# Fossil Fuels and European Power Markets - The 2007/08 Fossil Fuels Shock and its Causal Effects on European Power Markets

**Lucía Morales and Jim Hanly**

**ABSTRACT**

Fossil fuels were exposed to a significant shock during the Global Economic and Financial Crisis of 2007/08. This paper examines the influence of Brent Crude Oil, Natural Gas and Coal on three major European power markets (APXUK, NordPool, and Phelix) during this period of significant uncertainty. The research study offers historical insights on the dynamics of the markets over a critical period of economic and financial instability. A univariate and bivariate methodological framework supports the research study enabling the analysis of short-run, long-run and asymmetric power of market responses to fossil fuels dynamics. The results point to a stronger relationship between fossil fuels shocks and the APXUK market across all three generational fuels. In contrast, the results for Phelix are significant only in the case of coal and crude oil. For the Nordic region, there is no substantial evidence of a causal effect between the power market and the broader energy markets. Thanks to its strong focus on renewables, the Nordic market appears to be insulated from shocks emerging from fossil fuels. On the other hand, APXUK and Phelix accounted for a higher representation of fossil fuels on their energy mix, and as such, they were significantly exposed to fossil fuel fluctuations.

**Keywords:** Fossil Fuels, European Power Markets, Volatility, Causality

JEL classification: G10, G12, G15

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## 1. INTRODUCTION

Recent price changes and associated volatility in global energy markets have highlighted the importance of these markets due to their central role to support economic activity as they are a core input for every industry. Price fluctuations are a matter of significant importance due to the inelastic nature of the demand function and its impact on economic development. Moreover, energy prices variation has been cited as a causal effect concerning economic recessions, where unemployment appears to be a pivotal contributor to inflationary pressures (Edelstein and Kilian, 2009). Van de Ven and Fouquet (2017) point out the importance of diversified energy models with a strong representation of renewable energies to help to reduce economic vulnerabilities and enhance resilience to energy price shocks. Additionally, energy markets dynamics are clearly connected with financial markets due to its financialization reflected in the increasing use of derivative products, which have played a significant role in the market integration process (Xunpeng et al., 2019). Since the early 2000s, fossil fuels, and mainly crude oil prices, have been subject to dramatic price swings and increasing levels of volatility shifts as observed in July 2008, where oil prices reached an all-time high of $147 per barrel (Ji, 2012; Charles and Darné, 2014). The impact of the Global Health Crisis due to the outbreak of COVID-19 has also led to a massive shock in the oil industry, forcing oil prices (Crude Oil-West Texas Intermediate) to briefly go negative for the first time in history (OECD, 2020; Putnam and Norland, 2020). Within a context of significant instability affecting energy markets, this research study focuses on the historical impact of the Global Economic and Financial Crisis (GEFC) of 2007/08 on European power markets; and as such, it is of interest to highlight oil price behaviour during this specific period. In particular, the first half of 2008 was characterized as being more severe than in any previous period in history (Hamilton, 2009). The dynamics exhibited by oil prices point out the complex nature of this market. Economic factors, geopolitical tensions, and the high level of uncertainty over supply and demand combined with speculative practices appear to be at the centre of these extreme movements (Schmidbauer and Rosch, 2012; Kilian, 2008; Kilian 2009). A critical aspect of consideration is that the dramatic fluctuations in oil prices are triggered not just by factors affecting the supply and demand side, but also by actions taken by speculators that treat oil as a financial asset. A result of this has been that oil price dynamics may not align with the behaviour of more traditional commodities.

Interestingly, over the crisis period, the price increases experienced in the oil market were mimicked by the gas and coal market, with the gas market showing more stable behaviour than oil and coal (as depicted in figure 1 below). Indeed, in general, fossil fuels exhibited positive correlations and seemed to be moving together in the long run. At the same time, European power markets faced substantial increases in their spot prices, with significant movements registered during the early stages of the Global Economic and Financial Crisis (GEFC) of 2008. Price dynamics indicated that the markets could be reacting to the global turmoil and rising instability levels in the fossil fuels market.

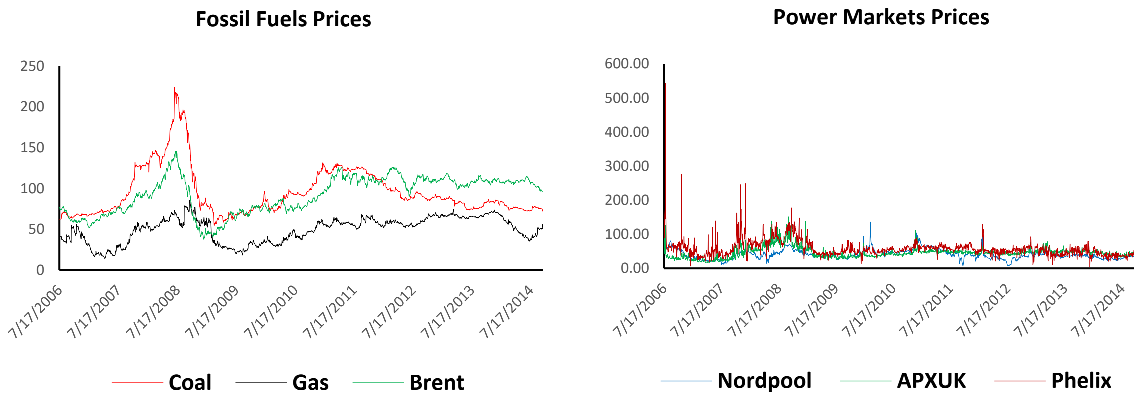


**Figure 1.** Fossil Fuels and Power Markets Spot Prices. Source: Refinitiv (2021).

Many papers have examined the existing connections between oil price shocks and their potential implications for global economic activity, stock market volatility and general economic performance and development (Venditti and Versonese, 2020; Fueki, et al., 2018; Kang et al., 2015; Degiannakis et al., 2014; Arouri et al., 2012; Vo, 2009; Chen, 2009; Killian and Park, 2009; Malik and Ewing, 2009; Nandha and Faff, 2008; Papapetrou, 2001; Sadorsky, 1999; Jones and Kaul, 1996). The extant literature shows evidence of linkages and transmission effects running from the oil market to the stock markets. Aggregate demand seems to impact market fluctuations significantly, while supply-side shocks and oil-specific demand shocks do not seem to influence stock market volatility greatly. A large body of work has also been done to analyse the relationship between oil price variations and other relevant macroeconomic variables (Apergis and Miller, 2009; Miller and Ratti, 2009; Gronwald, 2008; Park and Ratti, 2008). The findings have shown that the connection between oil and economic activity is not entirely linear and that adverse oil price shocks (price drops) tend to significantly impact economic growth more than positive surprises do (price increases). Researchers offer insights suggesting that positive shocks do not seem to have any particular implications for economic development and growth (Hamilton, 2003; Cologni and Manera, 2008). Furthermore, the extant literature also points out the importance of identifying the underlying source of oil price shocks regarding their influence on stock market performance (Killian and Park, 2009). Another issue examined in the literature is the impact of oil price shocks on the utility sector, given its use of oil-related products as an input. However, the main findings suggest that there is no evidence of significant effects of oil shocks generating a substantial impact on companies' returns. This may be related to the frequent use of hedging strategies that seek to protect corporations against the adverse effects of increasing oil prices on profitability (Arouri, 2011).

Considerably less work has been done on other fossil fuels such as coal and gas despite their importance as a significant input in the energy generation process both globally and within the European context. Ferkingstad et al., (2011) estimated a causal model looking at price dynamics at the Nordic and German electricity prices, finding that they are interlinked through gas prices movements. Oberndorfer (2009) finds that oil price increases negatively impact on stock returns of European utilities while leading to an appreciation of oil and gas stocks. Moreover, the study shows that neither the coal nor gas markets play a significant role in the pricing of Eurozone energy stocks when compared to oil price impacts, despite oil having a much smaller role in the generational mix for European electricity. However, the literature has relatively little to say about the implications of fossil fuel shocks and their potential transmission effects towards power markets and the impact that they might have on the price generation process. This gap is surprising given the significant role that fossil fuels play in most of the world's economies. This paper investigates these relationships and contributes to the literature in several contexts. Firstly, we examine whether the uncertainty affecting fossil fuel prices is having a causal impact on the formation of European power markets prices. We also investigate the impact of asymmetric causal effects using various models to cross-check our empirical findings. This approach is justified by the sensitivity of causal tests to their formulation, requiring the cross-check of research outcomes to ensure robustness and consistency. Volatility behaviour of the European power markets is also examined using both conditional (GARCH) and realized volatility models that aim to bring further insights into power markets dynamics and their relationship with fossil fuels (Bollerslev, 1986; Andersen and Bollerslev, 1998). Our analysis focuses on three of the key European power markets, namely APXUK, NordPool and Phelix. The markets' heterogeneity regarding their dependence on fossil fuels will help identify if European power markets exhibit different types of behaviour and reactions during times of significant market uncertainty. Our key findings indicate a strong relationship between fossil fuel shocks and APXUK and Phelix electricity markets. This is particularly true for the APXUK market, which shows significant causal effects for all three generational fuels. In contrast, there is no substantial evidence of a causal effect between the broader energy markets and the Nordic power market. These results have clear implications for electricity and energy market participants in that they must differentiate between these markets, in terms of how they measure and manage the risk and volatility of their exposures. For policymakers, the research findings also highlight that a homogenous approach may not be optimal.

The remainder of the paper is organized as follows. In section 2, the basic research background and the study motivation are outlined. Section 3 describes the data and the econometric research framework. Section 4 presents the empirical findings, starting with the discussion of basic descriptive statistics and moving towards the analysis of the core research findings. Section 5 concludes the paper by offering insights for investors, policymakers, and general thoughts for further research.

## 2. BACKGROUND AND MOTIVATION

Electricity as a commodity has characteristics that make its prices especially volatile. The demand must be satisfied in real-time, making it almost difficult to store. At the same time, its fossil fuel price inputs (coal, gas and oil) are also affected by high levels of uncertainty and significant fluctuations in prices (Muñoz and Dickey, 2009; Graus and Worrell, 2006). Moreover, fossil fuel prices are related to macroeconomic variables that impact electricity price formation, which adds further complexities to the analysis of fossil fuels prices and how they react to situations of market distress. The share of fossil fuels (see figure 1 below) in the overall fuel mix for electricity generation is generally of the order of 45 percent, primarily based on coal and natural gas, whereas oil-fired power generation is generally below 3 percent[1]. In the case of the United Kingdom, the fossil fuel mix is shared between coal and natural gas. While in the case of Germany, fossil fuel power generation relies mainly on coal. The case of Nordic countries is quite exceptional, as electricity generation is supported by hydropower representing around 50 percent of the mix for electricity generation. In comparison, coal-fired generation is around 40 percent. While oil may have only a marginal place in the generational blend, it is essential to consider that this energy resource has a significant impact on power markets via its role as a leading indicator of energy prices in general. Oil-indexation cannot be forgotten, as it is also another transmission channel of shocks from the oil market to the gas market, which generates spillover effects to those markets that do not rely on oil but that are indirectly connected (Till and McHich, 2020; Zhang and Sun, 2016). This highlights the importance of fossil

[1] https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment
http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview

fuels to European power markets and why an analysis of power market behaviour, particularly the impact of fossil fuel price shocks and their lasting effects, is vital.

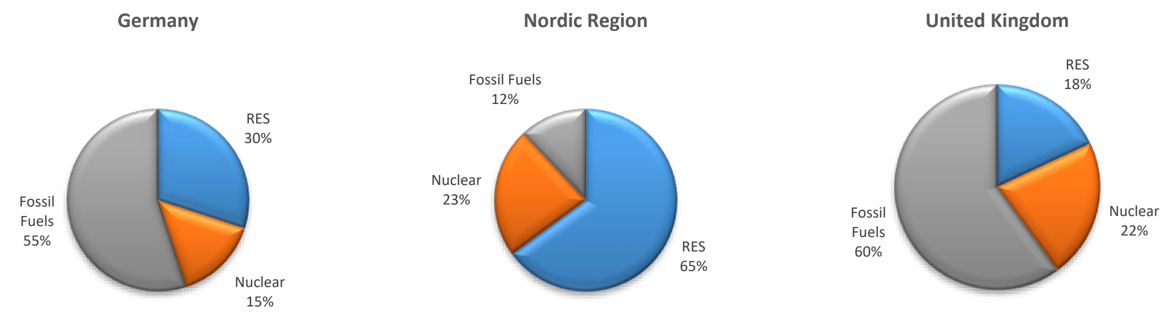


**Figure 1.** Electricity Energy Sources. Source: European Parliament's Committee on Industry, Research and Energy Report (2014)

We base our analysis on both the APXUK (UK) and Phelix (Germany) markets, given their strong connection with fossil fuels as sources used to fuel energy plants. We have also chosen the NordPool (Scandinavian) market as a control market due to its low dependence on fossil fuels. This approach allows us to cross-check the strength of the modelling outcomes and will offer further insights on power markets reactions to shocks that originate in the fossil fuels market. Figures 2 and 3 below portray realised and conditional volatilities for the markets under study. The results show clear signs of significant variations during the GEFC and highlight the dynamic nature of energy markets and the importance of examining such variations with the support of variance asymmetric models, as explained in the section that follows.

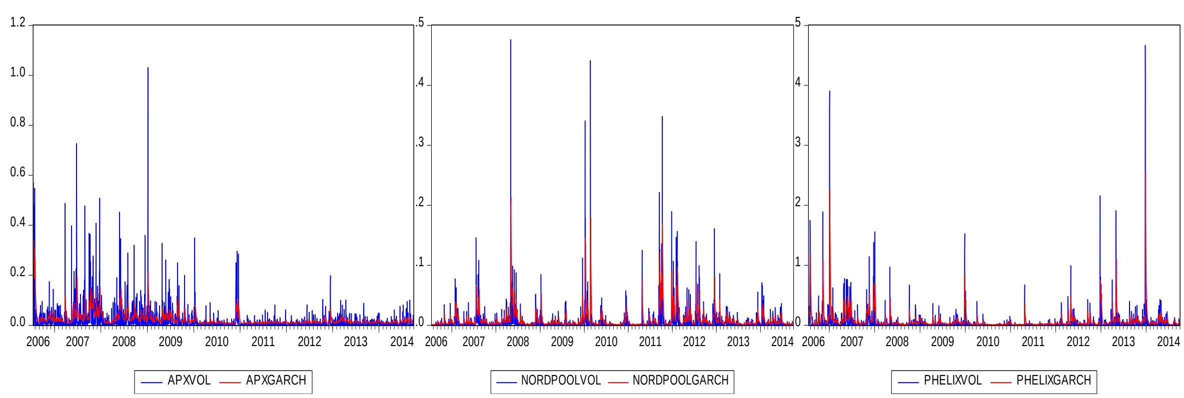


**Figure 2.** Power Markets Realised and Conditional Volatilities**.** Source: Authors (2021)

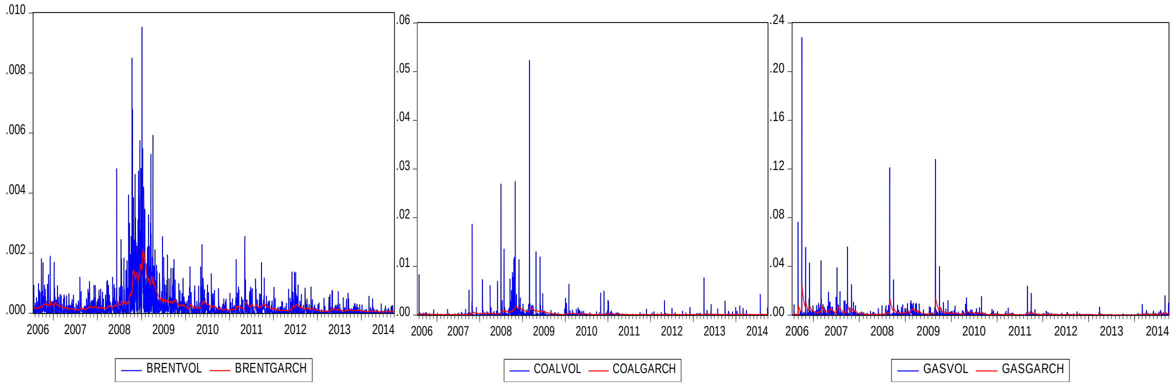


**Figure 3.** Fossil Fuels Markets Realised and Conditional Volatilities. Source: Authors (2021)

## 3. DATA AND RESEARCH METHODOLOGY

### 3.1 Data Description and Basic Econometric Framework

Daily spot prices are analysed for the period July 2006 to September 2014. Daily fossil fuel data was obtained on the Brent index, Coal ICE and ICE Natural Gas, and three electricity markets in Europe (NordPool, the UK APXUK/ICE and Germany – EEX/Phelix)[2]. The research sample comprises a dataset of 2,143 observations structured to ensure that only the 2007/08 market shock was considered[3]. Natural logarithms are used over a frequency of five days a week, and all holiday periods are removed from the sample. Table 1 below presents a summary of basic statistics for prices and returns for the period under study. The descriptive statistics offer evidence of non-normality on the selected series, as recorded by the Jarque-Bera test, and also evidence of leptokurtic series as exhibited by the excess level of kurtosis over the period. Electricity markets and fossil fuels average returns were flat, and were characterized by a high level of variations on the electricity sector, with limited deviations displayed by fossil fuels, in which standard deviations were below 5 percent.

In the case of power markets variation, the lower level was registered by NordPool at around 8 percent aligning with the idea that energy models with a potent mix of renewable energies exhibit more stable patterns in the context of economic shocks. However, when looking at the coefficient of variation outcomes, APXUK and NordPool offer evidence of similar behaviour. At the same time, Phelix appears to be more unstable, as recorded by its higher level of variation. In the case of fossil fuels, the results showed that coal and gas shared a similar variation, while the oil market appeared to be more stable. This is an interesting outcome, as one would expect that the oil sector would be much affected by uncertainty during this period. The Jarque-Bera test confirms that the series under study are non-normal, which justifies our asymmetric modelling approach.

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[2] See the following for more detailed information:
http://www.apxgroup.com/trading-clearing/apx-power-uk/
http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/
https://www.eex.com/en/products/power/power-derivatives-market

[3] This avoids incorporating noise generated in the markets like for example disruptions like the 2001 Oil shock due to the September 11 terrorist attacks, or the 2002 Worldcom and Enron collapses. At the same time, the selected time period allows the analysis of energy market dynamics during a time of remarkable uncertainty affecting energy markets and the global economy because of the Global Economic Financial Crisis and eliminates distortitons associated with the economic recovery process.

**Table 1: Descriptive Statistics**

| | Mean | Std. Dev. | Skewness | Kurtosis | Jarque-Bera |
|---|---|---|---|---|---|
| **Coal** | | | | | |
| Levels | 95.11 | 29.18 | 1.61* | 5.90* | 1672* |
| Returns | - | 0.02 | -1.49* | 42.41* | 139362* |
| **Gas** | | | | | |
| Levels | 49.59 | 15.33 | -0.43* | 2.12* | 135* |
| Returns | - | 0.03 | 3.35* | 36.80* | 105942* |
| **Brent** | | | | | |
| Levels | 92.01 | 22.73 | -0.36* | 2.10* | 118* |
| Returns | - | 0.02 | -0.23* | 7.01* | 1449* |
| **NordPool** | | | | | |
| Levels | 40.51 | 14 | 0.95* | 5.13* | 727* |
| Returns | - | 0.08 | 0.30* | 13.78* | 10393* |
| **APXUK** | | | | | |
| Levels | 45.73 | 15.9 | 1.75* | 9.11* | 4415* |
| Returns | - | 0.15 | 0.03 | 7.68* | 1954* |
| **Phelix** | | | | | |
| Levels | 58.25 | 25.57 | 5.74* | 82.45* | 574845* |
| Returns | - | 0.24 | -0.10 | 18.64* | 21820* |

*Notes: Descriptive statistics are presented for both prices (levels) and the log-returns of each series. The total sample period runs from 15/09/2004 until 01/10/2014. JB is the Jarque-Bera statistic that measures normality, and the * denotes significance at the 1% level.

The methodological framework starts determining the order of integration of the time series under study by applying standard and commonly used tests like the Augmented Dickey-Fuller (ADF). Additional well-known unit root tests were implemented for cross-checking purposes regarding the series stationarity patterns and to enhance the research outcomes. The analysis was followed by examining cointegration relationships between the selected power markets and fossil fuels needed to correctly carry out the causality framework. The study is followed by implementing a simple linear representation of the basic correlations in the selected historical data, following the work done by Edelstein and Kilian (2007). In this case, the proposed VAR (Vector Autoregression) approach is based on the estimation of daily bivariate autoregressions used to start the basic discussion looking at the relationship between electricity markets and the selected fossil fuels and that lead to the implementation of more sophisticated time series models. As standard practice when analysing financial time series, prices are transformed into returns (equation 1 and 2), and afterwards, the bivariate VAR is estimated (equation 3 and 4).

$$Pr_t = 100(lnPM_t - lnPM_{t-1}) \quad (1)$$

$$Fr_t = 100(lnFM_t - lnFM_{t-1}) \quad (2)$$

$$Pr_t = k_1 + \sum_{s=1}^{\partial} \emptyset_{11} Pr_{t-s} + \sum_{s=1}^{\partial} \emptyset_{12} Fr_{t-s} + \varepsilon_{1t} \quad (3)$$

$$Fr_t = k_2 + \sum_{s=1}^{\partial} \emptyset_{21} Fr_{t-s} + \sum_{s=1}^{\partial} \emptyset_{22} Pr_{t-s} + \varepsilon_{2t} \quad (4)$$

where $Fr_t$ is the fossil market returns for the series of interests (oil, natural gas, and coal), while $Pr_t$ is the price return for the selected European power market (APXUK, NordPool and Phelix). A VAR framework is also used to identify the appropriate number of lags used to support the analysis in terms of changes in electricity prices derived from the 2007/08 oil prices shock. To identify and confirm the existence of a breakpoint on oil prices, the Chow and Bai-Perron tests are used to verify a change that in turn helps in splitting the sample appropriately. The VAR model includes energy spot prices to identify the existence of any different potential dynamics among the selected series. The Hannan-Quinn and Schwarz Information Criterions determined the VAR lag order, as both criteria appeared to be relatively consistent in their results. The analysis is further developed by estimating the univariate GARCH (1,1) model introduced by Bollerslev (1986) that helps gain a better understanding of volatility patterns on the markets and generate the standardised residuals needed to run the asymmetric causal analysis outlined in section 3.2 below. The models' estimations are subject to residual checks looking for the absence of autocorrelation and ARCH effects that confirm that the model specification is appropriate and captures the returns' dynamics.

The cointegration relationship between fossil fuels and power markets is considered by using the Johansen and Juselius (1990) model based on a vector autoregressive (VAR) approach. The vector $X_t$ contains the endogenously seen variables and has the dimension $n\,x\,1$, where $n$ is the number of endogenous variables. Each variable follows a process that is influenced by its own lagged variables and the lagged variables of the other endogenous variables.

$$X_t = \Pi_1 X_{t-1} + \ldots + \Pi_k X_{t-1} + \varepsilon_t \quad \text{with } t = 1, \ldots, T \tag{5}$$

The matrix of coefficient $\Pi_k$ has the dimension $n\,x\,n$. Based on the equation above, the VAR can be transferred to a VAR of first differences. For this purpose, the lagged variable of the endogenous variables is subtracted from both sides and the system below arises.

$$\Delta X_t = \sum_{i=1}^{k-1} \Gamma_i \Delta X_{t-i} + \Pi_k X_{t-1} + \varepsilon_t \tag{6}$$

where,
$\Gamma_i = -I + \Pi_1 + \cdots + \Pi_i$ with $I = 1, \ldots, k-1$ and $\Pi = -(I - \Pi_1 - \cdots - \Pi_k)$ (Johansen/Juselius, 1990, p.170).

### 3.2 Asymmetric Specification

We differentiated between increases and decreases in the price of fossil fuels, and accordingly, we separated our variables according to the equations outlined below. The rationale behind the presented model following Mork (1989) and Hamilton (2003) is that fossil fuels fluctuations (increases and decreases in prices) may cause different effects. Since the selected electricity markets use oil, gas and coal in different proportions, we would expect different causal effects running from and to each one of them. This justifies the need for a more sophisticated analysis of asymmetric effects captured in the model presented in equation seven below.

$$Pr_{it} = \alpha + \beta_1^{+} Fr_t^{+} + \beta_2^{-} Fr_t^{-} + \varepsilon_{it} \tag{7}$$

where,

$Pr_{it}$ = Power market under study (APXUK, NordPool, Phelix)

$Fr_t^{+}$= Fossil fuel under study (increases in fossil fuels returns)

$Fr_t^{-}$= Fossil fuel under study (decreases in fossil fuels returns)

$\varepsilon_{it} \rightarrow N(0, h_{it})$

The model variance equation is specified as follows:

$$h_{it}^2 = \alpha + \sum_{k=1}^{q} b_k \, \varepsilon_{i,t-k}^2 + \sum_{l=1}^{p} \gamma_1 \, h_{i,t-l}^2 \tag{8}$$

where $Fr_t^{+}$ and $Fr_t^{-}$ are positive and negative fossil fuels price returns, respectively: $Fr_t^{+} = \max(Fr_t, 0)$ and $Fr_t^{-} = \min(Fr_t, 0)$. Thus, the coefficients $\beta_1^{+}$ *and* $\beta_2^{-}$ are the coefficients associated with increases and decreases in prices of the selected fossil fuel. In this case, there would not be evidence of asymmetry if the two coefficients are not significantly different from each other, which is tested by looking at the significance of the coefficients through the implementation of the Wald test.

#### 3.2.1 Causality Tests

The analysis is complemented by implementing the Granger causality test on the return series to identify the existence of unidirectional or bidirectional effects running from each power market and oil, gas and coal. The traditional Granger causality test based on the bidirectional VAR model is also used, as the causality test runs on the asymmetric specification to cross-check our results and identify the potential existence of significant changes among power markets and their relationship with fossil fuels. In addition, the analysis is enhanced with the estimation of causality in mean and causality in variance tests. The presented econometric framework is appropriate and more than justified given the complexities associated with power markets and the requirement of a variety of results that help verify if market dynamics are consistent, especially considering that the study is developed around a period of significant uncertainty.

$$Pr_t = \alpha + \beta' Fr_t + \varepsilon_t \tag{9}$$

$$h_t = \omega + \alpha \varepsilon_{t-1}^2 + \beta h_{t-1} \tag{10}$$

The simplest form of GARCH (p, q) model is identified as the GARCH (1, 1) specification is used in this paper to run an alternative Granger causality in mean and variance as per the approach developed by Cheung and Ng (1996), who propose the estimation of the univariate GARCH model for the stationary variables in order to get the conditional means and variances. The standardised residuals are obtained from the GARCH model, and the sample residual cross-correlation functions are derived from testing for causality. Overall, the combination of different causality tests offers the opportunity to cross-check findings and identify consistency or potential divergencies in markets performance and causal relationships of interest when understanding market dynamics in the selected European power markets. This also allows us to control for potential noise due to major shifts in market dynamics derived from the Global Financial Crisis and Fossil Fuel Shock clashes.

## 4 EMPIRICAL FINDINGS

The general correlation analysis presented in Table 2 below shows that correlations between natural gas, coal, oil, and electricity prices are positive, except for the case of oil and NordPool, which show a marginal negative relationship. It is also interesting to note the very low correlation (0.029) between oil and Phelix. Overall, the correlation coefficients for the period under study showed relatively low outcomes except for coal and gas in the context of the British energy market. The connection between oil and gas can be explained by oil-indexation contracts that have contributed to keeping European gas prices high[4]. On the other hand, an indirect impact on this market can be attributed to fundamental drivers, such as population growth and economic development, which generally lead to more robust demand for both fuels. The fact that a positive correlation is being recorded between oil and gas does not necessarily imply the existence of a causal link, and further analysis is required to establish the connection between both markets.

**Table 2: Prices Correlations**

| | Coal | Gas | Brent | NordPool | APXUK | Phelix |
|---|---|---|---|---|---|---|
| **Coal** | 1 | | | | | |
| **Gas** | 0.488 | 1 | | | | |
| **Brent** | 0.532 | 0.666 | 1 | | | |
| **NordPool** | 0.303 | 0.232 | -0.013 | 1 | | |
| **APXUK** | 0.656 | 0.670 | 0.413 | 0.356 | 1 | |
| **Phelix** | 0.437 | 0.275 | 0.029 | 0.382 | 0.533 | 1 |

Notes: *Correlations are positive in most of the cases except for Brent and NordPool. This situation is justified by the low representation of oil as a fuel used in the electricity generation process in the Nordic region.

The correlation between oil and coal are not primarily based on a cause-and-effect relationship, but the underlying price drivers for both are similar, most notably economic development. In fact, a decoupling of coal prices from oil and gas prices has been observed since 2011 with a remarkable shift taken place after 2013 (Market Observatory for Energy, 2013; Cai and Wu, 2020). Furthermore, coal is also a leading primary energy resource that has decreased its correlation with natural gas and oil since 2011. Coal remains a vital energy resource in Europe as it plays a significant role in the electricity generation process of countries like the UK and Germany.

We now turn to the estimation of a VAR(p,q) model to identify the optimal number of lags that should be used to support the causality analysis. The analysis starts with examining the stationarity properties of the series to ensure that the selected models would not lead to the generation of spurious results. The Chow and Bai-Perron Multiple Break tests were also applied to identify if the series were affected by structural changes over the period under study. The results show evidence of significant structural breaks affecting the series. The Chow and Bai-Perron tests showed that at least each one of the pairs was affected by more

[4] Natural Gas prices are directly impacted by oil prices due to oil-indexation of long-term contracts of gas that in the case of Europe the practice of oil-indexed contracts will vary across countries and seem to be a particular price driver in Central and Easter European countries. However, care is needed in terms of oil-indexation as this theory is subject to significant criticism, indicating that oil indexation showed a coupling relationship before 2013 with a mixed relationship after this year (Cai and Wu, 2020).

than five breaks. The excessive number of breaks adds substantial difficulties in terms of stability properties, and they show initial signs of market unpredictability over the selected years of study. Consequently, it was deemed appropriate to test the series for unit roots using several alternate tests to ensure robustness and the consistency of our results (see tables 3, 4 and 5 below).

**Table 3: Lag Structure (Schwarz Information Criterion)**

| Lag Structure | NordPool | APXUK | Phelix |
|---|---|---|---|
| **Coal** | Lags (0) | Lags (3) | Lags (3) |
| **Gas** | Lags (0) | Lags (4) | Lags (3) |
| **Brent** | Lags (1) | Lags (3) | Lags (3) |

Notes: *The Hannan-Quinn and Schwarz information criterion were considered to identify the optimal number of lags.

**Table 4: Bai-Perron Multiple Breakpoint Test**

| | NordPool | APXUK | Phelix |
|---|---|---|---|
| **Coal** | >5 breaks | >5 breaks | >5 breaks |
| **Gas** | >5 breaks | >5 breaks | >5 breaks |
| **Brent** | >5 breaks | >5 breaks | >5 breaks |

*Notes: The breakpoint test helped identify a significant number of shocks affecting the series under study., that needs to be considered as the cointegration and causal framework is developed.

**Table 5: Unit Root Tests**

| | Levels | | | | | First Differences | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ADF | DF-GLS | PP | KPSS | Unit Root with Break | ADF | DF-GLS | PP | KPSS | Unit Root with Break |
| **Coal** | 1.97 | 1.32 | 1.69 | 0.4 | 3.49 | 45.02* | 10.78* | 45.09* | 0.26* | 47.57* |
| **Gas** | 2.32 | 1.93 | 2.18 | 1.83 | 30.9* | 45.01* | 6.44* | 45.01* | 0.045* | 47.29* |
| **Brent** | 1.7 | 1.29 | 1.68 | 2.64 | 2.7 | 39.49* | 7.48* | 39.45* | 0.078* | 39.97* |
| **NordPool** | 4.51* | 3.59 | 5.19 | 0.46 | 5.75* | 35.46* | 35.45* | 49.24* | 0.015* | 48.45* |
| **APXUK** | 3.53 | 2.51 | 15.92* | 0.3 | 4.67* | 18.89* | 0.33 | 121.43* | 0.057* | 23.93* |
| **Phelix** | 4.96* | 1.55 | 28.34* | 1.58 | 5.92* | 19.42* | 0.68 | 0.04 | 146.02 | 20.35* |

Notes: *Results that are significant at 1% level.

The results from the stationarity tests are pretty consistent, indicating that in most cases, the series returns are stable. The only case where the results appeared to be quite controversial is the case of Phelix. Phelix was identified as the most volatile market, being affected by a substantial number of breaks that is impacting on the stability outcomes, and that would need to be taken into account when interpreting the cointegration and causal results for this market.

**Table 6: Johansen Cointegration Test**

| | NordPool | APXUK | Phelix | Brent |
|---|---|---|---|---|
| **Coal** | 0.5510(No) | 0.0237**(Yes) | 0.0006*(Yes) | 0.924 (No) |
| **Gas** | 0.3801(No) | 0.1534 (No) | 0.1655(No) | 0.1200(No) |
| **Brent** | 0.6813(No) | 0.4745 (No) | 0.6938(No) | n/a |

Notes: *The Johansen cointegration test was supported by the Engle-Granger cointegration test for robustness. Overall, the outcomes showed a lack of cointegration between variables. The Johansen test indicated no evidence of cointegration, with the Johansen test being considered a more robust test than the Engle-Granger approach. As such, the ECT (Error Correction Term) term was included as part of the Causality framework only in two cases: coal-APXUK and coal-Phelix.

The cointegration tests show that APXUK and Phelix prices are cointegrated with coal prices, offering significant evidence of the existence of a long-run equilibrium relationship between the UK, the German power market and coal. This is to be expected given the relevance of this fossil fuel to these two power markets. On the other hand, there is no evidence of a short-run relationship between the prices analysed for these variables. The results show evidence of causal effects from gas prices to the British power market and from coal to the Nordic market prices in terms of short-run effects. Our research findings are quite different from those of Mjelde and Bessler (2009) and Ferkingstad et al., (2011), who found evidence of long-run relationships. This may be explained by our selected time period that focuses on the 2008 GEFC where prices long-term relationship seemed to break, and it also highlights the dynamic dimension of prices in the long and short-run (see tables 7 and 8 below).

**Table 7: Granger Causality Test**

| | NordPool | APXUK | Phelix |
|---|---|---|---|
| **Coal** | Coal →NordPool (0.0090) * | 0.6409(No) | 0.8146(No) |
| **Gas** | 0.4204(No) | Gas →APXUK (0.000) * | 0.2714(No) |
| **Brent** | 0.8256(No) | 0.5855(No) | 0.6143(No) |

Notes: *Results that are significant at a 1% level.

Most of the electricity generated in the UK is produced by burning fossil fuels with a share of the energy generation process of around 65 percent, mainly natural gas, and coal with a very small representation of oil. In Germany, around 55 percent of the energy generated is supported by fossil fuels with coal having the major weight, just below 44 percent, natural gas 10 percent, and oil less than 1 percent. Finally, in the Nordic region fossil fuels represent less than 15 percent, as power generation in the region is dominated by hydropower with a representation above 50 percent. The results show that the energy mix in the considered power markets has a significant representation from fossil fuels, notably from coal and gas. Oil has a more limited role mainly associated with indirect impacts, as only about 3 percent of all EU electricity is produced from oil products. As a result, its impact on the generation of electricity prices should be quite limited. This is confirmed by the cointegration results, which do not show evidence of long-term relationships between EU power markets for most cases. Furthermore, as gas is the major fuel in electricity generation, it is expected that electricity prices would be mainly affected by uncertainty in the price formation process in the gas market. However, the results did not confirm the existence of a long-run relationship between gas, and any of the selected European power markets, a condition that the use of hedging techniques might explain.

The analysis turns now to the asymmetric evaluation of causal relationships for volatility to differentiate between market fluctuations and their impact on the formation of electricity prices (see tables 8 to 14 below). The results indicate that only in the case of decreases in gas prices there was evidence of a causal effect running towards the British energy market with no other significant effects registered between fossil fuels and the European energy markets. The results align with Mohammadi (2009) for the US electricity prices, which did not identify any significant evidence of long-run relationships between oil and electricity prices. The results are not surprising, given the small role of oil as an input fuel to support the generation of European electricity.

**Table 8: Granger Causality Test – Asymmetric Model Estimation and Coefficients Testing**

| | brent+ | brent- | coal+ | coal- | gas+ | gas- |
|---|---|---|---|---|---|---|
| NordPool | 0.215 | -0.025 | -0.222 | -0.046 | 0.038 | 0.224 |
| APXUK | -0.155 | 0.4977 | 0.066 | 0.576 | -0.038 | -0.987(**) |
| Phelix | -0.194 | 0.45 | -1.511 | 1.08 | 0.22 | 0.07 |
| **Coefficients – Wald Test for significance** | | | | | | |
| | brent+=brent- = 0 | brent+=brent- | coal+=coal-=0 | coal+=coal- | gas+=gas-=0 | gas+=gas- |
| NordPool | 0.2496 | 0.3581 | 0.7352 | 0.6332 | 0.3054 | 0.3536 |
| APXUK | 0.2719 | 0.2065 | 0.8305 | 0.7622 | 0.071 | 0.1219 |
| Phelix | 0.4795 | 0.2983 | 0.2022 | 0.0827 | 0.5567 | 0.818 |

Notes: *Only in the case of gas decreases in prices are the results significant at 5% in the case of APXUK. There is no evidence of asymmetry if β+ and β- are not statistically different from each other. Moreover, there is no evidence of non-asymmetry and null sensitives to fossil fuel price increases and decreases if β+= β- =0. The results from the Wald test show that the coefficients are insignificant for both null hypotheses.

The results from the Asymmetric model estimation show that in the case of price decreases affecting the gas sector, only APXUK prices appeared to be affected by a causal effect. Results that are confirmed by the outcomes of the Granger Causality test, which exhibited a similar pattern. Quite interestingly, the results do not show evidence of asymmetry or null sensitivities, as the coefficients are reported as being insignificant in all the cases.

**Table 9:** Granger Causality + & - Asymmetric Model Estimation - Summary

| | brent+ | brent- | coal+ | coal- | gas+ | gas- |
|---|---|---|---|---|---|---|
| NordPool | No | No | ←* | No | No | No |
| APXUK | No | →*** | ←* | No | ←* | ←* |
| Phelix | No | No | No | No | No | ←* |

Notes: This table presents the Granger causality results. The arrows towards the left indicate a causal relationship from the selected fossil fuel toward the European Power market under consideration. The arrow towards the right shows a causal relationship from the power market toward fossil fuel under consideration. *1% significance level, **5% significance level. ***10% significance level.

**Table 10. Granger Causality + & - Asymmetric Model Estimation – Detailed Estimations**

| **Granger Causality in Mean** | **APXUK and Brent** | | **APXUK and Coal** | | **APXUK Gas** | |
|---|---|---|---|---|---|---|
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | -0.240608894 | -0.240608894 | 0.467336506 | 0.467337 | 4.155131 | 4.155131 |
| 1 | 0.037016753 | 2.183988425 | 1.457534648 | 1.022588 | 0.041644 | -0.0509 |
| 2 | -0.374794624 | -0.633911895 | -0.990198142 | -0.66167 | 1.277078 | -0.04164 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | -0.310015306 | -0.694064118 | 0.268371459 | 1.998905 | -0.28225 | 0.226728 |
| 4 | -0.300761118 | 0.0786606 | 0.883774977 | -0.54137 | 2.262649 | -0.04164 |
| 5 | -1.017960707 | 1.776804142 | -0.097168977 | 0.499726 | 0.643166 | -0.02314 |
| 6 | 2.072938166 | -0.138812824 | -1.119756777 | -0.7681 | -0.18508 | -0.05553 |
| 7 | 0.536742918 | 0.217473424 | 0.689437024 | -0.25912 | 0.86064 | 0.930046 |
| **Granger Causality in Mean** | **NordPool and Brent** | | **NordPool and Coal** | | **NordPool and Gas** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.564505483 | 0.564505483 | 2.114582013 | 2.114582 | -1.45291 | -1.45291 |
| 1 | 0.541370012 | 1.374246954 | 3.530472814 | -0.11105 | -0.20822 | 0.735708 |
| 2 | 0.893029165 | 0.402557188 | 2.452359884 | 1.08274 | 1.994278 | 0.615404 |
| 3 | 0.555251294 | 1.004079424 | 0.985571048 | 0.749589 | 0.629285 | 1.184536 |
| 4 | -1.517686872 | 0.384048812 | -0.143439918 | -0.48584 | -0.03239 | 1.563958 |
| 5 | -0.379421718 | -0.652420271 | -0.934673012 | 0.532116 | 0.657047 | -0.79123 |
| 6 | 1.600974566 | -0.115677353 | -0.009254188 | -1.14752 | 1.281705 | 0.643166 |
| 7 | 0.1573212 | -1.207671565 | 0.425692659 | -1.01333 | 1.633364 | -0.26374 |
| **Granger Causality in Mean** | **Phelix and Brent** | | **Phelix and Coal** | | **Phelix and Gas** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.240608894 | 0.240608894 | 0.175829577 | 0.17583 | -1.73053 | -1.73053 |
| 1 | -1.138265154 | 0.624657706 | 0.286879835 | -1.65187 | 0.28688 | 1.147519 |
| 2 | -0.069406412 | 0.522861636 | 0.356286247 | 1.096621 | 1.707398 | 1.101248 |
| 3 | -0.99945233 | 1.008706518 | -0.425692659 | 1.272451 | 1.406637 | -0.36091 |
| 4 | -0.504353259 | -0.027762565 | 0.365540436 | -0.26837 | 0.101796 | 2.271903 |
| 5 | 0.985571048 | -1.082740024 | -0.444201036 | 0.694064 | 0.962436 | -0.0509 |
| 6 | -0.004627094 | 0.421065565 | -0.532115824 | 0.569133 | 0.268371 | 0.14344 |
| 7 | 0.198965047 | -1.170654812 | -0.166575388 | -0.63854 | 1.277078 | -0.73108 |
| **Granger Causality in Variance** | **APXUK and Brent** | | **APXUK and Coal** | | **APXUK Gas** | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 2.022040131 | 2.022040131 | 2.438478602 | 2.438479 | 0.222101 | 0.222101 |
| 1 | 0.124931541 | 0.879147883 | 0.217473424 | 1.008707 | -0.36091 | -0.45346 |
| 2 | -0.023135471 | -0.101796071 | -0.138812824 | 0.379422 | -0.33778 | -0.25449 |
| 3 | -0.564505483 | 0.351659153 | -0.319269494 | 0.370168 | 1.452908 | 0.277626 |
| 4 | 0.985571048 | 1.277077977 | 0.328523683 | 1.540822 | -0.0509 | 1.786058 |
| 5 | -0.161948294 | -1.522313966 | 0.930045918 | -0.4951 | 2.049803 | 0.069406 |
| 6 | 1.29095926 | -0.3146424 | -0.795860189 | -0.4951 | 0.421066 | -0.89766 |
| 7 | 0.856012412 | -0.809741471 | 0.277625647 | -1.11976 | 0.54137 | -0.72645 |
| **Granger Causality in Variance** | **NordPool and Brent** | | **NordPool and Coal** | | **NordPool and Gas** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | -0.453455224 | -0.453455224 | 1.753668672 | 1.753669 | 0.161948 | 0.161948 |
| 1 | -0.953181389 | -0.620030612 | 0.277625647 | -0.73108 | 0.411811 | -0.51361 |
| 2 | -0.203592141 | -1.059604554 | -0.569132577 | -0.52286 | -0.51823 | -0.71257 |
| 3 | 0.3146424 | -0.365540436 | 0.245235988 | -0.51361 | 0.013881 | -0.49047 |
| 4 | -1.272450883 | 0.060152224 | -0.99945233 | -0.17583 | 0.101796 | 0.448828 |
| 5 | 0.476590694 | -0.689437024 | -0.097168977 | 0.39793 | 0.647793 | -0.31002 |
| 6 | -0.814368565 | 0.21284633 | -0.143439918 | -0.78661 | -0.3933 | -0.51361 |
| 7 | 0.198965047 | 0.087914788 | -0.726453777 | 0.166575 | -0.53212 | -0.40256 |
| **Granger Causality in Variance** | **Phelix and Brent** | | **Phelix and Coal** | | **Phelix and Gas** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | -1.429772083 | -1.429772083 | 0.416438471 | 0.416438 | -0.10642 | -0.10642 |
| 1 | -0.84213113 | 0.416438471 | 0.680182836 | 1.832329 | -0.04627 | -0.53674 |
| 2 | -1.23543413 | -0.092541882 | 0.055525129 | -0.47659 | 0.374795 | -0.75884 |
| 3 | -0.541370012 | 1.411263707 | -0.508980353 | 0.129559 | 1.651873 | -0.30539 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | -0.148067012 | 1.883227307 | -0.351659153 | 1.332603 | -0.07403 | 0.249863 |
| 5 | 0.731080871 | -0.994825236 | -0.569132577 | -0.00925 | -0.43957 | -0.42569 |
| 6 | -0.434946847 | -1.272450883 | -0.768097624 | 0.846758 | -0.69406 | -0.62003 |
| 7 | -1.281705071 | 0.161948294 | -0.768097624 | 0.879148 | -0.53674 | -0.24061 |

**Table 11: Causality in Mean + & - Asymmetric Model Estimation - Summary**

| | brent+ | brent- | coal+ | coal- | gas+ | gas- |
|---|---|---|---|---|---|---|
| NordPool | →*** | No | ↔*** | ←** | ←** | ↔*** |
| APXUK | ↔*** | ←*** | No | ←*** | →* | →** |
| Phelix | No | No | ↔*** | →** | ↔*** | →*** |

**Notes:** This table presents causality in mean results. The arrows towards the left indicate a causal relationship from the selected fossil fuel toward the European Power market under consideration. The around towards the right shows a causal relationship from the power market toward fossil fuels. The arrow with two ends indicates bidirectional causality. *1% significance level, **5% significance level. ***10% significance level.

**Table 12: Causality in Mean + & - Asymmetric Model Estimation – Detailed Estimation Test-Statistics**

| **Granger Causality in Mean** | **APXUK and Brent +** | | **APXUK and Coal +** | | **APXUK Gas +** | |
|---|---|---|---|---|---|---|
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0373 | 0.0373 | 0.0225 | 0.0225 | -0.0119 | -0.0119 |
| 1 | -0.0134 | -0.0035 | 0.029 | -0.0027 | 0.0995 | 0.0161 |
| 2 | 0.0159 | 0.0055 | 0.0349 | 0.0272 | -0.0086 | -0.0156 |
| 3 | -0.0289 | -0.0034 | -0.0311 | -0.0116 | 0.029 | 0.0175 |
| 4 | 0 | 0.0234 | 0.0005 | 0.0145 | 0.0084 | -0.0052 |
| 5 | 0.0073 | 0.0199 | 0.0162 | -0.006 | 0.0334 | -0.0083 |
| 6 | -0.0147 | 0.0054 | 0.0182 | -0.0092 | 0.0045 | 0.0083 |
| 7 | 0.0318 | -0.0208 | -0.0266 | -0.009 | 0.0059 | 0.0101 |
| **Granger Causality in Mean** | **NordPool and Brent +** | | **NordPool and Coal +** | | **NordPool and Gas +** | |
| **Lags** | | | | | | |
| 0 | 0.0291 | 0.0291 | 0.0041 | 0.0041 | 0.0144 | 0.0144 |
| 1 | -0.0017 | 0.0225 | 0.0653 | 0.0201 | -0.0225 | -0.0171 |
| 2 | -0.0104 | 0.0057 | 0.0661 | -0.0045 | -0.0224 | 0.0106 |
| 3 | -0.0049 | -0.0099 | 0.0368 | 0.0168 | 0.0274 | 0.045 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | 0.003 | -0.0223 | 0.0153 | 0.0435 | 0.0061 | -0.0093 |
| 5 | -0.036 | -0.0036 | 0.002 | -0.0225 | -0.0354 | -0.0117 |
| 6 | 0.0033 | -0.0265 | 0.0082 | -0.028 | -0.0176 | -0.002 |
| 7 | 0.0431 | -0.0345 | 0.0108 | -0.0008 | 0.023 | 0.0006 |
| **Granger Causality in Mean** | **Phelix and Brent +** | | **Phelix and Coal +** | | **Phelix and Gas +** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0148 | 0.0148 | -0.0573 | -0.0573 | 0.0418 | 0.0418 |
| 1 | 0.0268 | 0.0118 | 0.0285 | 0.0143 | -0.027 | 0.011 |
| 2 | -0.0194 | 0.0158 | -0.0013 | 0.0178 | -0.0093 | -0.011 |
| 3 | -0.0165 | -0.0179 | -0.0008 | 0.0202 | 0.0069 | 0.0628 |
| 4 | -0.0209 | -0.0078 | 0.0021 | 0.0368 | 0.0198 | 0.0078 |
| 5 | 0.0103 | 0.0314 | -0.0102 | 0.0141 | 0.0133 | -0.0035 |
| 6 | 0.0303 | -0.0151 | 0.0255 | -0.0365 | 0.017 | 0.0163 |
| 7 | -0.0021 | -0.0014 | -0.007 | -0.0101 | 0.015 | 0.0083 |
| **Granger Causality in Variance** | **APXUK and Brent +** | | **APXUK and Coal +** | | **APXUK Gas +** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0345 | 0.0345 | 0.0224 | 0.0224 | 0.0108 | 0.0108 |
| 1 | 0.0914 | 0.0338 | 0.0214 | 0.0144 | 0.0178 | -0.004 |
| 2 | -0.0107 | 0.0303 | 0.0142 | -0.0097 | -0.0041 | 0.0035 |
| 3 | 0.0016 | 0.0392 | -0.005 | 0.0598 | 0.0015 | 0.059 |
| 4 | -0.0199 | -0.0168 | -0.003 | -0.011 | 0.0073 | -0.0016 |
| 5 | -0.005 | -0.0187 | 0.0298 | -0.0083 | 0.0264 | -0.0061 |
| 6 | -0.0188 | -0.0292 | 0.0285 | -0.0203 | 0.023 | -0.0042 |
| 7 | 0.0062 | -0.0283 | -0.0045 | -0.0192 | 0.0283 | 0.004 |
| **Granger Causality in Variance** | **NordPool and Brent +** | | **NordPool and Coal +** | | **NordPool and Gas +** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0087 | 0.0087 | -0.0117 | -0.0117 | -0.0051 | -0.0051 |
| 1 | -0.0121 | -0.0136 | 0.032 | -0.007 | -0.0019 | -0.0073 |
| 2 | -0.0102 | 0.01 | -0.0019 | -0.0188 | 0.0171 | -0.0115 |
| 3 | 0.0061 | -0.013 | -0.0042 | -0.0055 | -0.0134 | -0.0012 |
| 4 | 0.0283 | -0.0062 | 0.0188 | -0.0029 | -0.0089 | -0.0122 |
| 5 | -0.0273 | -0.001 | -0.0166 | -0.0112 | -0.0024 | -0.0102 |
| 6 | 0.0204 | 0.012 | -0.0086 | -0.0025 | 0.0193 | -0.0113 |
| 7 | -0.0079 | 0.0208 | -0.0021 | -0.0132 | -0.0085 | -0.0092 |
| **Granger Causality in Variance** | **Phelix and Brent +** | | **Phelix and Coal +** | | **Phelix and Gas +** | |

| Lags | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
|---|---|---|---|---|---|---|
| 0 | -0.0079 | -0.0079 | 0.0388 | 0.0388 | -0.0129 | -0.0129 |
| 1 | -0.0196 | -0.0062 | 0.0127 | -0.0118 | 0.0049 | -0.0124 |
| 2 | -0.0134 | 0.0924 | -0.0044 | 0.0024 | 0.0004 | -0.0038 |
| 3 | -0.0173 | 0.0028 | 0.0112 | 0.0007 | 0.0292 | -0.0008 |
| 4 | -0.0113 | -0.0128 | -0.0052 | 0.0018 | 0.0178 | -0.0057 |
| 5 | -0.0135 | -0.0063 | -0.0052 | 0.0279 | -0.0001 | -0.0094 |
| 6 | 0.0022 | 0.0108 | -0.0089 | -0.0003 | 0.0014 | -0.0069 |
| 7 | -0.0042 | -0.0031 | -0.0141 | -0.0077 | -0.0057 | -0.0161 |

**Table 13: Causality in Variance + & - Asymmetric Model Estimation - Summary**

| | brent+ | brent- | coal+ | coal- | gas+ | gas- |
|---|---|---|---|---|---|---|
| NordPool | No | No | No | No | No | →** |
| APXUK | ↔*** | →* | ←* | →** | ←* | ↔*** |
| Phelix | ←* | ←*** | ↔*** | No | No | →*** |

**Notes:** This table presents causality in variance results. The arrows towards the left indicate a causal relationship from the selected fossil fuel toward the European Power market under consideration. The around towards the right shows a causal relationship from the power market toward the fossil fuel under study. The arrow with two ends indicates bidirectional causality. *1% significance level, **5% significance level. ***10% significance level.

**Table14. Causality in Variance + & - Asymmetric Model Estimation – Summary Test Statistics**

| Granger Causality in Mean | APXUK and Brent - | | APXUK and Coal - | | APXUK Gas - | |
|---|---|---|---|---|---|---|
| Lags | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.034 | 0.034 | 0.0102 | 0.0102 | -0.0114 | -0.0114 |
| 1 | -0.0001 | -0.0172 | -0.0176 | -0.0115 | 0.045 | -0.0184 |
| 2 | -0.0097 | -0.0328 | 0.0119 | 0.0408 | 0.0246 | 0.0184 |
| 3 | 0.0163 | 0.0043 | 0.0006 | -0.0213 | 0.0196 | -0.0266 |
| 4 | -0.0104 | 0.0407 | 0.0003 | 0.0028 | -0.0262 | -0.0176 |
| 5 | -0.0239 | -0.0256 | 0.0153 | -0.0203 | 0.0474 | 0.0044 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 6 | -0.0192 | 0.0026 | -0.0338 | -0.0032 | 0.0029 | 0.0194 |
| 7 | 0.0389 | -0.0011 | -0.0034 | 0.0196 | -0.0149 | -0.022 |
| **Granger Causality in Mean** | **NordPool and Brent -** | | **NordPool and Coal -** | | **NordPool and Gas -** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0256 | 0.0256 | -0.0022 | -0.0022 | 0.016 | 0.016 |
| 1 | 0.0189 | -0.0097 | 0.0002 | 0.0032 | -0.0182 | 0.0277 |
| 2 | 0.0242 | 0.0313 | 0.0629 | 0.0247 | 0.0095 | 0.0095 |
| 3 | 0.0356 | 0.0186 | 0.0491 | -0.0439 | 0.0755 | 0.0005 |
| 4 | 0.0166 | -0.0065 | 0.0166 | -0.0228 | 0.0188 | -0.0311 |
| 5 | -0.0216 | -0.003 | -0.0014 | -0.0162 | 0.0325 | 0.0405 |
| 6 | -0.0182 | -0.023 | -0.037 | -0.0139 | 0.0569 | -0.0038 |
| 7 | 0.0101 | 0.0174 | -0.0127 | 0.0118 | 0.0113 | -0.0013 |
| **Granger Causality in Mean** | **Phelix and Brent -** | | **Phelix and Coal -** | | **Phelix and Gas -** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.013 | 0.013 | 0.0155 | 0.0155 | 0.0062 | 0.0062 |
| 1 | -0.0185 | 0.0043 | -0.0325 | 0.0146 | -0.0408 | 0.0146 |
| 2 | -0.0273 | 0.0182 | 0.0196 | 0.0297 | 0.0169 | -0.0047 |
| 3 | 0.0147 | 0.01 | 0.0181 | -0.0426 | 0.0353 | 0.0053 |
| 4 | -0.014 | -0.0345 | -0.02 | -0.014 | 0.0118 | -0.0304 |
| 5 | -0.0293 | -0.0195 | 0.0234 | 0.0021 | 0.0063 | -0.0048 |
| 6 | 0.0067 | -0.0242 | -0.0419 | 0.0147 | 0.0199 | -0.023 |
| 7 | -0.002 | 0.0062 | -0.0123 | 0.0204 | -0.0238 | -0.028 |
| **Granger Causality in Variance** | **APXUK and Brent -** | | **APXUK and Coal -** | | **APXUK Gas -** | |

| Lags | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
|---|---|---|---|---|---|---|
| 0 | 0.009 | 0.009 | 0.0148 | 0.0148 | -0.0298 | -0.0298 |
| 1 | -0.0005 | -0.0213 | 0.0451 | 0.0056 | 0.0363 | 0.0085 |
| 2 | 0.0029 | -0.0077 | -0.009 | 0.0218 | 0.0024 | -0.002 |
| 3 | -0.0073 | 0.006 | 0.0044 | 0.0021 | 0.0139 | -0.0012 |
| 4 | -0.0077 | -0.03 | -0.0118 | -0.0049 | 0.0115 | 0.0376 |
| 5 | 0.0554 | 0.0133 | -0.0211 | -0.0098 | 0.0039 | -0.0183 |
| 6 | 0.0235 | 0.0078 | 0.0019 | -0.0138 | 0.0245 | -0.0029 |
| 7 | 0.0141 | -0.0037 | -0.0227 | -0.0196 | -0.0115 | 0.0046 |
| **Granger Causality in Variance** | **NordPool and Brent -** | | **NordPool and Coal -** | | **NordPool and Gas -** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | -0.013 | -0.013 | -0.0071 | -0.0071 | -0.0024 | -0.0024 |
| 1 | -0.0124 | -0.0179 | 0.0209 | -0.0102 | 0.0126 | -0.0155 |
| 2 | -0.0154 | -0.0129 | 0.0064 | 0.0098 | -0.0119 | -0.0038 |
| 3 | -0.0083 | 0.0085 | -0.017 | 0.0057 | -0.0125 | 0.0196 |
| 4 | -0.0177 | -0.0121 | -0.0118 | 0.0232 | 0.0447 | 0.0292 |
| 5 | -0.0022 | 0.0112 | -0.0143 | -0.0143 | 0.0015 | -0.0002 |
| 6 | 0.0061 | -0.0117 | 0.002 | 0.0051 | -0.0096 | -0.0077 |
| 7 | -0.0221 | -0.0043 | -0.0053 | -0.0051 | -0.0062 | 0.01 |
| **Granger Causality in Variance** | **Phelix and Brent -** | | **Phelix and Coal -** | | **Phelix and Gas -** | |
| **Lags** | Lag-stat | Lead-stat | Lag-stat | Lead-stat | Lag-stat | Lead-stat |
| 0 | 0.0082 | 0.0082 | 0.0057 | 0.0057 | 0.0059 | 0.0059 |
| 1 | -0.023 | -0.0046 | 0.005 | -0.0013 | -0.013 | -0.0107 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2 | -0.017 | -0.0019 | 0.0238 | -0.0038 | 0.0028 | -0.0072 |
| 3 | -0.0217 | 0.0372 | 0.007 | 0.0348 | 0.0113 | 0.0333 |
| 4 | -0.0103 | -0.0121 | -0.0118 | -0.0024 | 0.0396 | 0.0045 |
| 5 | 0.0067 | -0.0164 | -0.0106 | -0.0035 | 0.0056 | -0.008 |
| 6 | 0.0106 | -0.0211 | -0.0073 | 0.0207 | -0.0128 | -0.0125 |
| 7 | -0.0068 | 0.0081 | -0.011 | -0.0126 | -0.0235 | -0.0195 |

The results outlined in the tables above outlines the outcomes for the asymmetric model estimation (tables 8 to 14). The core findings show evidence of causal effects in the case of APXUK being affected by increases in coal prices and also by upward and downward variations in the gas market. Coal price increases also have a causal effect in the Nordic market, and as do gas price decreases in the Phelix market. To summarise, these results indicate the lack of impact of oil prices fluctuations in the European power markets, with only APXUK showing a causal effect. The results also show evidence of the limited effect that fossil fuels variations have in the Nordic region. However, the outcomes for the causality in mean and variance estimation show conflicting results where oil price increases have a bi-directional impact in the case of APXUK and Phelix with no significant consequences for the Nordic region. In the case of coal price variations, they are found to have a causal effect on NordPool and Phelix, with only price decreases having a short impact on the case of APXUK. Finally, the gas market seems to have a significant effect on APXUK and NordPool but not in the case of Phelix. These results are not surprising as gas does not have a substantial weight in the German power market, which is dominated by the use of coal (Ferkingstad et al., 2011).

### 4.1 Comparison of fossil fuels causal effects on each European power market

Bunn and Fezzi (2007) findings show that the British power market is strongly related to gas and coal prices, which are confirmed by this study in the context of the causal in mean and variance asymmetric model. The findings are not surprising as coal has a heavy influence on the European electricity sector except for the Nordic energy markets. Furthermore, Panagiotidis and Rutledge (2007) find evidence of a long-run equilibrium relationship between the UK gas and oil prices, finding that the series were also cointegrated over their studied period (1996-2003). In our case, our results differ regarding the UK electricity market and its connection to the oil market. The results are not unexpected due to the insignificant role of oil in the generation of electricity in Europe, and also due to the low impact that oil-indexation practices have in the analysed markets. Mjelde and Bessler (2009) find that peak electricity prices move natural gas prices, which in turn influence crude oil prices. Our research findings show consistency in this regard, as natural gas prices showed causal effects in the APXUK, NordPool, and in the Phelix case, where results are supported by the causality in mean and variance models.

Overall, our main research findings confirm the importance of coal and gas prices given their causal effects in the European context, and they reaffirm the limited impact of oil prices in the generation of electricity prices. However, researchers, policymakers and practitioners need to be aware of those factors that could reinforce the impact of oil prices on European electricity prices. There are some factors that need to be considered carefully. The first one relates to gas production levels, prices, and costs. Production capacity is increasing globally while the European region is facing a reduction in supply capacity. On the other hand, price controls on gas are weakening and, in some instances, being eliminated, as is the case for electricity prices. The second issue of interest relates to the high share of network charges and taxes in retail gas and electricity prices that limit access to energy generation resources. The third point of interest refers to the implications that episodes that lead to the weakening of the Euro and other European currencies could have, and that combined with the increased global and European demand for gas, brings significant challenges regarding resources affordability. The fourth issue to be considered relates to reducing energy efficiencies and the development and use of renewable energy resources that will impact the demand for fossil fuels and weaken the potential effects of oil prices on electricity prices by reducing fossil fuel consumption levels.

## 5 CONCLUSIONS

Despite the importance of fossil fuels in the generational mix for European markets, little research has been done in this area. We address this research gap by analysing causal effects running from fossil fuels toward three major European electricity markets. Our research motivation is supported by the vital role that energy prices play in the global economy, as increases in energy prices are associated with economic recessions, high levels of unemployment, and inflationary pressures (Balaz and Londarev, 2006; Kilian and Park, 2009). The study is supported by econometric models that look at the long and short-run relationships between coal, gas and oil and three European electricity markets: APXUK, NordPool, and Phelix. Our key findings are that each of the three fossil fuels, particularly gas and coal, has significant causal relationships for both the APXUK and Phelix markets. This is particularly the case for the APXUK market. We also find that asymmetric fuel price shocks have differentiated effects on the European electricity markets. In the case of NordPool there is no evidence of causal effects from any of the energy fuels analysed. The research findings show that fossil fuels play a significant role in the generation of electricity in the European context and that the differentiation between price changes when markets are affected by shocks is needed. They also point toward the need to avoid treating similar energy markets as homogenous. Further research could address how energy markets are affected by prominent economic and financial shocks, and include a rolling window or spectral causality approach that would bring additional insights into markets' interlinkages and variation of their dynamics.

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