 2003 | Little support for rising fuel prices trend Evidence of significant declines in energy prices |
| José G. Dias, Sofia Ramos | 2014 | Regime-switching models effectively capture energy price dynamics. Different regime-switching dynamics exist for energy prices. |
| Roger Fouquet | 2010 | The upward trend in energy prices before the Industrial Revolution Downward trend in energy prices after the shift to fossil fuels |
| Igor Bashmakov, Anna Myshak | 2018 | Existence of energy cost constants in different sectors Energy efficiency policy needs rising energy prices |
| Roy Endre Dahl | 2015 | Volatility in electricity prices is a major concern. Oil price volatility has increased. |
| John Baffes | 2011 | Energy prices have played a key role in commodity price co-movement. The elasticity between energy and agricultural commodity prices increased post-2005. |
| Torsten Schmidt, Tobias Zimmermann | 2012 | Recent energy price hikes were demand driven Supply-driven energy price increases could still affect business cycles |

*Source: Authors' research*

Fouquet (2011) observes that energy prices showed an upward trend before the Industrial Revolution but experienced a decline after that, suggesting advancements in efficiency and transportation. Moreover, he emphasizes that although prices did increase in the latter half of the twentieth century, they reflected an increase in value for consumers as they transitioned toward more efficient energy sources.

According to (Baffes, 2010) research, there is a strong connection between energy and non-energy prices, particularly during elevated commodity prices. His study analyzes data from 1960 to 2008 and concludes that fluctuations in energy prices have a lasting impact on non-energy commodity prices.

In their research, (Berk and Yetkiner, 2014) explore the correlation between energy prices and economic growth. Through their analysis of sixteen countries from 1978 to 2011, they establish a longstanding connection between the two variables. Their findings suggest that incorporating more renewable energy sources can mitigate the detrimental effects of permanent increases in consumer energy prices.

Joëts (2014) analyzed the transmission of prices in European energy forward markets, both during normal and extreme fluctuations. He employed traditional Granger causality tests and their multivariate extension in tail distribution.

In their analysis, (Hasan et al., 2013) examined the volatility of energy prices. Their findings suggest that the volatility measures of energy prices display persistence, which indicates a long-term memory behavior and a slow decay rate after volatility shocks.

The findings of (Dias and Ramos, 2014) show energy prices in the U.S. market exhibit persistence, meaning they tend to stay in the same regime for a while. Barros et al. (2013) study shows that U.S. energy prices exhibit long memory, particularly in the case of natural gas.

Morel (1980) researched the fluctuations of actual energy costs in developed nations between 1973 and 1979. This study encompasses modifications in fuel pricing and economic circumstances during that period: the U.K. and other developed countries.

Chowdhury et al. (2021) indicate an unbalanced correlation between energy and food prices. This implies that alterations in energy prices have varying effects on food prices.

According to (Ghanem et al., 2000), if oil prices exceed $30 per barrel, oil demand and OPEC's market share could be reduced. They highlight the importance of maintaining a delicate balance between pricing and market dynamics.

His research (Mahasneh, 2003) delves into the various factors that impact the global energy market and highlights the role of OPEC in determining energy prices. His work provides valuable insights into the complex relationship between geopolitical and economic factors influencing energy prices.

The long memory characteristic of energy prices (persistence) is a crucial factor that holds significant implications for economic policy-making, financial decisions, and energy trading strategies. Extensive research has been conducted in this field, with varying results and conclusions. Research by (Hasan et al., 2013), (Barros et al., 2013) has provided evidence of persistence or long memory behavior in energy prices. Persistence in energy prices is important because it implies that energy price shocks will have a long-lasting impact with a slow decay rate. Such implications can be significant for investors, policymakers, and energy-dependent industries, as past energy price movements can influence future price levels and their decision-making.

It is important to acknowledge that the level of persistence differs among various forms of energy. According to research by (Barros et al., 2013), natural gas prices in the United States exhibit the most substantial persistence. Conversely, a study by (Dias and Ramos, 2014) suggests that energy prices tend to remain within the same range for an extended period, indicating the possibility of regime-switching dynamics. of significant

Despite the common belief that real energy prices have consistently risen over time, studies conducted by (Fouquet, 2011), (Fouquet and Pearson, 2003) challenge this assumption. Their research reveals significant declines in energy prices over the past five centuries.

Although there have been numerous studies (Bashmakov, 2016), (Bashmakov and Myshak, 2018), (Dahl, 2015), (Schmidt and Zimmermann, 2012) conducted on energy price persistence, further research is necessary to improve our current understanding. One area that requires attention is cross-regional variations in energy price persistence, as research in this field has been limited. Additionally, more sector-specific studies are essential to determine how different sectors of the economy respond to persistent energy prices. As the world shifts towards renewable energy, it is crucial to investigate how the increasing share of renewables in the energy mix affects energy price persistence. Changes in policies and regulations significantly impact energy markets, and it would be useful to comprehend the influence of different policy changes or regulatory interventions on energy price persistence. Lastly, technological advancements in energy extraction, production, and distribution could affect the persistence of energy prices, and further research is needed in this area.

Our study contributes to the literature by examining persistence in energy prices for different forms of energy and by looking into the persistence to get more information on energy persistence's true nature.

## Data and Method

We use data from (Bank, 2023) on various energy commodities to look into persistent changes over time. To study the difference in energy price persistence, this study uses monthly prices (real 2010 US$) and indices from 1960 to 2023.

### Data

Data include real prices on crude oil (average, Brent, Dubai, WTI), coal (Australian, South African), and natural gas (U.S., Europe, Japan, and natural gas index). For methodology description, index weights, and calculations for commodity price data, see more details in (Bank, 2023).

Oil 1 - crude oil, the average price per barrel of crude oil ($/bbl), January 1960 to May 2023,

Oil 2- crude oil, Brent price per barrel of crude oil ($/bbl), January 1960 to May 2023,

Oil 3- crude oil, Dubai price per barrel of crude oil ($/bbl), January 1960 to May 2023,

Oil 4- crude oil, West Texas Intermediate crude oil, (WTI) price per barrel of crude oil ($/bbl), January 1982 to May 2023,

Coal1, Australian, price per metric ton of coal ($/mt), january 1970 to may 2023m,

Coal2, South African, price per metric ton of coal ($/mt), january 1984 to may 2023,

Natural gas, U.S., ($/mmbtu) price per million British thermal units, January 1970 to May 2023,

Natural gas, Europe, ($/mmbtu) price per million British thermal units, January 1970 to May 2023,

Liquefied natural gas, Japan, ($/mmbtu) price per million British thermal units, January 1977 to May 2023,

Energy monthly indices, monthly indices based on nominal U.S. dollars, 2010=100, January 1960 to May 2023,

Non-energy monthly indices, monthly indices based on nominal U.S. dollars, 2010=100, January 1960 to May 2023.

### Method

***Geweke and Porter-Hudak (GPH)***

In this study, we employ the methodology proposed by (Geweke and Porter-Hudak, 1983) to estimate and analyze long memory time series models. This methodology provides a framework for capturing and understanding the persistence of autocorrelations over long periods in time series data.

We adopt the ARFIMA(p, d, q) model, which enhances the conventional autoregressive moving average (ARMA) models by incorporating fractional differencing. The ARFIMA model is adept at capturing long-term memory, with the degree of long-term memory determined by the fractional differentiation parameter d, where positive values of d indicate positive long-term memory and negative values indicate negative long-term memory.

To estimate the parameters of the ARFIMA model, we adopt the Whittle likelihood estimation method proposed by (Geweke and Porter-Hudak, 1983). This approach maximizes the Whittle probability function, which is derived from the time series' spectral density and accounts for autocorrelation structure in the presence of long-term memory. We employ the available software packages (specify specific software) that provide implementations of the Whittle likelihood estimation.

The model takes the form (Geweke and Porter-Hudak, 1983)

$$y_t = \mu + \sum_{i=1}^{p} \phi_i \,(y_{t-i} - \mu) + \epsilon_t + \sum_{j=1}^{q} \theta_j \,\epsilon_{t-j}$$

where:
$y_t$ represents the observed value of the time series at time t,
$\mu$ is the mean or intercept term,
$\varphi_i$ represents the autoregressive parameters of lagged values (from $t$-1 to $t$-$p$) of the time series $y_t$,
$\varepsilon_t$ is the error term or the white noise component at time $t$,
$\theta_i$ represents the moving average parameters of lagged errors (from $t$-1 to $t$-$q$) of the time series $y_t$.

***Modified Geweke and Porter-Hudak (MDGPH)***

Phillips (1999) explains how Discrete Fourier Transform (DFT) can be applied to examine fractional processes. The utilization of the DFT technique permits the decomposition of the time series into distinct frequency components, thereby enabling the analysis of spectral characteristics. The technique facilitates the detection of long memory through the evaluation of the behavior of the spectrum at lower frequencies.

(Phillips, 2007) postulates the utilization of the log-periodogram regression technique as a means to estimate the parameters of fractional processes. The process involves regressing the logarithm of the periodogram on a range of lagged log-periodogram values using this technique. The log-periodogram is instrumental in capturing the spectral density of the time series at distinct frequencies, while the regression accounts for the estimation of the long memory parameter.

The general form of the fractional process model can be represented as (Phillips, 1999):

$$y_t = \mu + \sum_{i=1}^{p} \phi_i \, y_{t-i} + \varepsilon_t$$

with:
$y_t$ is the observed value of the time series at time $t$,
$\mu$ represents the mean or intercept term,
$\varphi_i$ denotes the autoregressive parameters of the lagged values of the time series ($y_t - i$),
$\varepsilon_t$ is the error term or the white noise component at time $t$.
The log-periodogram regression model can be expressed as (Phillips, 2007):

$$log(P(f)) = \alpha + \sum_{i=1}^{q} \beta_i \, log(P(f-i)) + \epsilon(f)$$

where:
$P(f)$ represents the log-periodogram value at frequency $f$,
$\alpha$ and $\beta_i$ are the regression coefficients to be estimated,
$\epsilon_{(f)}$ is the error term or residual at frequency $f$.

***Robinsons' Log-Periodogram Regression (ROB)***

The regression of logarithmic values of periodogram against lagged log-periodogram values characterizes the technique of regression based on log-periodogram. This approach captures the spectral density of the time series at different frequencies. It facilitates the computation of the long-term dependence variable that defines the perseverance of autocorrelations over time. Robinson's approach is invaluable for handling time series data that exhibits long memory or long-range dependence, which traditional methods may not adequately capture. The log-periodogram regression approach is reliable for estimating the long-range dependence parameter and understanding the underlying structure of energy prices (Robinson, 1995).

Long memory estimation has the form

$$log(P(f)) = \alpha + \sum_{i=1}^{q} \beta_i \, log(P(f-i)) + \varepsilon(f)$$

with:
$\log(P(f))$ represents the logarithm of the periodogram value at frequency $f$,
$\alpha$ is the intercept term or constant,
$\beta_i$ represents the regression coefficients to be estimated for the lagged log-periodogram values at frequencies $f - i$,
$\varepsilon(f)$ denotes the error term or residual at frequency $f$.

***Local Whittle Estimation (WHIT)***

To implement the Local Whittle estimation, the first step entails computing the periodogram of the time series data, which represents the squared magnitude of the Fourier coefficients at different frequencies. Subsequently, a weighted average is applied to the periodogram, with more weight allocated to low-frequency components and reduced weight for higher frequencies. This weighting scheme facilitates a more precise estimation of the long-memory parameter. The Hurst exponent is ultimately determined using maximum likelihood estimation or another suitable technique. By employing the Local Whittle estimation approach, a robust estimation of the long-memory parameter is achieved, providing valuable insights into the persistence and autocorrelation characteristics of the energy time series data. (Baum et al., 2020).

Whittle function takes the form

$$log(P(f)) = c - 2\pi f^{d} + \varepsilon(f)$$

where:

*P(f)* represents the periodogram value at frequency *f*,

*c* is a constant term,

*d* is the long-memory parameter or Hurst exponent to be estimated,

*ε(f)* denotes the error term or residual at frequency *f*.

The equation captures the logarithm of the periodogram value as a function of the frequency and the long-memory parameter. By estimating the value of d, we can quantify the degree of persistence or autocorrelation in the time series. This estimation is typically performed using maximum likelihood estimation or other suitable techniques.

We check for the persistence in energy prices time series data using the above techniques to estimate the long memory parameter *d*.

### Empirical Estimates of Long Memory in Energy Prices

First, we report long memory test results for Oil 1 - crude oil, the average price per barrel of crude oil ($/bbl), from January 1960 to May 2023 in Table 2.

*Tab. 2 Persistence empirical estimates for crude oil data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 2.12 | 0.93 | 0.74 | 0.76 | 0.88 |
| Std error | 1.522 | 0.45 | 0.23 | 0.14 | 0.09 |
| MGPH | -0.08 | 0.78 | 0.65 | 0.77 | 0.75 |
| Std error | 0.356 | 0.373 | 0.648 | 0.770 | 0.750 |
| ROB | 2.115 | 0.92 | 0.68 | 0.75 | 0.87 |
| std error | 1.521 | 0.453 | 0.215 | 0.135 | 0.091 |
| WHIT | - | 0.99 | 0.79 | 0.78 | 0.89 |
| std error | - | 0.289 | 0.160 | 0.114 | 0.08 |

Source: Authors' research

The crude oil data series exhibits a significant persistence or long-range dependence. The results from the GPH, ROB, and WHIT tests consistently indicate a relatively high persistence across different window sizes (number of harmonic ordinates). The MGPH test, on the other hand, shows some variation, with a negative value suggesting potential mean-reversion for a specific window size. The power size of 0.6 returns the smallest standard errors giving us the best estimation sample size.

The estimated long memory parameters across different tests and window sizes suggest that shocks in crude oil prices tend to persist over time. This implies that a shock or disturbance to the market can have long-lasting effects, with past prices strongly influencing current and future prices. The persistence of shocks indicates that the crude oil market takes time to adjust and return to equilibrium after experiencing a shock.

Table 3 reports long memory test results for Oil 2- crude oil, Brent price per barrel of crude oil ($/bbl), January 1960 to May 2023.

*Tab. 3 Persistence empirical estimates for crude oil, Brent price data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.98 | 0.92 | 0.72 | 0.77 | 0.93 |
| std error | 1.43 | 0.42 | 0.21 | 0.13 | 0.1 |

| | | | | | |
|---|---|---|---|---|---|
| MGPH | -0.05 | 0.74 | 0.63 | 0.78 | 0.79 |
| std error | 0.358 | 0.345 | 0.161 | 0.122 | 0.075 |
| ROB | 1.984 | 0.92 | 0.68 | 0.77 | 0.93 |
| std error | 1.426 | 0.423 | 0.200 | 0.131 | 0.103 |
| WHIT | - | 0.98 | 0.78 | 0.79 | 0.90 |
| std error | - | 0.288 | 0.160 | 0.115 | 0.008 |

Source: Authors' research

The GPH model shows a strong level of persistence, implying that the Brent price exhibits a significant degree of stickiness or memory. This means that past price movements have a long-lasting effect on future prices, suggesting a trend-following behavior in the market.

The MGPH model demonstrates a moderate level of persistence, indicating a noticeable influence of past price dynamics on future prices, though to a lesser extent than the GPH model. This suggests that the Brent price shows some level of memory, but the impact of historical prices may decay more quickly.

The ROB model also exhibits a strong level of persistence, aligning with the findings of the GPH model. This confirms that past price patterns have a lasting influence on future prices, further emphasizing the presence of trend-following behavior in the Brent market.

The WHIT model shows a relatively high level of persistence. This indicates that the Brent price series tends to exhibit persistent behavior, with past price movements exerting a notable influence on future prices.

Following, we report empirical estimates for long memory in oil3, crude oil, Dubai price per barrel of crude oil ($/bbl), January 1960 to May 2023 (Table 4).

*Tab. 4 Persistence empirical estimates for crude oil, Dubai price data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.98 | 0.9 | 0.73 | 0.78 | 0.9 |
| std error | 1.43 | 0.43 | 0.21 | 0.13 | 0.09 |
| MGPH | 0.05 | 0.76 | 0.66 | 0.81 | 0.78 |
| std error | 0.33 | 0.33 | 0.16 | 0.12 | 0.07 |
| ROB | 1.98 | 0.9 | 0.68 | 0.78 | 0.9 |
| std error | 1.43 | 0.43 | 0.2 | 0.13 | 0.09 |
| WHIT | - | 0.96 | 0.79 | 0.8 | 0.9 |
| std error | - | 0.29 | 0.16 | 0.12 | 0.01 |

Source: Authors' research

The standard errors associated with the persistence estimates are relatively small compared to the corresponding estimates, indicating a relatively high confidence level in the results. The persistence values for crude oil Dubai price range from 0.68 to 0.90 across different tests and windows. These values indicate a significant degree of persistence in the price series. The differences in persistence estimates between the tests (GPH, MGPH, ROB, WHIT) are relatively small, suggesting a consistent pattern of persistence in crude oil Dubai prices.

Table 5 presents persistence in West Texas Intermediate crude oil (WTI) price per barrel of crude oil ($/bbl) from January 1982 to May 2023.

*Tab. 5 Persistence empirical estimates for crude oil, WTI price data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.23 | 0.96 | 0.68 | 0.79 | 0.86 |
| std error | 0.79 | 0.23 | 0.17 | 0.17 | 0.1 |
| MGPH | 0.15 | 0.94 | 0.7 | 0.69 | 0.85 |
| std error | 0.28 | 0.26 | 0.14 | 0.1 | 0.12 |

| | | | | | |
|---|---|---|---|---|---|
| ROB | 1.23 | 1.05 | 0.68 | 0.8 | 0.85 |
| std error | 0.79 | 0.2 | 0.17 | 0.16 | 0.1 |
| WHIT | - | - | 0.73 | 0.76 | 0.85 |
| std error | - | - | 0.17 | 0.13 | 0.09 |

Source: Authors' research

The observed persistence in WTI crude oil prices implies that the market retains past information, indicating non-random price changes. This phenomenon could be accredited to several factors, including sluggish adjustments in supply and demand imbalances, market participants' responses to news and events, and long-term economic trends' impact on oil prices. Understanding the persistence of crude oil prices is of utmost importance for market participants and policymakers to make informed decisions and effectively manage risks in the highly volatile oil market.

Now we turn to the investigation of coal prices persistence - coal1, Australian, price per metric ton of coal ($/mt), January 1970 to May 2023m (Table 6).

*Tab. 6 Persistence empirical estimates for coal, Australian price data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.05 | 0.39 | 0.22 | 0.43 | 0.83 |
| std error | 0.12 | 0.27 | 0.11 | 0.08 | 0.01 |
| MGPH | 0.88 | 0.61 | 0.31 | 0.46 | 0.67 |
| std error | 1.02 | 0.38 | 0.16 | 0.1 | 0.07 |
| ROB | 1.05 | 0.41 | 0.22 | 0.43 | 0.84 |
| std error | 0.12 | 0.22 | 0.11 | 0.08 | 0.08 |
| WHIT | - | 0.36 | 0.27 | 0.43 | 0.88 |
| std error | - | 0.32 | 0.17 | 0.14 | 0.13 |

Source: Authors' research

The GPH method estimates the persistence coefficient using a histogram-based approach. In the case of Australian coal prices, the coefficients range from 0.22 to 1.05 across different window sizes. These coefficients suggest a moderate to strong level of persistence in the series. The MGPH method improves upon the GPH method by incorporating modifications to enhance estimation accuracy. The estimated persistence coefficients for Australian coal prices range from 0.31 to 0.88. The ROB method calculates the persistence coefficient by employing a more robust estimator. The estimated coefficients for Australian coal prices using ROB are similar to those obtained from GPH, ranging from 0.22 to 1.05. This consistency in results reaffirms the presence of persistence in the coal price series. Whittle estimated coefficients range from 0.27 to 0.88. They indicate a positive autocorrelation in the Australian coal price series and suggest a certain degree of persistence.

To compare the robustness and differences in results, we perform the same test on the coal2 series, South African, price per metric ton of coal ($/mt), from January 1984 to May 2023. The results are visible in Table 7.

*Tab. 7 Persistence empirical estimates for coal, South African price data series*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 0.72 | 0.45 | 0.22 | 0.56 | 1 |
| std error | 1.64 | 0.45 | 0.21 | 0.15 | 0.11 |
| MGPH | -0.14 | 0.49 | 0.25 | 0.5 | 0.85 |
| std error | 0.16 | 0.27 | 0.16 | 0.12 | 0.11 |
| ROB | 0.72 | 0.39 | 0.22 | 0.56 | 1.04 |
| std error | 1.64 | 0.36 | 0.2 | 0.15 | 0.11 |
| WHIT | 0.55 | 0.61 | 0.37 | 0.57 | - |

| | | | | | |
|---|---|---|---|---|---|
| std error | 0.53 | 0.33 | 0.18 | 0.15 | - |

Source: Authors' research

In terms of the coefficient estimates, notable disparities in the magnitudes and directions of persistence are observable. Specifically, the GPH method yields affirmative coefficient estimates for all windows, signifying a positive correlation between prior and current coal prices. Conversely, the MGPH method offers a combination of affirmative and negative coefficient estimates, implying positive and negative correlations between prior and current prices. Similarly, the Robinson and Whittle methods confirm long memory in South African market coal prices.

In a time of energy transition, natural gas is becoming a resource of interest. Here we investigate persistence in natural gas prices across different markets to learn the level of persistence in natural gas prices (Table 8).

*Tab. 8 Persistence in Natural gas, U.S. market price*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 0.97 | 1.21 | 0.95 | 0.64 | 0.69 |
| std error | 0.18 | 0.27 | 0.15 | 0.13 | 0.12 |
| MGPH | 0.41 | 0.95 | 0.95 | 0.64 | 0.61 |
| std error | 0.33 | 0.18 | 0.12 | 0.14 | 0.09 |
| ROB | 0.97 | 1.21 | 0.85 | 0.64 | 0.69 |
| std error | 0.17 | 0.27 | 0.16 | 0.13 | 0.12 |
| WHIT | 0.96 | - | 0.89 | 0.59 | 0.64 |
| std error | 0.61 | - | 0.17 | 0.09 | 0.07 |

Source: Authors' research

U.S. natural gas prices exhibit significant persistence, particularly in the short term. This suggests that short-term fluctuations in gas prices due to factors such as changes in production or international political events can have long-lasting effects on prices. However, this persistence diminishes over longer periods, suggesting that prices have some degree of mean reversion in the long run. Here we compare the results with persistence in the European natural gas market (Table 9).

*Tab. 9 Persistence in Natural gas, European market price*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.12 | 0.37 | 0.24 | 0.36 | 0.79 |
| std error | 0.55 | 0.22 | 0.11 | 0.06 | 0.07 |
| MGPH | 0.34 | 0.01 | 0.09 | 0.26 | 0.66 |
| std error | 0.74 | 0.19 | 0.1 | 0.07 | 0.07 |
| ROB | 1.12 | 0.37 | 0.23 | 0.36 | 0.79 |
| std error | 0.55 | 0.22 | 0.1 | 0.06 | 0.07 |
| WHIT | - | 0.39 | 0.28 | 0.37 | 0.88 |
| std error | - | 0.27 | 0.16 | 0.12 | 0.12 |

Source: Authors' research

The European natural gas market has a complex long-memory structure where the impact of shocks varies over different periods. Particularly, both immediate (short-term) and more distant (long-term) shocks have a considerable influence on the prices, while the effect of medium-term shocks seems less prominent. This complexity may be due to a variety of factors, such as the interplay of supply and demand dynamics, regulatory changes, geopolitical events (war in Ukraine), or the influence of global energy prices (supply shocks disruption – pandemics).

Table 10 presents liquified natural gas persistence in the Japanese market.

*Tab. 10 Persistence in Liquified Natural Gas, Japan market price*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.72 | 0.67 | 0.63 | 0.67 | 0.96 |
| std error | 0.096 | 0.346 | 0.255 | 0.138 | 0.099 |
| MGPH | 0.08 | 0.69 | 0.68 | 0.84 | 1.02 |
| std error | 0.108 | 0.197 | 0.161 | 0.135 | 0.093 |
| ROB | 1.72 | 0.71 | 0.55 | 0.67 | 0.95 |
| std error | 0.096 | 0.276 | 0.239 | 0.138 | 0.096 |
| WHIT | - | 0.69 | 0.62 | 0.69 | 0.96 |
| std error | - | 0.275 | 0.171 | 0.131 | 0.114 |

Source: Authors' research

Given these results, the Japan LNG market appears to exhibit strong persistence, particularly in the short-term and long-term. The presence of long memory suggests that shocks to the LNG market, such as sudden changes in supply or demand, can have long-lasting impacts on prices.

Finally, we compare the persistence in energy and non-energy price indices (Tables 11 and 12).

*Tab. 11 Persistence in international energy price indices 2010=100*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 2.77 | 0.84 | 0.61 | 0.6 | 0.85 |
| std error | 2.0 | 0.64 | 0.3 | 0.16 | 0.1 |
| MGPH | -0.08 | 0.61 | 0.59 | 0.71 | 0.82 |
| std error | 0.28 | 0.28 | 0.16 | 0.13 | 0.09 |
| ROB | 2.77 | 0.84 | 0.55 | 0.6 | 0.85 |
| std error | 2 | 0.64 | 0.28 | 0.16 | 0.1 |
| WHIT | - | 0.93 | 0.72 | 0.71 | 0.92 |
| std error | - | 0.28 | 0.16 | 0.11 | 0.09 |

Source: Authors' research

Energy price indices (Table 11) demonstrate a high degree of short-term persistence (GPH: 2.77, ROB: 2.77), which decreases but remains significant in the medium to long term (GPH: 0.85, ROB: 0.85, WHIT: 0.92). This pattern suggests a propensity for shocks to the energy market, such as abrupt changes in supply and demand, geopolitical events, or policy shifts, to exert a long-lasting influence on energy prices. This lasting effect implies a strong memory or stickiness in energy prices, whereby historical prices heavily affect current and future prices. As a result, energy markets tend to display slower adjustment towards equilibrium following a market shock.

*Tab. 12 Persistence in international non-energy price indices 2010=100*

| Test | Window | | | | |
|---|---|---|---|---|---|
| | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| GPH | 1.03 | 0.83 | 0.78 | 0.94 | 1.07 |
| std error | 0.700 | 0.188 | 0.129 | 0.101 | 0.088 |
| MGPH | 0.54 | 0.68 | 0.78 | 0.82 | 0.86 |
| std error | 0.219 | 0.315 | 0.235 | 0.144 | 0.094 |
| ROB | 1.03 | 0.83 | 0.79 | 0.94 | 1.07 |
| std error | 0.700 | 0.188 | 0.119 | 0.101 | 0.088 |

| | | | | | |
|---|---|---|---|---|---|
| WHIT | 0.93 | 0.86 | 0.76 | 0.88 | - |
| std error | 0.836 | 0.302 | 0.171 | 0.129 | - |

Source: Authors' research

In contrast, Table 12 shows that non-energy price indices exhibit a more uniform persistence across various periods. The GPH and ROB estimates remain constant at 1.03 for the smallest window size (0.2), decreasing slightly to 0.94 and 1.07, respectively, for the largest window size (0.6). Meanwhile, the MGPH values increase from 0.54 to 0.86 across the same window sizes. These findings suggest a consistent influence of past shocks over time, indicating a uniform long-term memory characteristic, unlike the diminishing long-term memory property observed in energy price indices.

There are notable differences between the stability of energy prices and non-energy prices, which can be attributed to various factors that impact each market differently. Energy markets are particularly vulnerable to changes in supply and demand that can be influenced by geopolitical events, climate policies, and technological advancements. These factors can cause sudden and significant price fluctuations, which can have a lasting impact due to the market's sustained persistence.

However, non-energy markets are subject to wider economic factors such as inflation, interest rates, and overall economic growth (Fan et al., 2023). These factors generally shifting could explain the greater stability and long-term memory evident in non-energy price indices more slowly, which could explain the greater stability and long-term memory evident in non-energy price indices.

Regarding the standard errors associated with the persistence estimates, they are generally smaller for non-energy price indices, indicating a higher level of certainty in these findings compared to the energy price indices.

The robustness of our findings lies in the fact we used different variables for energy prices (money per unit and indices) across various long memory testing, and the results do not show significant differences.

## Discussion

Upon comparing our results with previous findings, we observe similarities and differences in the persistence of energy prices. Our study confirms the presence of long memory in energy price indices, aligning with previous research findings (Barros et al., 2013). This suggests that past shocks and fluctuations continue to exert a substantial influence on subsequent price movements over different time horizons. Additionally, our results indicate a significant short-term persistence in energy price indicators, which diminishes but remains noteworthy in the medium - to long-term. This finding is consistent with the notion that energy markets are durable to impacts and are influenced by political events, supply and demand imbalances, and global economic conditions (Baffes, 2010).

However, our study also reveals some disparities in the magnitudes and directions of persistence compared to previous research. For instance, the coefficient estimates obtained through the MGPH method in our study show a combination of affirmative and negative correlations between prior and current prices. This contrasts with previous findings that predominantly reported positive correlations (Bashmakov, 2016; Bashmakov and Myshak, 2018). These differences may be attributed to variations in the periods, geographical regions, and specific energy sources examined in the studies.

It is important to note that our study focuses on the persistence of energy prices in international markets, and further research is needed to explore cross-regional variations in energy price persistence. Additionally, sector-specific studies are necessary to understand how different sectors of the economy respond to persistent energy prices. Furthermore, as the world transitions towards renewable energy sources, it is crucial to investigate how the increasing share of renewables in the energy mix affects energy price persistence. Policies, regulations, and technological advancements in energy extraction and distribution may also influence the persistence of energy prices, warranting further investigation (Dahl, 2015; Schmidt and Zimmermann, 2012).

For market participants, understanding the persistence of energy prices can inform trading strategies and risk management measures. The long-lasting effects of past price movements suggest that unexpected fluctuations in energy prices could have prolonged impacts on earnings and trading methodologies. Energy companies and traders may need to prepare for the possibility of extended periods of price volatility and adjust their strategies accordingly.

Policymakers can also benefit from an understanding of energy price persistence. The enduring effects of price shocks highlight the importance of stabilization measures in the face of market disruptions. Policies aimed at increasing market liquidity and competition can improve the resilience of the energy market to shocks. Additionally, policymakers should consider that interventions to stabilize prices may need to be in place for longer than expected, given the persistence of shocks over different time horizons.

Our findings also have implications for energy price forecasting models. The presence of persistence suggests that these models need to account for the long-lasting effects of past price movements. Incorporating the persistence of shocks over different time horizons can improve the accuracy of price forecasts and help market participants make more informed decisions.

While our study provides valuable insights into the persistence of energy prices, areas still require further research. Investigating the root causes of persistence and its implications in a rapidly changing global economic environment is necessary. Additionally, exploring the individual factors that influence energy price indices can enhance our understanding of their dynamics and improve prediction accuracy.

In conclusion, our study contributes to the existing literature by providing insights into the persistence of energy prices in international markets. Our findings confirm the presence of long memory in energy price indices, indicating that past price movements have a lasting impact on future prices. This has important implications for market participants, policymakers, and researchers.

## Conclusion

The results presented here suggest considerable persistence in both energy and non-energy price indices across a wide range. The study consistently highlights the long-memory property in these markets, affirming that past shocks and fluctuations substantially influence subsequent price movements over different time horizons.

Our examination exposes a significant amount of short-term persistence in energy price indicators, which diminishes but remains noteworthy in the medium - to long-term. This discovery denotes the durability of energy markets to impacts. It emphasizes the persistent influences of political happenings, supply and demand discrepancies, and worldwide economic events on energy costs.

On the other hand, non-energy price indices present stable persistence across all time horizons, suggesting a consistent long-memory behavior. This indicates that non-energy markets respond to shocks consistently, irrespective of whether the shock is recent or in the distant past.

Upon examining the results from the MGPH and WHIT tests, we observe an increasing trend of persistence over time in both energy and non-energy price indices. This suggests a strengthening impact of shocks over time, pointing towards a long memory in these markets. However, a more regular pattern is observed in non-energy price indices, while energy price indices show a slight dip in the middle of the observation window.

These empirical discoveries offer precious insights for stakeholders in these markets, such as investors, policymakers, and traders. The demonstrated persistence in price indices can inform trading strategies, risk management measures, and policy decisions. Moreover, understanding the difference in behavior between energy and non-energy markets can help devise more effective and nuanced plans and policies.

The ramifications of these discoveries hold great significance for stakeholders in energy markets, encompassing traders, energy corporations, and governmental decision-makers. Understanding the long-range tendencies of these indices can prove advantageous in cultivating more precise predictive models, superior risk management tactics, and more impactful policy interventions. For example, energy companies and traders may be required to prepare for the possibility that unexpected price fluctuations could have a prolonged impact on their earnings or trading methodologies. Conversely, policymakers must consider the enduring effects of such shocks while crafting energy policies. The evidence of price persistence might underscore the importance of stabilization measures in the face of price shocks. It suggests the need for efforts to increase market liquidity and competition to improve the market's resilience to shocks.

Energy companies need to prepare for the possibility that short-term price shocks could impact their revenues for an extended period. At the same time, policymakers should consider that interventions to stabilize prices need to be in place for longer than expected. Additionally, these findings could be important for energy price forecasting models, as they suggest that such models need to account for the persistence of shocks over different time horizons.

Nevertheless, although these results are helpful in our comprehension of long-term memory dynamics in energy prices, more research is required to investigate the causes and their implications in a rapidly changing global economic environment. Furthermore, upcoming investigations may delve into the individual aspects that influence these price indices to understand their dynamics better and enhance prediction accuracy. This would also improve the strength of our empirical findings and provide market participants and policymakers with more pragmatic advice.

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