EVIDENCE ON PRICE FORMATION IN FINANCIAL MARKETS: A MULTITEMPORAL ANALYSIS

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ABSTRACT

Background: Although clean energy stocks have become a popular new asset class for market players, relatively little research has been done on risk management strategies for investors in clean energy stock markets. Gold and Silver are examples of precious metals typically considered suitable investments to hedge against uncertainty. Therefore, their demand tends to rise when stock markets decline.

Purpose: The study aims to analyse the influence of precious metals (Gold, Silver and Platinum) and green stock indices (Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy) on price formation during different economic periods between 1 January 2018 and 23 November 2023.

Methods: The periods analysed were Tranquil, 2020 pandemic, pre-conflict and Conflict (Russian invasion of Ukraine). To this end, a VAR Granger Causality/Block Exogeneity Wald model was estimated to identify different influence patterns during each period.

Results: During the Tranquil period, 15 movements affecting prices were observed, with Silver significantly influencing all its peers, while Gold impacted Platinum, S&P Global, Nasdaq and WilderHill. Platinum was the asset that received the most shocks from its peers. During the 2020 pandemic, there was an increase to 26 movements, with the S&P Global and Nasdaq Clean indices influencing most of their peers. Gold and Platinum continued to be the assets most influenced by their peers. In the pre-conflict period, 11 movements were identified, with the highlight being the mutual influence between Gold, the Nasdaq and WilderHill indices, and Platinum. During this period, Silver and S&P Global only affected the price formation of Platinum and Clean Energy Fuels, respectively. During the Conflict period, 18 movements were observed, highlighting the influence of Platinum and S&P Global on the price formation of various assets. Gold was the asset that received the most shocks from its peers during this period.

Conclusion: the results indicate changes in the interactions between assets throughout the different economic contexts, highlighting the importance of understanding these dynamics to make more informed decisions.

Keywords: Green Energies, Precious Metals, Comovements, Portfolio Diversification.

RESUMO

Referencial: Embora as acções no domínio das energias limpas se tenham tornado uma nova classe de activos muito popular entre os intervenientes no mercado, foram realizados relativamente poucos estudos sobre estratégias
de gestão do risco para os investidores nestes mercados. O ouro e a prata são exemplos de metais preciosos tipicamente considerados, investimentos adequados, para proteção em períodos de incerteza. Por conseguinte, a sua procura tende a aumentar quando os mercados financeiros descem.

**Objetivo:** O estudo tem como objetivo analisar a influência dos metais preciosos (ouro, prata e platina) e dos índices de ações ecológicas (Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy) na formação de preços durante diferentes períodos económicos entre 1 de janeiro de 2018 e 23 de novembro de 2023.

**Métodos:** Os períodos analisados foram: Tranquilo, pandemia de 2020, pré-conflito e conflito (invasão russa na Ucrânia). Para o efeito estimamos um modelo VAR Granger Causality/Block Exogeneity Wald com o propósito de identificar diferentes padrões de influência durante cada período.


**Conclusão:** Os resultados indicam variações nas interações entre os ativos ao longo dos diferentes contextos económicos, destacando a importância de compreender essas dinâmicas para uma tomada de decisão mais informada.

**Palavras-chave:** Energias Ecológicas, Metais Preciosos, Comovimentos, Diversificação de Carteiras.

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**PRUEBAS SOBRE LA FORMACIÓN DE PRECIOS EN LOS MERCADOS FINANCIEROS: UN ANÁLISIS MULTITEMPORAL**

**RESUMEN**

**Antecedentes:** Aunque la renta variable de energías limpias se ha convertido en una nueva clase de activos muy popular entre los participantes en el mercado, se ha investigado relativamente poco sobre las estrategias de gestión del riesgo para los inversores en mercados de renta variable de energías limpias. El oro y la plata son metales preciosos que suelen considerarse inversiones adecuadas para protegerse de la incertidumbre. En consecuencia, su demanda tiende a aumentar cuando caen los mercados bursátiles.

**Objetivo:** El estudio pretende analizar la influencia de los metales preciosos (oro, plata y platino) y los índices bursátiles ecológicos (Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy) en la formación de precios durante diferentes períodos económicos entre el 1 de enero de 2018 y el 23 de noviembre de 2023.

**Métodos:** Los periodos analizados fueron: Silencio, pandemia de 2020, preconflicto y conflicto (invasión rusa de Ucrania). Para ello, se estimó un modelo VAR Granger Causality/Block Exogeneity Wald con el fin de identificar diferentes patrones de influencia durante cada periodo.

**Resultados:** Durante el periodo de Silencio se observaron 15 movimientos que afectaron a los precios, destacando la influencia significativa de la Plata sobre todos sus pares, mientras que el Oro impactó en el Platino, S&P Global, Nasdaq y WilderHill. El platino fue el activo que recibió más impactos de sus pares. Durante la pandemia de 2020, se produjeron 26 movimientos, y los índices S&P Global y Nasdaq Clean influyeron en la mayoría de sus homólogos. El oro y el platino siguieron siendo los activos más influidos por sus homólogos. En el periodo anterior al conflicto, se identificaron 11 movimientos, destacando la influencia mutua entre el Oro, los índices Nasdaq y WilderHill, y el Platino. Durante este periodo, la Plata y el S&P Global sólo afectaron a la formación de precios del Platino y de los Combustibles de Energías Limpias, respectivamente. Durante el periodo de conflicto, se observaron 18 movimientos, lo que pone de manifiesto la influencia del Platino y del S&P Global en la formación.
de los precios de diversos activos. El Oro fue el activo que recibió más impactos de sus homólogos durante este periodo.

**Conclusión:** Los resultados indican variaciones en las interacciones entre activos en distintos contextos económicos, lo que pone de relieve la importancia de comprender esta dinámica para tomar decisiones con mayor conocimiento de causa.

**Palabras clave:** Energías Verdes, Metales Preciosos, Movimientos, Diversificación de Carteras.

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1 INTRODUCTION

Over the last two hundred years, polluting energy resources such as coal, oil and gas have played a key role in economic advancement and industrialisation. However, it has also been responsible for contributing significantly to environmental problems such as climate change, giving rise to growing concern about the viability of this model. Growing global attention to reducing carbon emissions and transitioning to clean energy sources has resulted in substantial investments in renewable technologies such as solar, wind, hydroelectric and geothermal energy. As a result, clean energy has become a crucial sector driving economic growth. To efficiently observe the progress of the clean energy industry, the WilderHill Clean Energy Index was created in 2004. In practical terms, this index tracks the performance of publicly traded companies involved in the study and production of clean technologies such as solar panels, wind turbines and biofuels and is recognised as the sector's leading benchmark and an indispensable tool for investors interested in this booming market (Dias, Horta, et al., 2023; Dias, Teixeira, et al., 2023).

The clean energy sector is currently one of the fastest-growing segments of the energy industry. Recent statistics reveal that between 2009 and 2019, the clean energy sector experienced an annual growth rate of 5 per cent, compared to dirty energy's annual growth rate of 1.7 per cent. As a result, a significant amount of capital is being redirected from conventional energy sources to clean energy. For example, global investments in the clean energy sector grew from $120.1 billion to $363.3 billion between 2009 and 2019. Even during the Covid-19 pandemic, investments in clean energy increased by 2 per cent. This has increased interest among market participants in clean energy stocks (Bloomberg New Energy Finance, 2019).

The emergence of clean energy stocks as a new asset class has attracted considerable attention from investors, professionals and academics. On the other hand, investments in
renewable sector stocks are not without risk, which suggests the need to consider suitable hedging assets to eliminate risk. Given that precious metals, notably Gold, are used as effective hedges against adverse movements in international stock market returns, one might wonder about the relationship between clean energy stock indices and precious metals, especially from the perspective of hedging and risk management (Elie et al., 2019).

Portfolio rebalancing in the capital markets is a process of adjusting the asset allocation in a portfolio to align it with the investor's investment targets and risk tolerance. This process is especially important during periods of uncertainty in the global economy, as it helps investors manage risk and maintain a desired level of portfolio diversification. Rebalancing can involve selling assets that have appreciated their value and reallocating the proceeds to underperforming assets to align the portfolio with its target allocation. Doing so helps reduce the risk of the portfolio becoming too heavily weighted in a particular asset class, sector or geographical region (Dias, Chambino et al., 2023; Dias, Chambino et al., 2023).

This study contributes to the body of literature in several ways. Firstly, although clean energy stocks have emerged as a new asset class for market participants, especially for environmentally concerned investors, existing studies pay very little attention to how investors in clean energy stock markets can reduce their risk. Precious metals, such as Gold and Silver, are traditionally considered hedging assets in times of uncertainty. Their demand tends to increase when stock markets fall, offering investors protection.

Based on the literature studied, precious metals can be effective in mitigating the risks of different asset classes, including stocks (Dias and Carvalho, 2020; Dias et al., 2021; Dias and Carvalho, 2021; Teixeira et al., 2022). However, the research on how Gold, Silver and Platinum can be considered hedging assets against green energy indices still lacks robust evidence. Secondly, this is also the first study to document the impact of the 2020 and 2022 events on the structural dynamics and correlations between precious metals and clean energy. Thirdly, the study follows a time-frequency perspective to investigate the interconnections between precious metals, given that the sample will be subdivided into four sub-periods: the Tranquil period from 1 January 2018 to 31 December 2019; the Covid-19 global pandemic period from 1 January 2020 to 31 December 2020; the pre-conflict period from 1 January 2021 to 23 February 2022; and lastly, the war between Russia and Ukraine, which covers the years from 24 February 2022 to 23 November 2023.

This paper is divided into section 2 for the literature review with different sub-sections. Section 3 provides the data and methodology. The empirical results are discussed in section 4, and section 5 covers the conclusion and the main practical implications.
2 LITERATURE REVIEW

In recent decades, the transition to a carbon-resilient economy has become a topic of great interest within academia, companies, investors and financial institutions. This transition involves moving from traditional carbon-intensive forms of energy, such as coal and oil, towards cleaner and more sustainable energy sources, such as solar and wind power. The Paris Climate Agreement, signed in 2015, has been one of the main drivers of this transition, as it set a target to limit global warming to less than 2 degrees Celsius above pre-industrial levels to limit global warming to 1.5 degrees Celsius. This aim cannot be achieved without significant reductions in greenhouse gas emissions, mainly from the energy sector.

The United Nations Climate Change Conference (COP26), held in November 2021, was critical in the global effort to deal with climate change. One of the main challenges in this transition is balancing the immediate economic benefits of traditional energy sources with the long-term environmental costs. Many companies and investors are now recognising the potential risks of investing in carbon-intensive industries, as the costs of carbon emissions are likely to rise over time, making these investments less attractive. At the same time, the transition to clean energy presents significant opportunities for companies and investors, particularly in areas such as renewable energy, energy efficiency and low-carbon transport (Ettinger et al., 2023; Tzeremes et al., 2023; van Asselt & Green, 2023).

2.1 RELATED STUDIES ABOUT HEDGING ASSETS

The growing interest and investment in the clean energy sector reflects global awareness of climate change and the pressing need to adopt more sustainable practices for the planet’s future. As a result, the clean energy stock market has witnessed a significant increase, accompanied by considerable volatility and several associated risks. In this context, hedging assets have emerged as essential tools for investors looking to mitigate the risks associated with investing in clean energy stock indices. Among the most common hedging assets are precious metals, namely Gold. When used strategically, these assets not only reduce the risks associated with investments in clean energy but also provide increased levels of security in the context of strategic portfolio diversification management (Chen and Wang, 2017; Bulut and Rizvanoglu, 2020; Caporale and Gil-Alana, 2022; Kakinuma, 2022).

Jin et al. (2019) examined three commonly used hedging assets: Bitcoin, Gold and crude oil. The results indicate that the dynamic correlations between the gold and crude oil markets...
are almost positive, while between Bitcoin and Gold, they are almost negative, thus showing the properties of hedging assets.

In 2022, the authors Gustafsson et al. (2022) and Erdoğan et al. (2022) studied the relationship between clean energy stock indices and energy metals that are sensitive to the growth in demand for clean energy solutions and make inferences about whether energy metals can act as hedges or safe havens for clean energy stock indices. Gustafsson et al. (2022) show statistically significant non-linear relationships between the markets studied. All energy metals, except cobalt, have a significant positive link with clean energy stock indices, and these associations are maintained during episodes of high volatility. Although none of the energy metals under study acts as a hedge for clean energy stock markets, the results support previous evidence on the hedging properties of precious metals, showing that Gold and Silver serve as hedges for certain clean energy stock indices. Complementary Erdoğan et al. (2022) show that there is a unidirectional causal link from clean energy stock returns to precious metal prices in the centre and left tail of the distribution. On the other hand, there is strong feedback between the variables in the right tail of the distribution. These results show that clean energy stock prices have an advantage in affecting precious metal prices and precious metals cannot be used as hedging assets for investments in clean energy stocks.

More recently, authors Dias, Chambino, et al. (2023) investigated the relationship between energy and precious metals to assess their suitability as safe-haven assets in clean energy investment portfolios during the 2020 and 2022 events. The authors showed a positive association between energy metals (excluding nickel futures) and clean energy indices, suggesting their potential as safe-haven investments for green investors diversifying their portfolios. Furthermore, the study confirms the reliability of precious metals such as Gold, Silver and Platinum as safe havens for clean energy stock indices. Moreover, Dias, Horta, et al. (2023) examined the co-movements between the capital markets of the Netherlands (AEX), France (CAC 40), Germany (DAX 30), the United Kingdom (FTSE 100), Italy (FTSE MIB), Spain (IBEX 35), Russia (IMOEX) and the spot prices of crude oil (WTI), Silver (XAG), Gold (XAU) and Platinum (XPT). The authors demonstrated a significant increase in the number of causal relationships between the market pairs analysed (62 causal relationships out of 110 possibilities), including a relative increase in the influence of commodities on capital markets and capital markets on commodities. These conclusions show that during the events of 2020 and 2022, the capital and commodity markets significantly accentuated their co-movements with each other, indicating that alternative markets such as WTI, XAG, XAU and XPT do not have the attributes of a safe haven for the capital markets in question. In line with this, the
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authors Dias, Alexandre, et al. (2023b) examined whether cryptocurrencies could be considered a safe haven for investments in sustainable energy indices during the events of 2020 and 2022. The empirical findings show that clean energy stock indices can offer a viable safe harbour for cryptocurrencies classified as "dirty" due to their excessive energy consumption. However, the precise associations differ depending on the cryptocurrencies analysed.

The recent events of 2020 and 2022 have highlighted the importance of studying the interconnections between clean energy stock indices and hedging assets in order to improve the performance of sustainable energy portfolios and risk mitigation in the face of the recent events, thus strengthening the resilience of investments in a context of climate change and disruptive events.

BenMabrouk et al. (2024) examined the effectiveness of hedging assets between five main segments of Non-Fungible Tokens (NFTs): namely Collectibles, Art, Games, Metaverse and Utility, and other asset classes, namely Bitcoin and US stocks (S&P500). The authors show weak dynamics between NFTs and other assets, indicating that these new digital assets are still relatively decoupled from traditional assets and Bitcoin.

3 MATERIALS AND METHODS

3.1 DATA

The data used in the research are the daily index prices of Gold (Gold, Handy & Harman), Silver (Silver, Handy & Harman) and Platinum (London Platinum), as well as sustainable energy stock indices such as Clean Energy Fuels, S&P Global Clean Energy, Wilderhill Clean Energy, and NASDAQ Clean Edge Green Energy, from 1 January 2018 to 23 November 2023. The sample was analysed in four sub-periods to add robustness to the study: the first comprises the years from January 2018 to 31 December 2019, referred to as Tranquil; the second includes the first wave of the Covid-19 pandemic, and comprises the months from 1 January 2020 to 31 December 2020; the third sub-period covers the years from 1 January 2021 to 23 February 2022, referred to as Pre-Conflict; the fourth and final sub-period covers the period from 24 February 2022 to 23 November 2023, referred to as Conflict. The data was obtained through the Thomson Reuters Eikon platform and is represented in local currency to offset exchange rate distortions and possibly bias results.
Table 1

*Countries and their indices*

<table>
<thead>
<tr>
<th>País</th>
<th>Índice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reino Unido</td>
<td>Gold, Handy &amp; Harman</td>
</tr>
<tr>
<td>Reino Unido</td>
<td>Silver, Handy &amp; Harman</td>
</tr>
<tr>
<td>Reino Unido</td>
<td>London Platinum</td>
</tr>
<tr>
<td>Estados Unidos</td>
<td>Clean Energy Fuels</td>
</tr>
<tr>
<td>Estados Unidos</td>
<td>S&amp;P Global Clean Energy</td>
</tr>
<tr>
<td>Estados Unidos</td>
<td>Wilderhill Clean Energy</td>
</tr>
<tr>
<td>Estados Unidos</td>
<td>NASDAQ Clean Edge Green Energy</td>
</tr>
</tbody>
</table>

Source: Own elaboration.

3.2 METHODOLOGY

This section describes the methodology and the tests used to answer the research question. In the first stage, the sample was characterised by applying a set of descriptive statistical methods. Furthermore, the Jarque and Bera (1980) adherence test was applied to analyse the data distribution of the seven time series and test the assumption of normality, and the quantile graphs were analysed to check the residuals of the time series. In the second stage, the panel unit root tests of Breitung (2000), Levin, Lin, and Chu (2002), and Im et al. (2003) were employed to validate the stationarity of the time series. The Dickey and Fuller (1981) and Phillips and Perron (1988) tests, with Fisher's transformation, were used to validate the results and also the quantile graphs. The Clemente et al. (1998) model will be used to identify the breaks in the structure. The research question, i.e. the existence of movements between precious metals and clean energy indices, will be answered using the Granger causality model (Engle and Granger, 1987; Granger, 1969, 1981). The concept of Granger relates to the idea of temporal precedence between variables, that is, considering two variables $X_t$ e $Y_t$, and it is said that $X_t$ causes $Y_t$, in the Granger sense, if the historical values of $X_t$ help predict the future values of $Y_t$. The Granger test allows validation of whether this predictive capacity of the values of $X_t$ relative to $Y_t$ is statistically significant, defending as a null hypothesis that the exogenous coefficients lagging behind the causality variable are null and therefore do not cause the dependent variable in the Grangerian sense and the alternative hypothesis postulates the existence of causality (Granger, 1969; Sims, 1980).

The VAR Granger Causality or Block Exogenety Wald Test model will be used to analyse the causal relationship between the financial markets in question. It uses the Wald statistic to assess whether the independent (or exogenous) variables contain information that helps explain the dependent variable's behaviour.
The model can be expressed as follows:

\[ X_t = A_1 X_{t-1} + \cdots + A_p X_{t-p} + C Y_t + \epsilon_t \]  

(1)

Where:

- \( X_t \) is a vector of endogenous variables \((k \times 1)\), \( Y_t \) a vector of exogenous variables \((d \times 1)\), \( A_1 \) to \( A_p \), represent the matrices of lag coefficients to be estimated, and \( C \) corresponds to a matrix of coefficients of exogenous variables. \( \epsilon_t \) denotes a white noise process, commonly referred to as innovations or shock term, with normal distribution and zero mean.

That said, according to Parzen (1982), statistical modelling proposes methods that are often applied automatically without adjustment. However, an important aspect to consider when estimating a robust autoregressive model is the specification of the number of lags considered in the model.

Lütkepohl (1993) also demonstrated the sensitivity of the VAR regarding the number of lags, stating that specifying a longer lag length could cause an increase in forecast errors. In turn, an insufficient adjustment could lead to autocorrelated error terms and, consequently, to the inefficiency of the VAR model estimators. To address this issue, the author highlighted Akaike’s information criterion (AIC), Schwarz’s information criterion (SIC) and Hannan-Quinn’s information criterion (HQ) among the classic selection procedures for the number of lags in the literature. In addition to these classic selection criteria, it is possible to specify the number of lags to include in the model using the FPE (Final Prediction Error) or the LR (Likelihood Ratio) test.

Finally, it is vital to test for autocorrelation in the error terms of a regression model, as their dependence results in estimating an unviable model. Diagnosing the correlation of the error terms (or residuals) has been recognised for decades as crucial to ensuring the robustness and suitability of the regression model.
4 RESULTS

4.1 DESCRIPTIVE STATISTICS

Figure 1 shows the daily return trends of Gold (Gold, Handy & Harman), Silver (Silver, Handy & Harman) and Platinum (London Platinum), as well as sustainable energy stock indices such as Clean Energy Fuels, S&P Global Clean Energy, Wilderhill Clean Energy, and NASDAQ Clean Edge Green Energy, over the period from 1 January 2018 to 23 November 2023. Graphical observation shows that the average returns appear relatively stable, oscillating close to zero. However, a closer look at the data reveals substantial fluctuations, emphasising the pronounced volatility experienced by these markets. This volatility is particularly evident during the first few months of 2020, coinciding with the beginning of the impact of the COVID-19 pandemic on the global economy.

Figure 1

Evolution, in returns, of the clean energy and precious metals stock indices from 1 January 2018 to 23 November 2023.

Table 2 shows the main descriptive statistics for Gold (Gold, Handy & Harman), Silver (Silver, Handy & Harman) and Platinum (London Platinum), as well as for sustainable energy stock indices such as Clean Energy Fuels, S&P Global Clean Energy, Wilderhill Clean Energy,
and NASDAQ Clean Edge Green Energy, for the period from 1 January 2018 to 23 November 2023. Based on the results, it is possible to see that the mean returns are positive, with the exception being the Platinum market (-2.10e-06). The Clean Energy Fuels index (0.0478) has the highest standard deviation, showing that it is the index with the highest levels of volatility. In addition, the reference levels for asymmetry and kurtosis differ from model values 0 and 3, respectively. Most of the asymmetries have non-zero and negative values, the exception being the Clean energy fuels index (0.6173). Regarding kurtosis, the Clean Energy Fuels has the most significant value (15.2943). The JB model was estimated to validate this evidence, showing that the hypothesis that the data follows a normal distribution is rejected at a significance level of 1%.

**Table 2**

*Summary table of statistics for the clean energy and precious metals stock indices from 1 January 2018 to 23 November 2023.*

<table>
<thead>
<tr>
<th>Clean energy fuels</th>
<th>Gold</th>
<th>Platinum</th>
<th>Nasdaq Clean</th>
<th>S&amp;P Global Clean</th>
<th>Silver</th>
<th>Wilderhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.00035</td>
<td>0.00028</td>
<td>-2.10e-06</td>
<td>0.00036</td>
<td>0.00025</td>
<td>0.00021</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.0478</td>
<td>0.0088</td>
<td>0.01700</td>
<td>0.02372</td>
<td>0.01702</td>
<td>0.01671</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.6173</td>
<td>-0.3134</td>
<td>-0.4453</td>
<td>-0.2974</td>
<td>-0.3817</td>
<td>-0.4543</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>15.2943</td>
<td>7.2186</td>
<td>8.4120</td>
<td>7.0004</td>
<td>10.3532</td>
<td>9.0201</td>
</tr>
<tr>
<td>Jarque-Bera</td>
<td>9790.7762</td>
<td>1165.4869</td>
<td>1929.0952</td>
<td>1048.9229</td>
<td>3504.6614</td>
<td>2376.9776</td>
</tr>
<tr>
<td>Probability</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Observations</td>
<td>1539</td>
<td>1539</td>
<td>1539</td>
<td>1539</td>
<td>1539</td>
<td>1539</td>
</tr>
</tbody>
</table>

Source: Own elaboration

Figure 2 shows the quantile graphs for the gold (Gold, Handy & Harman), silver (Silver, Handy & Harman) and platinum (London Platinum) price indices, as well as for sustainable energy stock indices such as Clean Energy Fuels, S&P Global Clean Energy, Wilderhill Clean Energy and NASDAQ Clean Edge Green Energy, for the period from 1 January 2018 to 23 November 2023. Through the graphical observation of quantiles illustrated in Figure 3, it is also possible to infer the normality of the time series data analysed. The normal distribution line is in orange, and the data distribution for each time series is in blue. Comparing the dispersion of the time series data with the normal distribution line reveals that none of the series completely overlap, with a certain amount of asymmetry.
4.2 DIAGNOSTIC

Table 3 shows the summary table of the stationarity tests applied to the time series for the clean energy and precious metals stock indices from 1 January 2018 to 23 November 2023. Breitung (2000), Levin et al. (2002), Im et al. (2003) tests were applied to confirm stationarity and the Dickey and Fuller (1981) and Perron and Phillips (1988) with Fisher Chi-square transformation and Choi (2001) tests were used to validate the results. Stationarity was obtained by performing the logarithmic transformation in first differences to smooth the time series so that the characteristics of white noise could be achieved (mean 0; constant variance), thus validating the assumption of stationarity by rejecting it at a significance level of 1%.
Table 3

Summary table of the stationarity tests applied to the time series for the clean energy and precious metals stock indices from 1 January 2018 to 23 November 2023.

<table>
<thead>
<tr>
<th>Method</th>
<th>Statistic</th>
<th>Prob.**</th>
<th>Cross-sections</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null: Unit root (assumes common unit root process)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levin, Lin &amp; Chu t*</td>
<td>420.09</td>
<td>0.0000</td>
<td>7</td>
<td>10674</td>
</tr>
<tr>
<td>Breitung t-stat</td>
<td>-6.08</td>
<td>0.0000</td>
<td>7</td>
<td>10667</td>
</tr>
<tr>
<td>Null: Unit root (assumes individual unit root process)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Im, Pesaran and Shin W-stat</td>
<td>-57.90</td>
<td>0.0000</td>
<td>7</td>
<td>10674</td>
</tr>
<tr>
<td>ADF - Fisher Chi-square</td>
<td>1828.15</td>
<td>0.0000</td>
<td>7</td>
<td>10674</td>
</tr>
<tr>
<td>PP - Fisher Chi-square</td>
<td>128.94</td>
<td>0.0000</td>
<td>7</td>
<td>10759</td>
</tr>
</tbody>
</table>

Note: ** Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Source: Own elaboration.

Figure 3 shows the summary table of the unit root test with structural breaks of Clemente et al. (1998) applied to the returns of Gold (Gold, Handy & Harman), Silver (Silver, Handy & Harman) and Platinum (London Platinum), as well as sustainable energy stock indices such as Clean Energy Fuels, S&P Global Clean Energy, Wilderhill Clean Energy, and NASDAQ Clean Edge Green Energy, for the period from 1 January 2018 to 23 November 2023. Based on the results, we see that the most significant falls in precious metals and the main clean energy stock index occurred in 2020, as follows: Gold (24/03/2020), Platinum (16/03/2020), Silver (16/03/2020), Wilderhill Clean Energy (24/03/2020). On the other hand, the other green energy indices show their most significant structure breaks in 2021, for example, S&P Global Clean Energy (07/01/2021), NASDAQ Clean Edge Green Energy (07/01/2021), Clean Energy Fuels (08/02/2021).
Figure 3
Clemente's unit root test with structural breaks on returns applied to the time series for the clean energy and precious metals stock indices from 1 January 2018 to 23 November 2023.
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Dickey-Fuller autoregressive coefficients

LONDON PLATINUM
Break Date: 16/03/2020

NASDAQ CLEAN EDGE GREEN ENERGY
Break Date: 07/01/2021

S&P GLOBAL CLEAN ENERGY
Break Date: 07/01/2021
4.3 METHODOLOGICAL RESULTS

Table 4 shows the results of the VAR Granger Causality/Block Exogeneity Wald test during the Quiet period, relating to the clean energy stock indices Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy, and the precious metals Gold, Handy & Harman, Silver, Handy & Harman and London Platinum.

The results indicate that 15 movements (out of 42) affect price determination. When examining the results, it was found that Silver influences the price determination of all its peers except Clean Energy Fuels. Meanwhile, Gold influences Platinum, S&P Global, Nasdaq and WilderHill but has no impact on Silver and Clean Energy Fuels. WilderHill Clean Energy influences the pricing of Platinum, S&P Global and Nasdaq but does not affect the other markets. Meanwhile, Nasdaq Clean only influences Platinum and WilderHill. To a lesser extent, Platinum only influences the Nasdaq Clean without affecting the other markets. Similarly, S&P Global only influences the determination of Platinum prices without having any predictive
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power over the other markets. Clean Energy Fuels does not influence its peers, while Platinum is the market that receives the most shocks from its peers (5 out of a possible 6). These results highlight the complexity of the interactions between the different assets within the clean energy markets and regarding precious metals.

Table 4
Granger causality/Block Exogeneity Wald Tests of the financial markets analysed during the Tranquil period

<table>
<thead>
<tr>
<th></th>
<th>Gold</th>
<th>Platinum</th>
<th>Silver</th>
<th>S&amp;P Global Clean</th>
<th>Nasdaq Clean</th>
<th>Clean Energy Fuels</th>
<th>Wilderhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0.79 (2)</td>
<td>0.73 (2)</td>
<td>0.73 (2)</td>
<td>0.74 (2)</td>
<td>0.81 (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>10.06*** (2)</td>
<td>0.06** (2)</td>
<td>15.52*** (2)</td>
<td>4.10** (2)</td>
<td>5.84*** (2)</td>
<td>1.15 (2)</td>
<td>7.78*** (2)</td>
</tr>
<tr>
<td>Silver</td>
<td>0.34 (2)</td>
<td>1.39 (2)</td>
<td>0.29 (2)</td>
<td>1.67 (2)</td>
<td>1.05 (2)</td>
<td>1.34 (2)</td>
<td></td>
</tr>
<tr>
<td>S&amp;P Global Clean</td>
<td>3.03** (2)</td>
<td>1.35 (2)</td>
<td>2.79* (2)</td>
<td>0.89 (2)</td>
<td>0.05 (2)</td>
<td>4.84*** (2)</td>
<td></td>
</tr>
<tr>
<td>Nasdaq Clean</td>
<td>4.75*** (2)</td>
<td>3.71** (2)</td>
<td>5.04*** (2)</td>
<td>0.22 (2)</td>
<td>*****</td>
<td>0.10 (2)</td>
<td>4.62** (2)</td>
</tr>
<tr>
<td>Clean Energy Fuels</td>
<td>0.19 (2)</td>
<td>0.11 (2)</td>
<td>0.45 (2)</td>
<td>1.32 (2)</td>
<td>1.42 (2)</td>
<td>*****</td>
<td>0.76 (2)</td>
</tr>
<tr>
<td>Wilderhill</td>
<td>5.59*** (2)</td>
<td>1.46 (2)</td>
<td>3.93** (2)</td>
<td>1.49 (2)</td>
<td>3.11** (2)</td>
<td>0.29 (2)</td>
<td>*****</td>
</tr>
</tbody>
</table>

Note: The markets in the column cause the markets in the row. The value in brackets corresponds to the level of lags (in days). The asterisks ***, **, * represent the significance level at 1%, 5% and 10% respectively.
Source: Own elaboration.

Table 5 displays the results of the VAR Granger Causality/Block Exogeneity Wald test during the 2020 pandemic period, relating them to the clean energy stock indices, Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, and WilderHill Clean Energy and the precious metals stock indices, Gold, Handy & Harman, Silver, Handy & Harman and London Platinum.

The results show that 26 movements (out of a possible 42) affect price determination in the markets studied. When examining the results, the S&P Global and Nasdaq Clean indices (5 out of 6 possible) influence the price determination of all their peers, except for the WilderHill Clean Energy index. Similarly, Platinum influences the pricing of Silver, S&P Global, Nasdaq and WilderHill without impacting the other markets. Clean Energy Fuels only influence the prices of Gold, Platinum, S&P Global and Nasdaq. On the other hand, Silver influences the Gold market, Platinum and the Nasdaq index, while WilderHill influences Gold, Platinum and the Clean Energy index without influencing the other markets. Gold influences the price formation of the Nasdaq and WilderHill stock indices, but the shocks to the other markets are not significant. It can be seen that during this period of stress in global markets, Gold and Platinum are the assets that receive the most shocks from their peers (5 out of a possible 6).
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Table 5

Granger causality/Block Exogeneity Wald Tests of the financial markets analysed during the Covid-19 Pandemic

<table>
<thead>
<tr>
<th></th>
<th>Gold</th>
<th>Platinum</th>
<th>Silver</th>
<th>S&amp;P Global Clean</th>
<th>Nasdaq Clean</th>
<th>Clean Energy Fuels</th>
<th>Wilderhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>1.62 (9)</td>
<td>2.18** (9)</td>
<td>2.22** (9)</td>
<td>2.03** (9)</td>
<td>2.04** (9)</td>
<td>1.95** (9)</td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>1.12 (9)</td>
<td>2.57*** (9)</td>
<td>2.97*** (9)</td>
<td>2.34** (9)</td>
<td>3.93*** (9)</td>
<td>2.30** (9)</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>0.76 (9)</td>
<td>3.24*** (9)</td>
<td>2.81*** (9)</td>
<td>1.83* (9)</td>
<td>1.44 (9)</td>
<td>1.98** (9)</td>
<td></td>
</tr>
<tr>
<td>S&amp;P Global Clean</td>
<td>1.53 (9)</td>
<td>2.59*** (9)</td>
<td>1.19 (9)</td>
<td>2.04** (9)</td>
<td>1.78* (9)</td>
<td>1.13 (9)</td>
<td></td>
</tr>
<tr>
<td>Nasdaq Clean</td>
<td>2.31** (9)</td>
<td>3.42*** (9)</td>
<td>1.72* (9)</td>
<td>2.08** (9)</td>
<td>1.96** (9)</td>
<td>1.14 (9)</td>
<td></td>
</tr>
<tr>
<td>Clean Energy Fuels</td>
<td>0.95 (9)</td>
<td>0.94 (9)</td>
<td>0.84 (9)</td>
<td>1.77* (9)</td>
<td>1.94** (9)</td>
<td>1.75* (9)</td>
<td></td>
</tr>
<tr>
<td>Wilderhill</td>
<td>1.68* (9)</td>
<td>3.22*** (9)</td>
<td>1.29 (9)</td>
<td>1.29 (9)</td>
<td>1.44 (9)</td>
<td>1.54 (9)</td>
<td>1.13 (9)</td>
</tr>
</tbody>
</table>

Note: Os mercados em coluna causam os mercados em linha. O valor entre parêntesis corresponde ao nível de desfasamento (em dias). Os asteriscos ***, **, * representam o nível de significância a 1%, 5% e 10%, respectivamente.
Source: Own elaboration.

Table 6 provides the results of the VAR Granger Causality/Block Exogeneity Wald test for the pre-conflict period, focussing on stock indices related to sustainable energy, such as Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy, and the precious metals Gold, Handy & Harman, Silver, Handy & Harman and London Platinum. The study reveals the presence of 11 movements (out of a possible 42) that influence price formation.

Based on the results, Gold and the Nasdaq and WilderHill indices (2 out of 6 possible) have an equal influence on the precious metal Platinum and the Clean Energy index and no influence on the other markets. Platinum influences the S&P Global indices, and Clean Energy Fuels is not significant for the other markets analysed. To a lesser extent, Silver and Clean Energy only influence the price formation of the precise metal Platinum, while the S&P Global index only affects the price formation of Clean Energy Fuels.

Table 6

Granger causality/Block Exogeneity Wald Tests of the financial markets analysed during the Pre-conflict subperiod

<table>
<thead>
<tr>
<th></th>
<th>Gold</th>
<th>Platinum</th>
<th>Silver</th>
<th>S&amp;P Global Clean</th>
<th>Nasdaq Clean</th>
<th>Clean Energy Fuels</th>
<th>Wilderhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0.19 (2)</td>
<td>0.39 (2)</td>
<td>0.59 (2)</td>
<td>0.26 (2)</td>
<td>1.34 (2)</td>
<td>0.23 (2)</td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>3.47 (2)**</td>
<td>9.07 (2)**</td>
<td>1.83 (2)</td>
<td>4.51 (2)**</td>
<td>3.26 (2)**</td>
<td>4.88 (2)**</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>1.69 (2)</td>
<td>0.43 (2)</td>
<td>1.22 (2)</td>
<td>1.18 (2)</td>
<td>1.71 (2)</td>
<td>0.92 (2)</td>
<td></td>
</tr>
<tr>
<td>S&amp;P Global Clean</td>
<td>0.20 (2)</td>
<td>0.41 (2)</td>
<td>0.62 (2)</td>
<td>0.29 (2)</td>
<td>0.21 (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nasdaq Clean</td>
<td>0.20 (2)</td>
<td>2.39 (2)**</td>
<td>1.19 (2)</td>
<td>2.22 (2)</td>
<td>0.02 (2)</td>
<td>0.68 (2)</td>
<td></td>
</tr>
</tbody>
</table>
Table 7 shows the results of the VAR Granger Causality/Block Exogeneity Wald test for the Conflict period, focusing on stock indices related to sustainable energy, such as Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy, and the precious metals Gold, Handy & Harman, Silver, Handy & Harman and London Platinum. The results reveal the presence of 18 movements (out of a total of 42 possible) that impact price formation, while in the Pre-conflict sub-period, there were only 11 movements. The precious metal Platinum influences the price formation of Silver, S&P Global, Nasdaq and Clean Energy Fuels, while the S&P Global index affects the price formation of Gold, Platinum, Nasdaq and WilderHill and does not affect the prices of the other markets. The Clean Energy index influences the price formation of Gold, Silver, Nasdaq and WilderHill, while Nasdaq Clean affects the price formation of Gold, Platinum and WilderHill and has no influence on the prices of the other markets. To a lesser extent, the WilderHill Clean Energy index only affects Gold prices, while the Gold market does not influence the price formation of any markets analysed. In addition, Gold is the asset that receives the most shocks from its peers (4 out of a possible 6).

### Table 7
**Granger causality/Block Exogeneity Wald Tests of the financial markets analysed during the Conflict subperiod**

<table>
<thead>
<tr>
<th>Clean Energy Fuels</th>
<th>Gold</th>
<th>Platinum</th>
<th>Silver</th>
<th>S&amp;P Global Clean</th>
<th>Nasdaq Clean</th>
<th>Clean Energy Fuels</th>
<th>WilderHill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilderhill</td>
<td>0.24 (2)</td>
<td>1.92 (2)</td>
<td>1.37 (2)</td>
<td>1.29 (2)</td>
<td>0.93 (2)</td>
<td>0.09 (2)</td>
<td>****</td>
</tr>
</tbody>
</table>

Note: Os mercados em coluna causam os mercados em linha. O valor entre parêntesis corresponde ao nível de desfasamentos (em dias). Os asteriscos ***, **, * representam o nível de significância a 1%, 5% e 10%, respectivamente.

Source: Own elaboration.
5 CONCLUSION

In this study, the aim was to assess the influence on price formation of precious metals such as Gold, Silver and Platinum and green stock indices such as Clean Energy Fuels, Nasdaq Clean Edge Green Energy, S&P Global Clean Energy, WilderHill Clean Energy, in the period from 1 January 2018 to 23 November 2023. The sample was subdivided into four periods: Tranquil, the Covid-19 pandemic, pre-conflict and Russia's invasion of Ukraine.

The VAR Granger Causality/Block Exogeneity Wald model was used to understand the dynamics, revealing that during the Tranquil period, 15 movements affected price formation, highlighting the significant influence of Silver on all its peers, while Gold has an impact on Platinum, S&P Global, Nasdaq and WilderHill. Furthermore, Platinum is the market that receives the most shocks from its peers. During the 2020 pandemic, there was an increase in the number of movements, totalling 26, with the highlight being the S&P Global and Nasdaq Clean indices, which influence most of their peers. Gold and Platinum remained the assets that received the most shocks from their peers. In the Pre-Conflict period, 11 movements were identified, with emphasis on the mutual influence between Gold, the Nasdaq and WilderHill indices, and Platinum, while Silver and the S&P Global only affect the price formation of Platinum and Clean Energy Fuels, respectively. In the Conflict period, there were 18 movements, with Platinum influencing the price formation of various assets and the S&P Global. Notably, Gold was the asset that received the most shocks from its peers during this period. In conclusion, the results indicate variations in the interactions between assets throughout the different economic contexts, highlighting the importance of understanding these dynamics for more informed decision-making.

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https://doi.org/10.1016/j.energy.2019.04.155


