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The Relationship Between Liquefied Petroleum Gas and Crude Oil Prices: A Case Study of the Polish Fuel Market*

Zależność pomiędzy cenami gazu płynnego a ropy naftowej – studium przypadku polskiego rynku paliw

Abstract

This study investigates the interdependence between LPG and crude oil prices by leveraging the Seasonal Auto-Regressive Integrated Moving Average time series model with exogenous variables (SARIMAX model). Three scenarios are considered, incorporating price indices for the Western Index, Eastern Index, and Total Index, which is calculated as a weighted average of the two preceding indices. The study focuses on Poland, which, during the analysed period, was heavily dependent on energy resource supplies from Russia. The findings of the econometric analysis show that: (1) there is a strong and statistically significant association between changes in oil prices and changes in gas prices for imports to Poland regardless of their source; (2) this relationship is strongest for the Western Index; (3) weekly LPG price changes adjusted for the relationship between oil and LPG prices do not exhibit a particularly long memory or seasonality; and (4) the Eastern Index is characterised by a fairly high elasticity with respect to the past (short-term) dynamics of current LPG prices. Thus, the conflict in Ukraine and the resulting decline in LPG imports from Russia are unlikely to result in long-term market instability in Poland.

Streszczenie

W niniejszym artykule zbadano współzależność między cenami LPG i ropy naftowej, wykorzystując model szeregów czasowych Seasonal Auto-Regressive Integrated Moving Average ze zmiennymi egzogenicznymi (model SARIMAX). Rozważono trzy scenariusze uwzględniające indeksy cen dla indeksu zachodniego, indeksu wschodniego i indeksu całkowitego, który jest obliczany jako średnia ważona dwóch poprzednich indeksów. Badanie koncentruje się na Polsce, która w okresie analizy była silnie uzależniona od dostaw surowców energetycznych z Rosji. Wyniki analizy ekonometrycznej pokazują, że: 1) istnieje silna i statystycznie istotna zależność między zmianami cen ropy a zmianami cen gazu dla importu do Polski ze wszystkich kierunków; 2) zależność ta jest najsilniejsza w przypadku

Słowa kluczowe:
ceny ropy naftowej, gaz płynny, rynek paliw, zależność cenowa LPG

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indeksu zachodniego; 3) tygodniowe zmiany cen LPG skorygowane o związek między cenami ropy naftowej a cenami LPG nie wykazują szczególnie długiej pamięci ani sezonowości; 4) indeks wschodni charakteryzuje się dość dużą elastycznością względem przeszłej (krótkookresowej) dynamiki aktualnych cen LPG. Tak więc konflikt na Ukrainie i wynikający z niego spadek importu LPG z Rosji prawdopodobnie nie spowodują długoterminowej niestabilności rynku w Polsce.

Introduction

As a result of Russia's invasion of Ukraine, European countries, which rely heavily on the supply of energy resources from the east, have been forced to explore other options. In this context, determining the potential impact on the Polish market of a shift away from liquefied petroleum gas (LPG) imports from Russia has gained importance, and the findings of this study are relevant for energy policy across the entire Central and Eastern Europe (CEE) region, especially given the volatility of natural resource commodity prices and the economic uncertainty triggered by the COVID-19 pandemic [**Liu, Chen, 2022**]. The primary aim of this study is to explore the relationship between LPG and oil prices and to demonstrate that price fluctuations are driven by short-term economic shock factors such as armed conflicts, changes in supplier structures, temporary disruptions in production, and broader market conditions. In periods of economic turmoil or crisis, the relationship between policy uncertainty and energy prices becomes stronger [**Dash, Maitra, 2021**], and managing the risk associated with gas price volatility becomes particularly important [**Chiou-Wei et al., 2020**].

The proposed analysis examines whether these factors distort the relationship between LPG and crude oil pricing in the short or long run. This relationship was previously studied using a wavelet analysis method based on index returns and more directly on price levels [**Hung, 2020**]. Other papers on direct LPG modelling include **Yeboah** [**2015**], who employed the ARIMA (1,1,1) process to capture LPG demand dynamics in Ghana, a country classified as a small open economy. **Arfaoui** [**2018**] examined the relationship between spot and futures prices for crude oil and refined products using the ARDL model. Price cycles in the Perth area of western Australia were found to be substantially longer and more asymmetric than gasoline price cycles in the same market [**Isakower, Wang, 2014**]. Apart from the price of crude oil, the increase in shale gas production [**Brehm, 2019**; **Oglend et al., 2016**] and the construction of natural gas networks [**Boslett, Hill, 2019**; **González, Lagos, 2021**] stand out among the studied LPG price factors. Nonetheless, the literature emphasises that the fundamental predictor of LPG prices is the price of crude oil [**Bai, Lam, 2019**; **Ederington et al., 2019**; **Khan et al., 2023**; **Oglend et al., 2015**]. The SARIMAX econometric time series model was used to demonstrate the relationship between LPG and oil prices. In the study discussed here, the following three indices were considered in detail:

1. The western index based on Argus CIF ARA L C3 and Argus CIF ARA L C4 expressed in US dollars per metric tonne;
2. The eastern index equal to the Argus Daf Brest propane-butane mix, which accounted for about 70% of total crude imports to Poland, and
3. The total index calculated as a weighted average of the two previous indices, where the weights reflect the import structure (with 25% of imports assumed to come from the north-west).

Weekly average values of these indices, which directly inform the variables employed in the model, were derived based on the indices influencing the price of LPG from the eastern and north-western directions respectively. The study focused on data covering weekly averages for 284 observations (the quantitative analysis includes daily readouts from 3 January 3, 2017 to 31 May 2022).

The principal contribution of this paper lies in the application of the SARIMAX model to examine the relationship between crude oil and LPG prices on the Polish market, enabling the quantification of both the strength and direction of the impact of oil prices on derivative products such as LPG. To date, the proposed SARIMAX model has not been applied to the analysis of the specified indices.

In addition to capturing autoregression and seasonal price fluctuations, it enables us to model the relationship between crude oil and LPG prices. Moreover, the analysis utilises data for two different delivery points (east and west) and extends the analysis to include a third variant corresponding to the total index. Such a variant-based analysis using the SARIMAX model can provide important and practical conclusions for policy makers, particularly in the areas of shaping energy policy and ensuring the country's energy security. The added value of this study also lies in conducting such an analysis for a country with a unique geopolitical context. Poland's strong prewar dependence on Russian energy and its direct border with Russia justify a separate, country-specific investigation, which has not yet been undertaken.

The paper begins with a literature review, which is divided into two parts: LPG use in Poland and worldwide, and a brief report on similar recent econometric research. Following that, the methodology section justifies the selection of indices, defines the scope of the analysis, and covers the implementation of the SARIMAX time series model. The findings of the estimation for the total index for Poland are discussed in the following section, while the concluding section offers final remarks about energy policy in Poland and the wider CEE region.

Literature review

The LPG market in Poland and worldwide

LPG is a co-product of crude oil refining or is obtained during natural gas extraction [**Engelen, Dullaert, 2010**]. The growth of the LPG market has tended to coincide with fuel crises [**Buczaj, 2013**], for example periods when oil production does not meet demand [**Socha, Wdowiński, 2018**]. LPG, as a low-carbon energy source, is becoming increasingly important in worldwide energy use [**Peng et al., 2020**] since it burns effectively, is easy to use, and can help reduce emissions [**Amegah, Jaakkola, 2016**; **Tuan, Dong, 2022**; **Woo Jeong et al., 2024**]. However, since LPG is a fossil fuel, its use will not result in complete decarbonisation. In the BRICS-T countries, despite the positive impact of LPG on the ecological footprint, it is also said to have an adverse impact on CO_2 emissions [**Tekin, Dirir, 2024**]. As a result, it can only be considered as stopgap solution. According to **Bruce et al.** [**2017**], using LPG instead of solid fuels can improve not only people's health, but also the environment, notably forests. Additionally, it can reduce household emissions and promote economic growth [**van Leeuwen et al., 2017**; **Williams et al., 2020**]. It has already been shown that sustainable economic practices have a positive impact on CO_2 emissions [**Zemri, Khetib, 2024**]. In keeping with the UN Sustainable Energy for All Initiative, increasing household LPG use charts one of the several possible paths to achieving universal access to clean cooking and heating solutions by 2030 [**Kojima, 2011**; **Sharma et al., 2019**], as it enables significant reductions in PM2.5 emissions, in contrast with other sources of energy used for these purposes [**Grieshop et al., 2011**]. Research conducted in India shows that if households used only LPG, the country's primary energy consumption would be reduced by almost 3.5% [**Guta et al., 2024**].

The data on the structure of the LPG market, imports and exports presented below are based on the latest report by the Polish LPG Organisation [**POGP, 2022**]. In 2021, total LPG consumption in Poland exceeded 2,435,000 tonnes, of which 2,160,000 were imported. In 2021, Poland sourced most its LPG from Russia (1,257,000 tonnes), which shows how dependent it was on imports from that country. In 2021, Poland's largest trading partners for LPG were Sweden, Lithuania, Belarus and the United Kingdom. The data show that purchases from Russia are being replaced by supplies from Sweden (imports increased from 47,000 tonnes in 2018 to 437,000 tonnes in 2021). There is also a noticeable tendency to switch to supplies from other Western European countries. The share of Poland's LPG imports from the European Union increased from about 28% in 2020 to nearly 33% in 2021. Poland also exports a fair amount of LPG, with 225,000 tonnes exported in 2021, mostly to Germany, Hungary, the Czech Republic, and Slovakia. Poland's LPG market structure comprises autogas (74.5%), heating fuel (14.6%), and cylinders for off-grid home use (10.9%). LPG is also extensively used by the municipal sector (10.5%), the industrial sector (7.4%), and for agricultural purposes (4.9%).

Unlike in Poland, LPG is used around the world to heat houses rather than as a vehicle propellant. The Asia-Pacific region is by far the largest consumer of LPG for this purpose, accounting for 57% of global consumption, compared with 12% in North America, 12% in Latin America, and only 6% in the Europe and Eurasia region [**Morgan, 2021**]. Globally, the largest user of LPG is the municipal sector (44%), followed by the chemical sector (28%), manufacturing (10%), refining (9%), and transport (8%). The pattern is slightly different for the Europe and Eurasia region, where the chemical sector consumes the most LPG with over 40%, followed by the transport sector at around 28%, the municipal sector at over 18%, the industrial sector at around 10%, and the refining sector at around 0.5% [**POGP, 2022**]. LPG meets the heating needs of more than 20 million EU citizens and 700,000 companies mainly in areas inadequately served by the natural gas grid. Moreover, LPG powers a fleet of more than 15 million vehicles and serves a network of 47,000 stations across Europe [**Liquid Gas Europe, 2021**]. The findings of experimental studies – both laboratory and real-world road tests – show that LPG produces lower CO_2 and particulate matter emissions compared with petrol. Moreover, all emissions were found to comply with the Euro 6 standards [**Bellin et al., 2022**]. Therefore, LPG and BioLPG constitute an alternative to fossil fuels in the EU [**Montuori, Alcázar-Ortega, 2024**].

The largest LPG producers in the world are the United States (87,442,000 tonnes), China (44,286,000 tonnes), and Saudi Arabia (26,420,000 tonnes) [**POGP, 2022**]. In 2020, Russia was the largest producer of the commodity in Europe and Eurasia (16,280,000 tonnes), followed by Norway (5,100,000 tonnes), and the UK (3,739,000 tonnes) [**POGP, 2022**]. The leading consumers of LPG are China, the USA and India. Poland is the eighth-largest LPG consumer in the Europe and Eurasia region [**POGP, 2022**].

Energy consumption, in terms of both quantity and quality, is a major indicator of economic growth [**Peng et al., 2020**] as well as pollution [**Murshed, Alam, Ansarin, 2021**]. For obvious reasons, this is particularly true of fossil fuel-based economies [**Ali et al., 2021**; **Asongu et al., 2020**]. Therefore, increasing the share of low-carbon fuels in their energy mix supports economic development while mitigating the negative environmental impacts [**Murshed, Ali, Banerjee, 2021**]. In countries where coal is the main source of power and heat, the transition to a zero-carbon economy may pose a considerable challenge in terms of the population's standard of living. **Dong et al.** [**2018**] showed that, under such circumstances, CO_2 emissions can be reduced by switching to natural gas, which is less harmful to the environment [**Peng et al., 2020**]. A study conducted in Bangladesh showed that a 1% increase in LPG use in a natural gas constrained situation can effectively reduce per capita CO_2 emissions and overall greenhouse gas emissions by 0.13% and 0.19% respectively in the long term [**Murshed, Alam, Ansarin, 2021**].

Research to date and model selection rationale

The empirical literature that explores the associations between LPG and crude oil pricing is not extensive. **Hung** [**2020**], who examined the weekly averages of the Propane Argus Far East Index (PAFEI), the Propane CP swap (PCPS), and the Propane Mt Belvieu (PMB) from January 2006 to March 2018, investigated the prices of LPG considered as one of the so-called propane-based goods. Crude oil prices are most likely to contribute, in a Granger sense, to the price of LPG products, according to the wavelet analysis based on index returns and directly on price levels in the short and medium terms (2–8 and 8–32 weeks respectively). Meanwhile, in the long term (32–128 weeks), propane product prices unidirectionally influence Brent crude pricing trends. Depending on the index and timescale used, the Granger causality test for wavelet analysis yields slightly different results. Additionally, it should be highlighted that, contrary to what is expected in econometric studies, the distinction between the short and long term was determined ex-post on the basis of results obtained for specified frequencies.

Other studies that look at the links and causality between changes in oil and propane pricing find that the overwhelming direction is from oil prices to derivative product prices [**Bai, Lam, 2019**; **Socha, 2014**]. Far fewer papers suggest that changes in propane prices induce changes in oil prices [**Caporin et al., 2019**], implying that the prices of oil products affect the pricing of oil. These analyses were carried out with quarterly or lower-frequency data [Ederington et al., 2019]. Asche et al. [2003] conducted a monthly data study to determine the relationship between the prices of Brent crude oil (US$ per barrel) and four of its principal derivative products (US$ per metric tonne) quoted on the Rotterdam market. Spot prices were examined since they involve physical delivery of the goods and thus reduce the impact of speculative swings on the futures market. The key result concerns the direction of the impact of crude oil prices on the prices of its products, which were weakly exogenous to oil product prices.

Oglend et al. [2013] examined the impact of extra LPG supply gained from shale gas production on the historically high effect of the oil price on propane and butane pricing. The previously evident causal relationship diminished by the arrival of relatively cheaper LPG obtained from shale gas, and the price differential expanded. For monthly data, Westgaard [2008] employed time series models with unobservable components paired with stochastic trend and seasonality for propane, butane and paraffin traded on the northern European market. The findings show that petroleum product prices can be described by stochastic processes in which the coefficients vary continuously and unpredictably over time, while the seasonal patterns appear to be constant. This implies random erring with fixed seasonal parameters for the time series, resulting in high forecasting uncertainty. Yeboah [2015] used the ARIMA (1,1,1) process to capture LPG demand dynamics in Ghana, a country ranked as a small open economy, whereas Arfaoui [2018], using the ARDL model, examined the relationship between spot and futures prices for crude oil and processed products from January 2007 to April 2015. He discovered long-run equilibrium links between crude oil and associated product prices by focusing on long-run and short-run elasticities and causation as well as the shape of the VEC. Increased shale gas production, which resulted in greater output of derivative LPG, was one of the causes contributing to the weakening of the LPG/crude oil association [Oglend et al., 2016]. The development of natural gas grids, which results in an average reduction of LPG retail prices by 2–4% [González, Lagos, 2021], is another factor that contributes to a decrease in LPG prices in a given market.

Another research question involves the degree to which LPG prices respond to changes in the direction of oil prices. Do LPG prices react more strongly and quickly when crude oil prices rise, and less strongly and more slowly when they fall? These relationships are especially important in crisis situations, as they determine the path of return to equilibrium following a shock. LPG prices may react differently depending on the geographical location. The frequency of empirical data collection and the analytical timeframe may also be relevant for assessing the interdependence of oil and LPG prices. In Poland, no studies on the relationship between Brent crude oil and LPG prices have been conducted so far. Determining whether the direction and strength of the impact are currently maintained is critical for trade, market organisation, and forecasting the future pricing trends, because if there was a strong relationship between LPG and oil prices in the past, it is likely to continue in the future, despite economic shocks.

Research methods

Rationale for the choice of indices

Following Russia's invasion of Ukraine, European countries that relied heavily on Russian energy fuels were forced to reconsider their import structures. The war has raised questions about future energy commodity pricing, which are now the subject of broad public debate, although the interconnectedness of the European gas market has increased since 2015 [Papież et al., 2022]. In its communication of 3 June 2022, the Council of the European Union announced the adoption of a sixth package of sanctions banning the import and transfer of oil and selected petroleum products from the aggressor state [European Commission, 2022]. It therefore makes good sense to investigate how shifts in the direction of raw material imports – such as LPG, which was previously sourced primarily from Russia – will affect the Polish market. The structure of Poland's LPG imports highlights this dependence clearly: in 2021, supplies from Russia and Belarus accounted for 58.2% and 3.2% of total imports respectively, underscoring Poland's heavy reliance on energy supplies from the East [POGP, 2022].

The following analysis of pricing trends is based on indices relevant to LPG imports to Poland, including Argus daf Brest, Argus cif ARA, FCA, and the Argus North Sea Index. For many years, the Argus daf Brest index was considered to be the primary benchmark for LPG prices in Poland, but in recent years LPG consumers started to rely on Western index prices, which are more predictable and reliable than the geopolitically sensitive Eastern index. Argus daf Brest is an index reflecting price estimates for LPG transported from the East to Poland by rail (Argus Media group), while the FCA index applies to LPG already at Polish terminals in the north and east of the country (e-petrol.pl). The Argus cif ARA index, which also underpins the Argus North Sea Index (ANSI) monthly quotation (Argus Media group), is considered to be the most widely used LPG price index in north-western Europe. All Argus index prices are expressed in US dollars per tonne, while the FCA index price is expressed in PLN per tonne.

The scope of the analysis

A quantitative analysis based on an econometric model and time series data can help determine the extent of changes in the LPG market. To date, no comparable analysis has been conducted for Poland. The proposed model makes it possible to assess the relationship between crude oil and LPG pricing trends in the Polish market by quantifying both the strength and direction of the impact of crude oil prices on LPG prices. Poland imports 95% of its LPG from the eastern (Brest) and north-western routes, which differ in their price indices and, to some extent, in the factors that determine them. For this reason, the empirical analysis draws on two basic indices reflecting the two main directions of imports: the Argus Daf Brest Popan-Butane mix, which determines the price of LPG from the east, and two indices of propane and butane prices: Argus CIF ARA L C3 and Argus CIF ARA L C4, determining the price of the commodity obtained via the north-western route. These were used to create an aggregate index that tracks the cost of the LPG blend, which contains 60% propane and 40% butane. These ratios are season-independent. Each assigns a price in USD per metric tonne for the commodity. North-western Europe's spot and futures contracts frequently employ the Argus cif ARA wholesale pricing indices, which reflect the continent's sizable and liquid wholesale LPG market. These are the region's most liquid reference LPG prices, hence they have been adopted for the econometric model used in this paper.

The quantitative analysis comprises daily data collected from 3 January 2017 to 31 May 2022, which were used to compute the weekly averages of the indices that directly inform the model's variables. The size of the data set ensures that the model is accurate and that the estimation results are stable. The quantitative analysis is intended to establish the association between the price of LPG and the price of Brent crude oil, which is acknowledged as the primary driver of the price of the former. To predict how the propane-butane market will evolve in the future in relation to oil prices, it is essential to investigate the existence, nature and strength of the short-, medium-, and long-term relationships. It is to be expected that if such relationships existed in the past, they would persist, despite the changing geopolitical conditions. Economic shock factors, such as armed conflicts, shifts in supplier structures, temporary disruptions in production and market conditions, can only affect such dependence temporarily, before it resumes its long-term trend. Macroeconomic factors influence both the price of oil and LPG, although their impact may vary.

The association between oil and LPG prices is commonly seen as the effect of crude oil prices on LPG prices due to the manufacturing process. LPG of natural origin accounts for up to 10% of the liquid gases present in natural gas production, which include propane, isobutane, and butane. LPG derived from crude oil represents 1–4% of the volume processed. Bio-LPG is also available now, with about 60% obtained from waste and sludge processing, and the remaining 40% derived from vegetable oils, with a negligible impact on LPG pricing. Due to the diverse structure of LPG production, a variety of factors may affect its price. The literature tends to recognise the price of crude oil as LPG's main pricing driver [**Bai, Lam, 2019**; **Ederington et al., 2019**; **Oglend et al., 2015**]. The LPG blend imported into Poland from the north-west is typically made up of 60% propane and 40% butane, while that from the east, depending on the refinery, usually has a fixed ratio of 50%

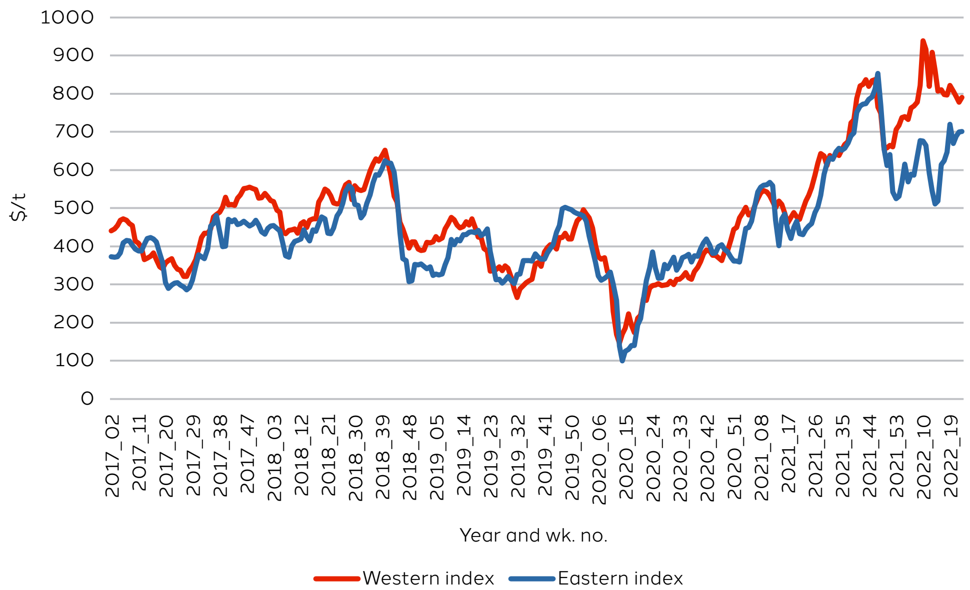
each. These proportions do not vary seasonally, unlike the LPG sold at petrol stations. These varying proportions mean that the respective price indices are not entirely comparable. However, if it is assumed that these indices reflect the price of the mixture of gases, the composition of which is known to consumers and recognised as LPG with a certain margin of tolerance, it is possible to construct an aggregate index of the prices of the raw material imported to Poland weighted by origin.

A single-equation econometric model used for time series analysis was adopted to determine the strength of the price relationship in question. This model estimates the strength and direction of the influence of two prices derived from market quotations, yet it cannot forecast future oil or LPG pricing, as the trend will be primarily affected by general macroeconomic and political conditions as well as unpredictable economic shocks. Likewise, the model does not forecast LPG demand or probe its underlying microeconomic drivers. Investigating the determinants of price and demand from diverse consumer groups requires extensive empirical study, which is outside the scope of this paper. The weekly averages used for the study are based on 284 observations and three indices:

1. The **western index** based on Argus CIF ARA L C3 and Argus CIF ARA L C4 expressed in USD per metric tonne. These comprise the basic inputs into the index of the LPG blend (60% propane and 40% butane), which accounts for approximately 20% of total imports to Poland.
2. The **eastern index** equal to the Argus Daf Brest Propane-Butane mix index, which accounts for about 70% of total imports to Poland.
3. The **total index** is constructed as the weighted average of the two previous indices, where the weights represent the import structure, assuming that 25% of imports originate from the north-west. This is explained by the fact that imports from this route will increase as a result of import substitution from the east.

The model described below explores the relationship between these indices and the price of Brent crude oil. All relevant empirical data are shown in the figures below. The year and calendar week are displayed on the X-axis. The changes in LPG price levels over time were similar until early 2022, when the western price index surpassed the eastern one. The plot of the combined index resembles the latter due to the breakdown of imports to date. When Brent crude oil and LPG prices are compared, it is clear that the two move over time in very similar ways and are affected by the same factors (the Y-axis on the right-hand side of the graph represents the price of Brent crude).

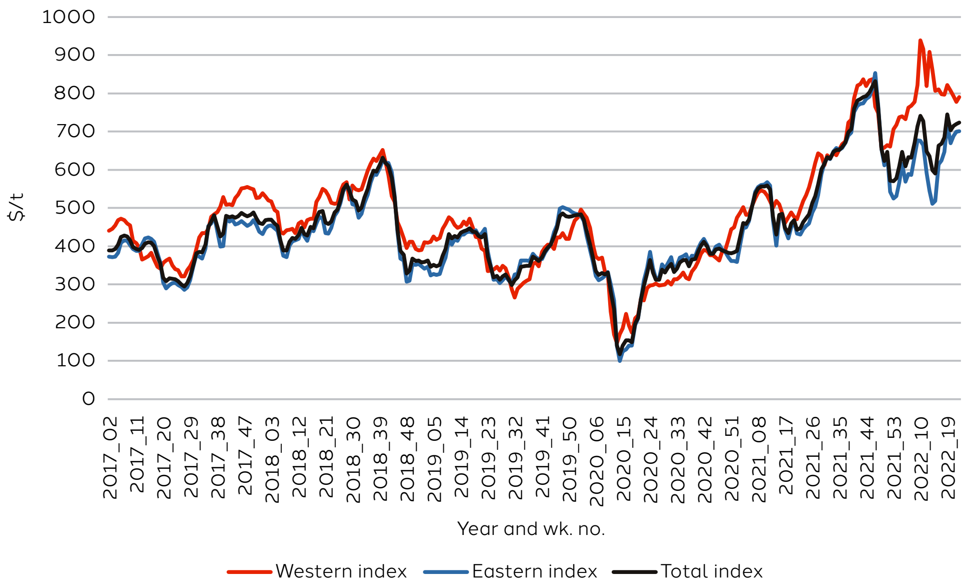
Figure 1. Eastern and western LPG price indices



Source: Authors' own elaboration based on Energy Information Administration [2022].

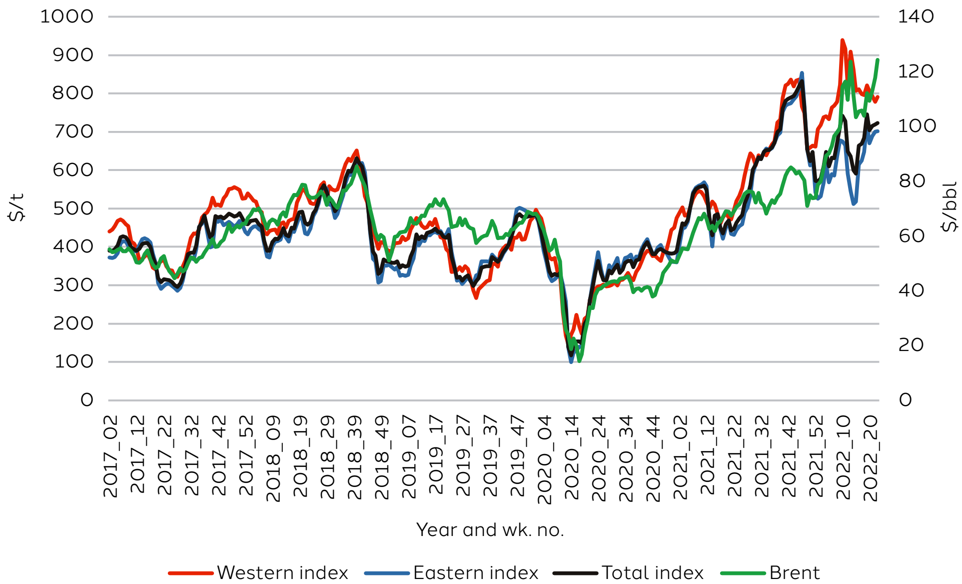
By switching to logarithmic index returns, it is possible to analyse price volatility over time in more detail. The spike in volatility from spring to autumn 2020 was associated with the outbreak of a global pandemic and the slow response of financial markets. In contrast, there is no comparable increase in volatility as a result of the conflict in Ukraine, which strongly suggests that prices in global oil and LPG markets are mostly affected by other factors.

Figure 2. LPG price indices



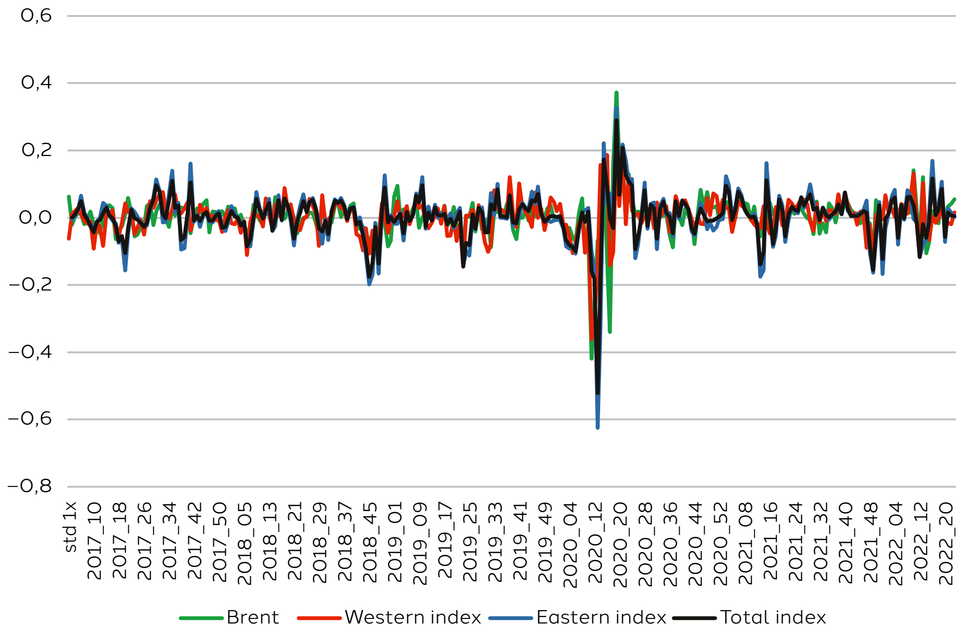
Source: Authors' own elaboration based on Energy Information Administration [2022].

Figure 3. LPG and Brent price indices



Source: Authors' own elaboration based on Energy Information Administration [2022].

Figure 4. Logarithmic rates of return



Source: Authors' own elaboration based on Energy Information Administration [2022].

This implies that import prices from the north-west should not change significantly for Poland. However, price variations may reflect changes in Polish economic conditions as well as adjustments to the structure and sources of supply. The beginning of 2020 saw a shift in the western indices, which was most likely due to the global energy crisis.

Results

This paper uses the SARIMAX (Seasonal Auto-Regressive Integrated Moving Average with eXogenous factors) time series model. To obtain an idea of how it works, let us first consider the following fairly standard stochastic process of the ARMA (p,q) class (AutoRegressive Moving Average; cf. [Durbin, Koopman, 2012]:

$$y_t = \sum_{j=1}^{r} \phi_j y_{t-j} + \sum_{j=1}^{r} \theta_j \varepsilon_{t-j} + \varepsilon_t. \tag{1}$$

where $r = \max\,(p;\, q + 1)$. It describes a time series in which a relationship holds between the current value of the dependent variable (y) (here it is the logarithmic rate of return on LPG price; cf. Fig. 4); dependent on its previous states (y_{t-j}) and the previous states of the random component (ε_{t-j}), where the latter can be interpreted as e.g. the effect of a disturbance or shock, understood as the deviation of the actually observed value in the series from the anticipated value if the shock has not occurred. The effect of lags y as well as the lags of the random component ε itself in the model are captured by parameters in vectors ϕ of length (number of elements) p, and θ of length q. The lengths p and q of vectors ϕ and θ describe the maximum degree of delay, and hence the memory (persistence) of the process in both the autoregressive component $AR(p)$ and the moving average component $MA(q)$. Thus, for example, the ARMA(2,1) model has a "memory" of y-values from the previous period and from two periods ago, as well as a memory resulting from the level of the random component (disturbance, shock) in the previous period. The individual parameters in vectors ϕ and θ determine the effect of a given lag (previous states of y and ε) on the current level of y. The values of the individual parameters are estimated using standard econometric methods. The level of lags (p, q), and hence the number of parameters themselves in vectors ϕ and θ, must be empirically determined before estimating the model itself. In this study, all the possible combinations of ARMA models up to $p_{\max} = q_{\max} = 8$ are considered.

To assess the impact of crude oil pricing on LPG pricing trends, the model defined above was extended to the ARMAX(p, q) model (AutoRegressive Moving Average with eXogenous variables):

$$y_t = x_t\beta + \sum_{j=1}^{r} \phi_j y_{t-j} + \sum_{j=1}^{r} \theta_j \varepsilon_{t-j} + \varepsilon_t. \tag{2}$$

where x_t is the logarithmic rate of return on oil price in week t, whereas β determines the strength of the relationship between oil price volatility and LPG price volatility. Thus, a 1% increase in oil price rate of return in a given week results in a β per cent increase in the LPG price in the same week.

As a further extension to the SARMAX(p, q) × (P,Q,s) specification, it is also possible to capture the so-called seasonal effects in both the autoregressive component AR(P) and the moving average component MA(Q). The model may include extra lags occurring every few periods (season 's') to account for the seasonality of the event being modelled. In this case, it is also necessary to specify the number of observations that make up season 's' (e.g., four weeks per month, 12 months per year, or approximately 52 weeks per year), as well as the number of lags within these periods. Monthly, quarterly and yearly seasonal cycles were considered in this study. The memory of the process extends up to one season because the number of seasonal lags (P,Q) is expected to be zero or one.

The final extension, SARIMAX(p, d, q) × (P,D,Q,S), additionally allows for the modelling of a non-stationary process once the degree of its integration I(d) has been determined, where d represents the integration. Bringing a stochastic integrated process of order d to stationarity is traditionally achieved by varying the observations in the time series by d times, with the number of variations (d) required to bring the process to stationarity determining precisely its integration level. Economic processes are typically considered to be integrated of order one, I(1), or less frequently of order zero, I(0), in which case they are stationary. As the literature commonly models logarithmic price returns – defined as differences in the logarithms of the original LPG prices – it is appropriate to assume that the series follows a stationary process. This assumption is supported by the pattern shown in Figure 4. Accordingly, the integration order of the SARIMAX model is set to zero.

In summary, this study considers a set of SARIMAX(p, 0, q) × (P,0, Q,s) models for p = {0, 1, ... 8}, q = {0, 1, ..., 8}, P = {0, 1}, Q = {0, 1} and s = {0, 4, 12, 52}. A total of 1,296 variants of the SARIMAX model were considered. The optimal model for a given dataset was determined based on the Schwarz information criterion – also known as the Bayesian Information Criterion (BIC) – given by the following formula:

$$BIC = k\ln(n) - 2\ln(\hat{L}) \tag{3}$$

where $\hat{L}$ is the value of the reliability function at its maximum, n is the number of observations, and k is the number of estimated parameters. The lower the BIC, the more reliable the model given the available data. Component k ln(n) is responsible for penalising overly expanded models, i.e. those in which an increase in the value of maximum reliability $\hat{L}$ is not compensated for (at least) by increased model complexity (i.e. an additional number of parameters). The empirical section presents the results for the best-performing models selected from a set of 1,296 estimated SARIMAX variants applied to three time series: the eastern LPG price index, the western LPG price index, and the total LPG price index.

The SARIMAX estimation results for the total index are shown in Table 1. According to the adopted BIC-minimising criterion, the optimal variant of the model for this time series is a simple moving average process MA (1) with one lag, without seasonality, and with the Brent crude oil price as the independent variable for the LPG pricing volatility on Poland's market. An increase in oil price volatility defined as a 1% rise in return in a given week results in a 0.438% increase in LPG price return by 0.438% in the same week. This result is statistically significant and demonstrates a fairly strong positive correlation between crude oil price volatility and LPG price volatility. The statistically significant MA (1) component demonstrates that LPG pricing in Poland is characterised by short memory over time, which is mostly due to the effect of the random component (indeterminate external shocks). A positive shock in the previous week, defined as a deviation in the actual return rate above its theoretical value predicted by the model by 1%, increases the volatility of the LPG price in the current week by about 0.2834%.

Table 1. SARIMAX estimation results for the total index

Variable	Estimate	SE	t-value	p-value
Oil price (Brent)	0.4380	0.0350	12.61	0
MA: 1 time lag	0.2834	0.0450	6.30	0
Variance	0.0029	0.0001	32.17	0
Intercept	0.0009	0.0050	0.19	0.85
Model fitness estimation:				
Reliability logarithm (L)	426.42			
BIC	**−830.26**			

Source: Authors' own elaboration.

The results of identical calculations for the western index are shown in Table 2. The optimum SARIMAX model version in this context is a seasonal autoregressive process with a monthly amplitude and the oil price as the independent variable. In the current week, a 1% rise in oil price volatility translates into a 0.5888% increase in LPG price volatility. This index attains the highest values of the three studied, indicating a significant association between the volatility of the western LPG price index and the volatility of the Brent crude oil price index. The volatility of the western LPG index over time is characterised by minor, yet statistically significant monthly swings. These represent corrective fluctuations, which means that a 1% cent rise in the volatility (expressed in weekly return terms) of the LPG price four weeks prior results in a 0.1528% drop in current LPG price volatility.

Table 2. SARIMAX estimation results for the western index

Variable	Estimate	SE	t-value	p-value
Oil price (Brent)	0.5888	0.0230	25.91	0
AR: season (month)	−0.1528	0.0330	−4.68	0
Variance	0.0019	0.0001	24.99	0
Intercept	0.0004	0.0030	0.14	0.89
Model fitness estimation:				
Reliability logarithm (L)	487.41			
BIC	**−952.24**			

Source: Authors' own elaboration.

For the eastern index, significant autoregressive dynamics and a first-order moving average component are observed (see Table 3). A 1% increase in LPG price volatility in the previous week is associated with a 1.2225% rise in current volatility. By contrast, a 1% positive shock–defined as a deviation of observed weekly volatility above the theoretical value returned by the model by 1% in the previous week–leads to a 0.9998% decrease in current LPG price volatility.

The net effect of both processes is thus moderately positive, at approximately 0.22%, implying that the previous week's LPG price volatility has a moderately positive effect on the current week's LPG pricing. The memory of LPG pricing in the eastern market is also somewhat longer, as the second lag of the autoregressive process AR (2) is also an important component of the SARIMAX model. The previous fortnight's 1% increase in LPG price volatility was accompanied by a 0.3084% drop in current LPG price volatility. The net impact of all these stochastic processes of order one and two on current LPG price volatility is negligible. The impacts of these processes on the LPG price in the current week are almost cancelled out, and the sum of the simple elasticity of LPG pricing with respect to these processes hovers around zero (at –0.08%). Thus, their inclusion in the model, while justified and supported by the statistical significance of their variables, appears to be limited to explaining the short-term dynamics of LPG pricing in the eastern market as it has no significant effect on LPG price movements in a period of time beyond one week.

Table 3. SARIMAX estimation results for the eastern index

Variable	Estimate	SE	t-value	p-value
Oil price (Brent)	0.4472	0.050	9.00	0
AR: 1 lag	1.2225	0.049	25.09	0
AR: 2 lag	–0.3084	0.045	–6.83	0
MA: 1 lag	–0.9998	0.514	–1.95	0.05
Variance	0.0044	0.002	2.02	0.04
Intercept	0.0009	0.001	1.28	0.20
Model fitness estimation:				
Reliability logarithm (L)	363.47			
BIC	**–693.07**			

Source: Authors' own elaboration.

The association between oil price volatility and LPG price volatility in the eastern index is also fairly strong and statistically significant, as was the case with the first two indices. When the price of Brent crude oil increases by 1% in a particular week, the price of eastern LPG also rises by 0.4472% in the same week. As a result, the estimation outcome for this variable is comparable for Poland as a whole, but much lower than the estimation outcome for the western index.

Discussion

For the total index, an increase in oil price volatility (i.e. an increase in the return rate by 1%) in a given week results in an increase in the return rate on LPG price by approximately 0.4% in the same week. This result is statistically significant and indicates a strong positive association between oil price volatility and LPG price volatility in Poland. The statistically significant moving average component of order 1 demonstrates that the pricing mechanism is characterised by a short memory over time, which is mostly due to indeterminate external shocks (i.e. factors shaping LPG prices beyond the Brent price). This means that fluctuations in LPG prices are primarily determined by oil prices and are significantly but transiently influenced by external disturbances. The volatility of the LPG price in the current week increases by less than 0.3% for a positive shock in the previous week defined as a departure of the observed return rate over the theoretical one returned by the model by 1%.

Likewise, a 1% rise in the volatility of the oil price in a given week results in a 0.6% increase in the volatility of the LPG price, which exceeds the response of the total and eastern indices respectively. This is indicative of a bigger and smoother Western European LPG market, where Brent crude oil price volatility is more smoothly communicated to LPG price volatility. Any monthly changes are minor and mostly corrective in nature.

Since first- and second-order autoregressive components as well as the moving average play a major role in the adopted model, the eastern index is characterised by more inertia than the western one. In a given week, a 1% rise in Brent crude oil price volatility is accompanied by a 0.4472% increase in eastern LPG price volatility, a response that is weaker than that for the western index. The calculation of the econometric model for the eastern index confirms the existence of a robust and statistically significant association between crude oil and LPG price volatility. Last but not least, the estimates presented here, like other econometric models, are based on historical data and capture previous relationships that are expected to continue.

The econometric analysis of the three aggregated LPG price indices leads to several significant conclusions about their pricing over time in relation to Brent crude oil prices. LPG price indices for both north-western and eastern import routes are driven primarily by oil price volatility. The relationship between crude oil and LPG pricing has been extensively researched in the literature and reflects not only production linkages but also prevailing market conditions and the general macroeconomic situation. A review of the literature and the available empirical data lead to the conclusion that crude oil price dynamics have a considerable and fundamental impact on LPG price dynamics, with crude oil prices generally exhibiting slightly higher volatility than LPG prices.

From an econometric point of view, the fluctuations of LPG and Brent price indices follow a similar pattern, which implies they share a stochastic trend. Moreover, their primary trends are almost parallel, hence any divergence between them is temporary and unlikely to persist. This relationship holds true for both current price fluctuations and those that span medium and longer time periods. It is thus reasonable to assume that the historically strong price correlation will continue into the future and remain critical in assessing future market movements, despite changing geopolitical conditions. Economic shocks, such as armed conflicts, shifts in supplier structures, temporary disruptions in production and changes in market conditions, can only temporarily disturb this correlation. Once they have subsided, the trend will revert to its long-term pattern. Macroeconomic factors affect both crude oil and LPG prices, although their exact effects may vary.

A limitation of this study is the use of data covering only a specific time period, based on aggregated weekly observations. The choice of model is somewhat arbitrary; however, we argue that it offers a better representation of price formation dynamics than those commonly used in the existing literature. Nevertheless, it is an a-theoretical, technical model that describes price dynamics using primarily past realisations and, as such, does not incorporate structural factors other than crude oil price. This means it does not account for the broader range of international macroeconomic determinants influencing price development. The model assumes that the historical relationship between LPG and crude oil prices will persist into the future. It is also important to note that during the studied period, LPG consumption in Poland accounted for no more than one-fifth of the energy supplied by natural gas and was primarily used in transportation. This may explain the absence of a distinct seasonal pattern in the model.

Conclusions

Through the application of the SARIMAX model to examine the relationships between crude oil and LPG prices across the three proposed variants for Poland, several conclusions can be drawn. In all three cases, there is a clear and statistically significant association between changes in oil and LPG prices. This association is stronger in the case of the western index, although it is fairly robust across all the analysed indices.

Once the relationship between oil and LPG price changes is accounted for, weekly LPG price variations do not exhibit long memory or significant seasonality – or, more accurately, any discernible seasonality appears to be explained by swings in oil prices. The western index has a minor impact on monthly cyclicality. Moreover, the eastern index demonstrates relatively high elasticity with respect to short-term past dynamics (up to around two weeks earlier). However, these effects essentially cancel each other out, i.e. the net effect of these dynamics is comparable to those observed for the other indices.

This study contributes to the literature by applying the SARIMAX model to analyse the crude oil-LPG price relationship. However, its most important contributions lie in its practical implications. The findings discussed in this paper are crucial for devising and implementing an effective energy policy as well as for preventing price bubbles in the gas market [**Akcora, Kandemir Kocaaslan, 2023**]. They strongly suggest that regulatory intervention in the LPG market in response to temporary shocks may be unnecessary, as LPG prices tend to stabilise relative to oil prices over the longer term. This conclusion is also important in the context of discussions on Poland's energy security [**Czech, 2017**; **Jasiński, Ścianowska, 2015**; **Jonek-Kowalska, 2022**].

Overall, the results deepen our understanding of the long-term dynamics between the prices of these commodities and provide a solid foundation for further empirical research in energy economics. Given the significant volatility in energy prices triggered by Russia's invasion of Ukraine, these insights warrant continued investigation and validation in future studies.

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