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Navn:	**Rebekka Helland og Oda Høybakk Djupvik**

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Dynamics of the EU Natural Gas Market: Investigating the Impact of Supply and Demand Shocks on Natural Gas Prices

Authors

Oda Håbakk Djupvik and Rebekka Helland

Supervisor

Malgorzata Ryduchowska

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Oda H. Djupvik

Oda Håbakk Djupvik

Rebekka Helland

Rebekka Helland

Abstract

This thesis examines the dynamics of the EU natural gas market, investigating the impact of supply and demand shocks on natural gas prices. Focusing on the EU's dependence on Russian gas, we employ a structural vector autoregressive model based on the methodology of Kilian (2009). To estimate the effects of structural shocks on natural gas prices in the EU, we include natural gas imports from Russia, EU primary production, real economic activity, and the real price of gas as variables in our model. Our results suggest that demand shocks play a dominant role in explaining the variation in natural gas prices in the short term. Over time, supply shocks gain more explanatory power, particularly Russian supply shocks. Analysing the impulse responses, we observe that Russian supply shocks lead to increasing prices with a lag. This implies that the EU may be able to temporarily compensate for supply shortfalls in the short term, whereas the high dependence on Russian gas presents challenges in the long term.

Contents

1 Introduction

The price of natural gas is of significant economic interest to several stakeholders. Natural gas serves as a primary fuel for residential and commercial heating, as well as a critical input for industrial applications and electricity generation (EIA, 2022). In addition, natural gas is considered a key component to combat climate change, given its lower carbon emissions compared to other fossil fuels and its ability to balance intermittent renewable energy sources (IEA, 2019).

The European Union (EU) is one of the world's largest consumers of natural gas, with 83% of its total consumption being imported in 2021 (Eurostat, 2022). Russia has been the largest supplier of natural gas to the EU for several years, accounting for approximately 50% of the EU's total natural gas imports from 2019 to 2021 (European Council, 2022a). This dependence has enabled Russia to weaponise gas flows in Europe to promote its political objectives. After decades of conflicts, Russia invaded Ukraine in February 2022. Following the invasion, the natural gas market gained significant attention as the prices became extremely volatile.

In this thesis, we investigate the dynamics of the EU natural gas market. The current political environment makes it particularly interesting to investigate the impact of Russian supply shocks on natural gas prices. Notably, the existing literature on the EU natural gas market does not specifically investigate the effects of these shocks. This triggered our interest in the following research question:

"What are the dynamics of the EU natural gas market and how do Russian supply shocks influence natural gas prices?"

We hypothesise that a decrease in EU natural gas imports from Russia has contributed to increasing prices, with increasing explanatory power over time. To test our hypothesis, we construct a structural vector autoregressive (VAR) model to investigate the dynamics between natural gas imports from Russia, EU primary production, real economic activity, and the real price of gas. We follow the methodology of Kilian (2009), who proposes a trivariate structural VAR model for the crude oil market. Our model expands on this idea by applying it to the EU natural gas market.

Our results indicate that natural gas prices in the EU respond to shocks in supply and demand variables differently over time. As expected, we find positive responses to positive aggregate and gas-specific demand shocks. However, the responses to negative supply shocks are more complex and harder to interpret. Russian supply shocks are insignificant the first year, before they materialise and cause the prices to increase. The lagged effect may indicate that the EU can substitute supply shortfalls in the short term, whereas the high dependence on Russian gas might make it difficult to cope with the supply reduction in the long term. EU supply shocks result in a price increase upon impact, before triggering a price decline after seven months. This effect may indicate that a decline in EU primary production does not necessarily lead to a reduction in total supply and higher prices, considering the EU's dependence on natural gas imports. The demand shocks manage to explain most of the variation in the prices during the first 18 months of forecast, whereas the supply shocks increasingly gain explanatory power in the medium to long term. Further, we find that the impact of the structural shocks on natural gas prices increases over the data period. This coincides with the increased volatility in natural gas prices after 2020. Supporting our hypothesis, we conclude that a decrease in EU natural gas imports from Russia has contributed to increasing prices, with increasing explanatory power over time.

The remainder of our thesis is organised as follows: In section 2, we provide background for our analysis. Section 3 delves into the relevant existing literature. In section 4, we go through the methodology and outline our structural VAR model specification. Section 5 presents a description of the data. Further, in section 6, we present our main results, including a discussion of the impulse response functions, forecast error variance decompositions, historical decomposition, and robustness tests. Finally, we summarise our concluding remarks and suggestions for future research in section 7.

2 Background

To provide background for our analysis, we begin with an overview of the characteristics of the natural gas market in general. We then delve into the political background, where we discuss the political tensions between Russia and Ukraine, and their impact on the EU's relationship with Russia as a major natural gas supplier. Additionally, we discuss the key measures implemented by governments and regulators and assess the overall political risk. Lastly, we address the characteristics of the natural gas market in the EU.

Box 1: Characteristics of the Natural Gas Market

Composition

Natural gas is a fossil fuel primarily consisting of methane, as well as smaller amounts of other molecular compounds. These may include various hydrocarbons like ethane, propane, and butane, or non-hydrocarbons such as nitrogen, carbon dioxide, and hydrogen. The thermal and physical properties of natural gas vary depending on its composition. Commercial natural gas sold for heating purposes usually contains around 85 to 90% methane, with the remainder mainly nitrogen and ethane (Britannica, n.d.).

Transportation

One important characteristic of natural gas production is the need for major investments in transportation infrastructure, such as gas pipelines. This is the most cost effective and reliable method for moving large volumes of gas over long distances (Norwegian Petroleum Directorate, 2022). Alternatively, natural gas can be transformed into other forms, such as liquefied natural gas (LNG) and compressed natural gas (CNG), for transport by ships or trailers (Molnar, 2022). The process of compressing or liquefying natural gas reduces the volume and makes it more feasible to transport. However, LNG and CNG need to be regasified at the destination before consumption (Eiknes, 2021).

Storage

To ensure a steady and reliable supply of natural gas to meet fluctuating demand, it is often stored in underground storage facilities. These facilities are typically depleted gas fields, salt caverns, or aquifers close to the areas of high gas consumption. Natural gas can also be stored in the transportation pipelines or as LNG or CNG in specially designed storage tanks (Speight, 2007).

Local Character

Although natural gas is a globally traded commodity, it has a local character compared to oil. This is due to the (1) transportation and storage challenges, (2) specialised infrastructure requirements, and (3) concentration of uses in certain regions. Transportation of natural gas is more expensive and must be done in a timely manner due to limited storage capacity. Additionally, natural gas has limited uses and is not as easy to extract and process compared to oil. This contributes to its local character, since the demand for natural gas is more concentrated in certain regions where these uses are more prevalent (Strauss Center, n.d.).

2.1 Political Background

2.1.1 Russia-Ukraine Gas Disputes

After the dissolution of the Soviet Union in the early 1990s, Russia has strategically employed natural gas prices and export quantities as political tools to promote its political objectives in Europe. This has resulted in a series of gas disputes between Russia and Ukraine. Upon analysing the timeframe of these gas disputes, it becomes evident that they tend to arise during times when Ukraine is prone to implement reforms in pursuit of its EU alignment goals. The most important gas disputes are mentioned below, and a more detailed overview can be found in Appendix A1.

The first major gas dispute between Russia and Ukraine began in March 2005. Russia increased the price of natural gas and halted gas flows after accusing Ukraine of retaining gas intended for Europe. This dispute occurred the year after the Orange Revolution, when the pro-Western government came to power in Ukraine, following the annulment of the pro-Russian victory due to electoral fraud (Pirani, 2007).

The gas dispute in 2009 arose after Russia and Ukraine failed to reach an agreement on gas prices and transit fees for the coming year (Pirani et al., 2009). It is considered one of the most influential gas disputes for the overall European gas market, as it affected 18 other European countries who reported major supply disruptions from Russia (Reuters, 2009). This was also during a period when Ukraine was under a pro-Western government, and the EU-Ukraine partnership was a key political topic.

In 2013, when the Ukrainian government was pro-Russian, mass protests erupted after the government decided to abandon an agreement with the EU in favour of closer ties with Russia. The protests, also known as Euromaidan, eventually led to the ousting of the president in February 2014. This was a major threat to Russian interests, and as a response, Russia officially annexed the Ukrainian peninsula Crimea in March 2014 (European Union, 2021). Although the annexation was effectively accepted in favour of escalating to a wider European war, it was widely condemned by many countries. This resulted in a significant deterioration of Russia's relations with the West (Energy Council, 2022).

Russia's political agenda against Europe and the related aggressions towards Ukraine created a long-lasting "frozen" conflict[1], with Russia being prone to conflict instead of following the agreements. After the annexation of Crimea, the dust settled for many years, until Russia started a military build-up near the Ukrainian border in 2021 (Bowen, 2022). On February 24, 2022, Ukraine was invaded by Russian military forces, which marked the beginning of the war between Russia and Ukraine (CNBC, 2022a). The invasion has had significant consequences for the EU natural gas market in terms of supply disruptions and price volatility. This caused a short-term significant spike in the natural gas price before temporarily reverting to its level before the invasion.

2.1.2 Russia-EU Gas Dispute

The military invasion of Ukraine in 2022 brought the EU's dependence on Russian gas to the spotlight and triggered a gas dispute between Russia and the EU. Since the annexation of Crimea in 2014, the EU has progressively imposed sanctions against Russia, involving asset freezes, travel bans, trade restrictions, and suspending political cooperation agreements (Eur-Lex, 2023). Nevertheless, the Russian share of total gas imported to the EU remained elevated until 2021[2], with limited attention on the threat it posed to energy security in the EU. Despite the increased emphasis on sanctions after 2014, the EU's efforts to reduce its dependence on Russian gas flows have faced several obstacles. One contributing factor is countries exploiting loopholes in leaky sanction regimes that enable Russian gas to flow through the EU without violating any laws (Global Witness, 2022). Additionally, some EU member countries heavily rely on natural gas imports from Russia, leading to a relaxation of import restrictions to meet their energy needs.

The transition away from fossil fuels with higher emissions has further contributed to keeping the dependency high (IEA, 2020a). Since 1990, there has been a drastic decrease in coal consumption in Europe, mainly due to increased focus on reducing greenhouse gas emissions (Appendix A2, Figure 15). The Russia-Ukraine conflict, which had remained relatively stagnant for many years, was not perceived as an urgent threat to energy security in the EU. Consequently,

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[1] A frozen conflict can be described as an ongoing conflict where no overall political solution has been made, despite several ceasefires (Corboy et al., 2014).

[2] Russian imports accounted for ~50% of total imports to the EU between 2014 and 2021 (European Council, 2022a).

policymakers may have prioritised emissions reduction over efforts to reduce the dependence on Russian gas.

The ongoing gas dispute between the EU and Russia is characterised by disruptions in the gas trade, affecting both parties involved. As a response to the sanctions imposed on Russia in connection with the invasion, Russia has exploited the EU's vulnerable position by cutting gas supplies. During the summer in 2022, Russia drastically reduced gas supplies to Europe through the Nord Stream 1, before the gas flows was cut indefinitely on August 31, 2022 (CNBC, 2022b). This was reflected in natural gas prices, which increased in line with the reduced gas supplies, reaching its highest level at end of August.

2.1.3 Policy Measures

In response to the energy crisis in Europe in 2022, authorities were prompted to implement policy measures to address supply disruptions and meet the increasing energy demands. Only few days after the invasion, the International Energy Agency (IEA) announced its 10-point plan to reduce the EU's gas imports from Russia by more than one-third within one year (IEA, 2022). In addition, the European Council established a temporary mechanism to control excessive gas prices. The price cap of €180 per MWh came into effect on February 15, 2023 and will remain in place for one year (European Commission, 2022). Another significant measure is the EU's proposal to reform the electricity market. This reform involves decoupling electricity prices from gas prices by modifying existing EU legislations. It encourages longer-term contracts with non-fossil fuel power generation and promotes clean flexible solutions, like demand response and storage, to compete with gas (European Commission, 2023).

Considering the historical background explored in this section, it becomes evident that political risk plays an important role in understanding the dynamics of the EU natural gas market. Hence, when interpreting the results of our model, we keep in mind its sensitivity to political factors. As a response to external shocks, governments are prone to implement measures to reduce the severity of the expected price impact. These measures can affect or limit the price effect of structural shocks on the variables in the model.

2.2 The European Gas Market

Europe heavily relies on natural gas imports, with Russia being a significant supplier (Eurostat, 2022). Other significant suppliers include Norway, Algeria, and Qatar. The pipeline system (Box 2) has been crucial to ensure a stable and secure supply of natural gas to the EU, as most natural gas imports are transported through these pipelines.

Box 2: Russia-EU Natural Gas Pipeline System

Source: Deutsche Welle & Entsog (2022)

Natural gas deliveries from Russia to the EU has four main transport routes: Nord Stream (via the Baltic Sea), Yamal (via Poland), Soyuz and Brotherhood (via Ukraine), and Turkstream (via Turkey) (Bruegel, 2023). Ukraine has for many years been subject to political tensions with Russia. Hence, efforts have been made to reduce the EU's dependence on Ukrainian transit by building new pipelines such as Nord Stream 2. However, the process was suspended in 2022 due to the Russo-Ukrainian war (Planete Energies, 2022).

Over the past years, there has been an increase in LNG imports to the EU (Appendix A3, Figure 16). One of the key drivers is the shale gas revolution in the United States (U.S.). The oversupply of natural gas lowered the domestic natural gas prices and enabled the country to become a major exporter of LNG (Aruga, 2016). In addition, the EU has recognised the need to invest in LNG infrastructure, including import terminals and storage facilities, to meet its increasing energy demand and reduce the dependence on a few major suppliers. In the first half of 2022, almost 50% of total LNG imports to the EU came from the U.S. Other major exporters of LNG to Europe include Qatar and Australia. In total, the EU's overall LNG import capacity represents around 40% of the total natural gas demand. However, it is important to emphasise that the LNG infrastructure is uneven and scarce across the EU (Appendix A4, Figure 17). Overall, the increased imports of LNG in Europe have provided greater energy security and flexibility, ensuring a more stable and sustainable energy supply for the region (European Council, 2022b).

3 Literature Review

The following section presents a summary of the relevant literature on structural VAR models and situates our thesis within the existing body of research. We begin with an overview of several papers that employ the methodology to investigate the dynamics of crude oil markets, as the extensive research made on these provide the foundation for subsequent analyses of natural gas markets. Further, we focus on similar papers investigating natural gas markets. Lastly, we state our contribution to the existing literature.

3.1 Structural Vector Autoregressive Approach

The structural VAR approach was introduced in the seminal work of Sims (1980) as an alternative to traditional large-scale macro econometric models. Sims criticised the traditional models for their approach to solve the identification problem by excluding variables without any theoretical or statistical justification. Hence, he introduced the structural VAR methodology, which only required a priori knowledge of which variables should enter the system in reduced form. The methodology makes it possible to determine the lag length, deterministic components, and handle non-stationary components afterwards.

Structural VAR analyses employ various types of identification schemes, each imposing different restrictions on the system of variables. The purpose of imposing these restrictions is to identify the causal relationships between the variables. This is based on assumptions or prior knowledge about the economic relationships we want to investigate. Sims (1980) introduced zero contemporaneous restrictions, also known as the Cholesky decomposition, assuming a lower triangular reduced form error matrix. The identification scheme allows for a clear and interpretable identification of the structural relationships between the variables. Cooley & LeRoy (1985) criticised this "atheoretical" identification scheme, arguing that the restrictions' long-run neutrality assumption may be unrealistic. This critique led to the development of alternative identification strategies for structural VAR models. The zero long-run identification scheme was first introduced by Blanchard & Quah (1988) and further specified by Galí (1999). The identification scheme assumes some shocks have zero cumulative effect on some of the endogenous variables in the long run. Faust (1998) introduced the sign restriction identification scheme, allowing researchers to use economic theory to guide the identification of shocks in the model. Lastly, Stock & Watson (2012) and Mertens & Ravn (2019) show how external instruments can be used to identify structural shocks. Following the methodology of Kilian (2009), we employ the Cholesky decomposition (Sims, 1980) in the identification of our model.

3.2 Crude Oil Markets Dynamics

The benchmark specification of the structural VAR framework in context of studying commodity market dynamics was proposed by Kilian (2009). The paper proposes a structural VAR model explaining the dynamics between changes in global oil production, global economic activity, and the real price of oil. Kilian's contribution is two-fold. Firstly, he suggests an index for global economic activity based on dry cargo freight rates and demonstrates its effectiveness as a measure of demand for industrial commodities. Secondly, Kilian provides evidence that the real price of oil is primarily influenced by global economic activity and unexpected shifts in oil-specific demand, while the impact of supply shocks is much less significant. This assertion was met with controversy, as the consensus view at the time was that oil price changes were mainly attributable to supply shocks (Hamilton, 2003). Our analysis is based on Kilian's model structure by applying it to the natural gas market.

Kilian's baseline specification of the model has been extended in many ways for oil market research. Kilian & Murphy (2014) argue that the oil price effect occurring from the desirability of holding oil inventories is not adequately captured by Kilian's model (2009). Hence, they expand the trivariate specification by including an additional variable representing changes in global crude oil inventories. Baumeister & Hamilton (2019) added to this discussion by showing how inventories can be incorporated, while acknowledging the possibility of considerable error in the estimates for inventories.

There is no clear consensus view on the best measure when it comes to economic activity. However, researchers investigating both crude oil and natural gas markets have introduced several alternative measures to Kilian's index to represent real economic activity. For example, real GDP (Jacks & Stuermer, 2020; Rubaszek et al., 2020), industrial production (Hailemariam & Smyth, 2019; Wiggins & Etienne, 2017), the index of industrial metals (Caldara et al., 2019), and a common factor extracted from prices of numerous commodities (Alquist et al., 2020; Delle Chiaie et al., 2017). Following Kilian (2009), we apply the Kilian index as the measure for real economic activity in our model.

The discussion of identification schemes has evolved from the originally proposed recursive structure by Kilian (2009). The sign restriction identification scheme has been employed by various research papers on oil markets (Baumeister & Peersman, 2013; Kilian & Murphy, 2012, 2014). Alternatively, Baumeister & Hamilton (2019) proposed a fully Bayesian interpretation, treating the structural disturbances as Gaussian and discuss the Bayesian interpretation for both the Cholesky and sign restriction identification schemes. Braun (2021) further expanded on the Bayesian interpretation to account for non-Gaussian shocks.

3.3 Natural Gas Markets Dynamics

Although the literature on crude oil markets is more widespread, similar approaches have been applied to studies on natural gas markets. However, these often focus on the global or U.S. markets. Arora & Lieskovsky (2014) apply the structural framework proposed by Kilian (2009) to analyse the dynamics between the U.S. natural gas production, natural gas prices, and economic activity. According to the paper, gas-specific demand shocks account for the majority of the variation in the natural gas prices in the short term. However, the contribution decreases as the aggregate demand and supply shocks gain more explanatory power over time. Similarly, Hou & Nguyen (2018) and Rubaszek & Uddin (2020) apply Kilian’s approach to investigate the dynamics of the U.S. natural gas market, using different proxies for economic activity. Hou & Nguyen (2018) use U.S. industrial production, while Rubaszek & Uddin (2020) use the ADS Business Conditions Index developed by Aruoba et al. (2009). Both studies reveal that natural gas prices are more influenced by gas-specific demand shocks than aggregate demand and supply shocks after the market deregulation. Although we use Kilian’s index as economic activity and investigate the EU market, we get similar results. However, over time, we find that supply shocks gain relatively more explanatory power on the real price of gas.

Wiggins & Etienne (2017) investigates the role of inventories in the U.S. natural gas market, following Kilian & Murphy's (2014) four-variate extension of Kilian (2009). The study concludes that the primary contributors to fluctuations in natural gas prices from 1993 to 2015 were supply and demand shocks, with speculative activities having a minor influence during a portion of this period. Studying several volatile periods over the sample, the paper also reveals that although fundamental factors are the primary determinants of natural gas price fluctuations, supply and demand shocks have evolved significantly over time. Hailemariam & Smyth (2019) examine the primary drivers of U.S. natural gas price volatility by applying a structural heterogenous VAR, introducing shocks to both the coefficient and the volatility. They argue that while gas-specific demand shocks are the primary drivers of natural gas price volatility, supply shocks also play a significant role in explaining movements in natural gas prices.

The abovementioned literature on natural gas market dynamics focuses either on the global or the U.S. markets. However, there are some papers looking at more regional markets in Europe. Nick & Thoenes (2014) introduce a rich economic structural VAR model of the German natural gas market. In contrast to the aforementioned empirical research, their model does not exclusively focus on supply and demand variables, but rather allows for a more comprehensive assessment of seven variables interacting in the European gas market. Misund & Øglend (2016) does not examine the direct price effects but employs the structural VAR methodology to model gas price volatility in the UK. This paper is also more comprehensive compared to the abovementioned papers on crude oil markets, with 13 variables in its system.

3.4 Crude Oil and Natural Gas Markets Relationship

The literature on natural gas markets reveals that a significant portion of research investigates the interaction between natural gas prices and prices of other energy commodities, such as crude oil. Although we do not investigate this relationship in our model, we find the literature relevant to justify our application of Kilian's model for the crude oil market to the EU natural gas market.

Hartley et al. (2008) and Brown & Yücel (2008) have employed cointegration and error correction models to capture the mechanisms linking natural gas and crude oil markets both in short and long term. These studies have employed natural gas inventory data, heating degree days, and shut-in gas production in their models. Their findings suggest that natural gas and crude oil prices in the U.S. are closely related. Jadidzadeh & Serletis (2017) also examined the dynamics between the two commodities by augmenting Kilian's (2009) model with the real price of natural gas. Their findings suggest that oil market-related shocks account for nearly 50% of the variation in natural gas prices.

3.5 Contribution to Existing Literature

Following the work of Kilian (2009), employing structural VAR models has become a growing trend in the field of analysing commodity market dynamics. The literature mentioned above primarily focuses on analysing the dynamics of crude oil markets. However, there has been an increase in research on the dynamics of natural gas markets.

One contribution to the existing body of research is that we investigate the EU natural gas market as a sole market. Another novelty to our approach is that we introduce EU imports of natural gas from Russia as a supply variable. This allows us to investigate the impact of Russian supply shocks, which is highly relevant in the current political environment.

4 Methodology

This section introduces the empirical model that we use to analyse the dynamics of the EU natural gas market. We employ the structural VAR methodology introduced by Sims (1980) to analyse the effects of structural shocks on the variables and decompose unexpected changes in the real price of gas. Our research focuses on investigating the implications of supply shocks resulting from a decrease in EU natural gas imports from Russia. Commencing the section, we discuss the properties of structural VAR models. Further, we provide an introductory overview of the model in general form, which is subsequently identified and specified based on Kilian (2009).

4.1 Properties of Structural VAR Models

There are several useful properties with a structural VAR model. The implementation of the model is easy, as it only requires a priori knowledge of which variables should enter the system in reduced form (Bjørnland & Thorsrud, 2015; Sims, 1980). The model allows us to generate impulse response functions, which reveal the average response of the variables to each of the structural shocks. As a result, we can draw causal inferences about the variables' responses to specific shocks, including their path and persistence. In addition, we can generate forecast error variance decompositions, which enable us to examine the relative impact of the shocks on the variance of the variables. Lastly, we can generate a historical decomposition by using the cumulative contribution of the identified shocks. The purpose is to determine how the shocks have influenced each variable over the sample period (Kilian, 2011).

We employ a structural VAR model based on Kilian (2009) to analyse the interdependencies between the main fundamentals in the EU natural gas market. This framework allows us to investigate relevant transmission channels that affect the real price of gas. The structural VAR model extends the concept of a univariate autoregressive (AR) model to a multivariate framework, considering all variables in the system as endogenous and symmetric (Kotzé, n.d.). This enables high flexibility, because it allows the variables to directly and indirectly influence each other, without assuming any causal relationships (Gottschalk, 2001). Hence, the approach is ideal for investigating our research question, enabling us to test the effects of unexpected shocks imposed on the variables.

4.2 Structural VAR Models in General Form

The following structural VAR model in reduced form represents a system of equations that expresses the endogenous variables in terms of their lagged values and contemporaneous exogenous variables. As a result, each endogenous variable becomes a function of the other variables in the system, disregarding other exogenous shocks and factors that may affect the variables:

$$Y_t = \mu + \sum_{p=1}^{P} A_p * Y_{t-p} + e_t \tag{1}$$

Y_t represents the vector of endogenous variables, μ is the vector of intercept terms, A_p denotes the coefficient matrix that relates Y_t with its p lags, and e_t represents the vector of reduced form errors.

The model's fundamental assumptions entail that the reduced form errors are white noise, follow a normal distribution with a mean of zero, and that the covariance matrix (Σ_e) is symmetric and positive semi-definite. Additionally, the values of the reduced form errors are independent and identically distributed over time. This makes it possible to use a lag operator (L) to compress the model by expressing variables at different lags:

$$A(L)Y_t = \mu + e_t \tag{2}$$

$A(L) = (I - \sum_{p=1}^{P} A_p * L^p)$. $A(L)$ is polynomial in L that corresponds to the sum of lagged values up to lag p.

We aim to obtain the moving average (MA) representation of the reduced form VAR, which captures the contemporaneous and lagged relationships between errors and endogenous variables. The representation expresses each endogenous variable as a linear combination of its lagged values and the corresponding errors at different points in time. This enables us to analyse the effects of exogenous shocks over time and develop a comprehensive understanding of the model dynamics. We can obtain the MA representation if the inverse of the lag operator matrix exists. In order for the inverse to exist, all eigenvalues of $A(L)$ must have an absolute value less than one. This condition ensures that we can multiply by the inverse, $A(L)^{-1}$:

$$Y_t = \alpha \ + A(L)^{-1} * e_t \tag{3}$$

where $\alpha = A(L)^{-1}\mu$. The stability of the structural VAR model relies on the abovementioned condition about the eigenvalues. The model must be stable because it ensures that the effects of structural shocks will diminish over time. This condition directly impacts the model's utilisation and, consequently, the feasibility of our analysis. By performing a stability check, we conclude that our model is stable (Appendix A5). This allows for a relatively straightforward estimation process of the reduced form VAR (Lütkepohl, 2005).

From an economic point of view, the shocks to the variables are unlikely to occur independently. The presence of correlated error terms in the reduced form errors (e_t) would make the covariance matrix non-diagonal. This correlation could make it difficult to infer causality and potentially lead to misleading results. To address this issue, we express the reduced form errors (e_t) as a linear combination of a matrix (S), which describes the relationships between the uncorrelated structural shocks (ε_t):

$$e_t = S * \varepsilon_t \tag{4}$$

Matrix S maps the uncorrelated structural shocks (ε_t) to the reduced form errors (e_t), which is multiplied with $A(L)^{-1}$ that captures the lag structure and coefficients of the model. The relationship between matrix S and $A(L)^{-1}$ stems from the identification strategy of the structural VAR model. This makes the choice of identification scheme crucial in the estimation of the model. The identification of matrix S allows us to draw causal inferences from the observed data by ensuring that the structural shocks are uncorrelated and of unit variance.

We employ the Cholesky decomposition (Sims, 1980), which involves identifying the model by imposing recursive contemporaneous restrictions on matrix S. This implies that the variables only have a contemporaneous impact on the variables that are ordered below them in the system (Bjørnland, n.d.). The recursive identification structure ensures that matrix S is lower triangular, with the elements above the diagonal restricted to zero. The zeros indicate that it takes time to transmit their effects of lower ordered variables in the system. Additionally, the matrix is required to have positive elements on the diagonal to satisfy the assumption $E[\varepsilon_t \varepsilon_t'] = I$ (Appendix A6). This assumption supports the validity of our identification strategy, since it makes all error terms (e_t) orthogonal, and thus uncorrelated. Consequently, matrix S distinguishes the contemporaneous and lagged effects of the variables to obtain more accurate estimates of the dynamics between the variables. This forms the unique identification of the structural parameters and effectively address the issue of uncorrelated structural errors.

By defining $A(L)^{-1} * S = \theta(\mathrm{L})$, we can further derive the relationship between the variables:

$$Y_t = \alpha + \theta(\mathrm{L}) * \varepsilon_t \tag{5}$$

The equation above highlights the necessity of identifying matrix S to compute $\theta(\mathrm{L})$ through $A(L)^{-1}$. Additionally, the structural parameters in $\theta(\mathrm{L})$ have to be identified, which require minimum $(P + 1)/2$ identifying restrictions, where P is the number of variables in the system (Kilian, 2011).

4.3 Model Specification

Our model is built upon the work of Kilian (2009) on the dynamics of the global crude oil market. Kilian's model is based on Sims (1980) and includes global crude oil production, a self- constructed index of real economic activity, and the real price of oil at monthly frequencies from 1973:01 to 2007:12. We augment this model structure by introducing EU imports of natural gas from Russia as an additional variable to examine the impact of the EU's dependence on Russian gas. We consider this as a highly relevant variable as Russia has been the largest supplier of natural gas to the EU for several years. Moreover, we replace the global crude oil production with the primary production of natural gas in the EU. Lastly, we use the real price of gas rather than the real price of oil. These substitutions are necessary since we focus on the EU natural gas market and the variables capture specific characteristics of that market.

The equation below represents our structural VAR model specification:

$$\begin{bmatrix} \Delta imp\_ru \\ \Delta \mathrm{prod} \\ rea \\ rpg \end{bmatrix}_t = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} + \begin{bmatrix} \theta_{11} & 0 & 0 & 0 \\ \theta_{21} & \theta_{22} & 0 & 0 \\ \theta_{31} & \theta_{32} & \theta_{33} & 0 \\ \theta_{41} & \theta_{42} & \theta_{43} & \theta_{44} \end{bmatrix} \begin{bmatrix} \varepsilon^{\text{russian supply shock}} \\ \varepsilon^{\text{EU supply shock}} \\ \varepsilon^{aggregate\ demand\ shock} \\ \varepsilon^{gas-specific\ demand\ shock} \end{bmatrix}_t + lags \quad (6)$$

where Δimp_ru denotes the log differences of EU natural gas imports from Russia[3], $\Delta \mathrm{prod}$ refers to the log differences of EU natural gas primary production[4], rea represents the index of real economic activity in discrete returns[5], and rpg is the real price of natural gas expressed in logs. The model is based on monthly data from 2014:01 to 2022:12[6]. Stationary tests reveal that Δimp_ru, $\Delta \mathrm{prod}$ and rea are stationary, whereas rpg is non-stationary (Appendix A7). However, model stability, which is confirmed in Appendix A5, is more important than stability in the individual time series. As mentioned in Section 4.1, the model must be stable as it directly impacts the model's utilisation and thus the feasibility of our analysis.

We determine the optimal number of lags to establish an effective structural VAR model. These lags correspond to the number of past observations of the variables that contribute to predicting the current value of each variable. As a result, the lag selection process is crucial in capturing the relevant temporal dependencies and dynamics in the data. Kilian (2009) customary specifies 24 lags in his model for the crude oil market. However, as we focus on natural gas rather than oil, we use the Akaike Information Criterion (AIC) to determine the appropriate number of lags in our model (Akaike, 1974). This information criterion takes into account the number of parameters that need to be estimated relative to our sample size. The AIC lag selection approach is supported by Ivanov & Kilian (2007), who argue

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[3] $\Delta \mathrm{imp\_ru} = \ln(\mathrm{imp\_ru}_t) - \ln(\mathrm{imp\_ru}_{t-1})$

[4] $\Delta \mathrm{prod} = \ln(\mathrm{prod}_t) - \ln(\mathrm{prod}_{t-1})$

[5] $\mathrm{rea} = \frac{\mathrm{rea}_t - \mathrm{rea}_{t-1}}{|\mathrm{rea}_{t-1}|}$. We use discrete returns rather than log differences because the index can take on both positive and negative values with different magnitude.

[6] The starting date is decided by the availability of data from Eurostat. However, we deem this satisfactory as it represents our period of interest.

that it is the best approach for determining the appropriate lag length in VAR models when working with monthly data. In line with this, the AIC suggests that 19 lags is suitable for capturing the relevant temporal dependencies and dynamics in our dataset (Appendix A8).

Our identification strategy involves making assumptions about the contemporaneous structural relationships between the shocks and variables. The ordering of the variables in the system follows Kilian (2009), with the supply variables ordered at the top, followed by aggregate demand, and ultimately, the real price of gas. This is based on an economic interpretation of the interdependencies between the variables, taking into account our research question that focuses on how the real price of gas responds to supply shocks. The equation below specifies Equation (4) and represents the reduced form errors:

$$e_t \equiv \begin{bmatrix} e^{\Delta ruimp} \\ e^{\Delta prod} \\ e^{rea} \\ e^{rpg} \end{bmatrix}_t = \begin{bmatrix} s_{11} & 0 & 0 & 0 \\ s_{21} & s_{22} & 0 & 0 \\ s_{31} & s_{32} & s_{33} & 0 \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix} \begin{bmatrix} \varepsilon^{russian\ supply\ shock} \\ \varepsilon^{natural\ gas\ supply\ shock} \\ \varepsilon^{aggregate\ demand\ shock} \\ \varepsilon^{gas-specific\ demand\ shock} \end{bmatrix}_t \tag{7}$$

where matrix S is lower triangular, with positive elements on the diagonal and the elements above the diagonal restricted to zero. The decomposition of the system emphasises the importance of the variable ordering, as it affects the variables' responses to shocks in the other variables. The zeros decide which shocks have no contemporaneous impact on the different variables.

Natural gas supply shocks are unexpected changes in supply of natural gas in the EU. Our model distinguishes between two types of negative supply shocks: Russian supply shocks and EU supply shocks. Russian supply shocks represent a sudden change in imports of natural gas from Russia to the EU. On the other hand, EU supply shocks arise from an unexpected change in primary production of natural gas within the EU. By ordering the supply variables at the top of the system, the model postulates a vertical short-run supply curve of natural gas (Kilian, 2009). In other words, the supply curve is inelastic. This implies that the supply variables do not respond to aggregate demand shocks nor gas-specific demand shocks within the same month. Hence, EU imports from Russia and EU primary production are likely to respond to these innovations with a lag due to costs of adjusting production and uncertainty regarding the timing of business cycles (Kilian, 2009). This is consistent with changes in prices having a limited impact on the quantity of natural gas supplied in the short run. We incorporate this inelasticity in our model specification by setting $s_{13} = s_{14} = s_{23} = s_{24} = 0$ in Equation 7.

We place imports from Russia above EU primary production. This decision is based on Russia using natural gas as a political rather than an economic tool and will thus not respond immediately to natural gas supply shocks in the EU. However, natural gas producers in the EU will react instantaneously to Russia's actions, within the limits of their capacity, especially in a situation where Russia decides to cut its natural gas exports to the EU. We find this to be plausible because imports from Russia represent a large chunk of the natural gas supply in the EU, and the EU has experienced that Russia uses natural gas as a political weapon. Hence, it is more realistic that production of natural gas in the EU tracks imports from Russia to prevent a supply deficit[7]. This relationship is explained by $s_{12} = 0$ in Equation 7.

Aggregate demand shocks are abrupt changes in the economic activity and are represented by shocks to the demand for all industrial commodities. The model imposes an exclusion restriction implying that economic activity takes one month to adjust to gas-specific demand shocks. This is reflected in our model specification with $s_{34} = 0$ in Equation 7. This is a plausible assumption as economic agents tend to adjust their behaviour more sluggishly compared to changes in prices. Hence, the impact on real economic activity is typically delayed by at least one month, which is consistent with the findings of Kilian (2009).

Lastly, gas-specific demand shocks are defined as innovations to the real price of gas that cannot be explained by natural gas supply shocks or aggregate demand shocks. These shocks reflect exogenous shifts in precautionary demand for natural gas that arises from expectations about the future state of the EU natural gas market[8]. This is consistent with Kilian (2009), who states that there are no other plausible candidates. The price movements induced by these shocks are highly correlated with independent measures of the precautionary demand (Alquist & Kilian, 2007). The real price of gas is the variable of main interest in our thesis and is therefore unrestricted in our model. This is reflected by no exclusion restrictions in the last row of matrix S, allowing for an analysis of instantaneous

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[7] We check whether we receive notably the same result when switching the ordering between EU imports from Russia and EU primary production in Section 6.4.

[8] These shocks reflect all residual variation in natural gas prices that is not explained by the other endogenous variables.

impacts of all variables on the real price of gas. This is intuitive considering that the price is often directly affected by supply and demand shocks. A significant reduction in the supply of natural gas likely results in higher prices. Conversely, a significant increase in the supply of natural gas can result in lower prices. Hence, allowing the price of natural gas to instantaneously react to supply and demand shocks seems reasonable.

5 Data

The model incorporates four variables to estimate the effects of structural shocks on natural gas prices in the EU. These include a proxy for natural gas prices in the EU, an indicator for real economic activity, and two variables representing the supply of natural gas in the EU. All of the time series comprises monthly data from 2014:01 to 2022:12, representing 108 observations.

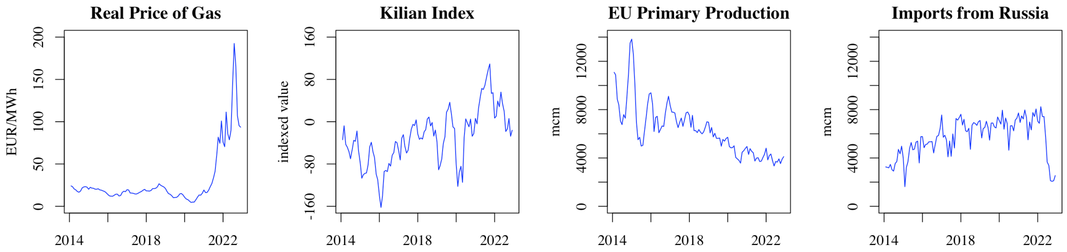

Figure 4: Plot of the variables in the model expressed in original units.

We use the Dutch TTF natural gas one-month futures contract as the proxy for natural gas prices in the EU, because it is the most common benchmark for European natural gas prices (Bennett, 2019). The descriptive statistics are outlined in Appendix A9. The contract reflects the price of natural gas delivered at the virtual trading point in the Netherlands. This is a hub for gas trading due to its location at the crossroads of several major pipelines in Europe. In addition, the TTF market is considered the most liquid and transparent market, ensuring reliable prices. Moreover, supporting our choice of proxy, Asche et al., (2013) find that European natural gas prices are relatively well integrated with each other. We use futures prices on monthly frequency rather than spot prices as the European gas market is more integrated and reliant on long-term contracts (IEA, 2020b). The futures prices are retrieved from Bloomberg and quoted in EUR/MWh, with the original source of the data being the energy exchange ICE Endex. To ensure consistency in our data set, we use daily prices to calculate the average monthly prices. Further, we deflate the nominal natural gas prices using the EU CPI (Eurostat, n.d.-b). The price variable is expressed in log levels in our model.

As a proxy for the real economic activity in the industrial commodity markets, we use an index constructed by Kilian (2009). The index is retrieved from Federal Reserve Bank of Dallas and updated on a monthly basis. It is based on dry cargo freight rates and captures changes in demand for industrial commodities as the economic activity and business cycle shift over time (Federal Reserve Bank of Dallas, n.d.). This makes it one of few indices that captures these shifts accurately and in a timely manner. The index's ability to capture this comprehensive view of economic fluctuations has made it a preferred measure for economic activity since inception. However, one limitation is that it weights all commodities and routes equally. This may introduce the possibility for the index to become biased over time, since routes and individual commodities are expected to change over time (Kilian, 2008, 2009). We express the index in discrete returns in our model, because the index can take on both positive and negative values.

To represent the supply side of natural gas in the EU, we include EU primary production and imports of natural gas from Russia. Contrary to Kilian (2009), we include EU primary production rather than global oil production, since we focus on the regional natural gas market within the EU. As depicted in Figure 4, the production of natural gas in the EU has exhibited a declining trend over time. The data is retrieved from Eurostat on monthly frequencies, measuring million cubic metres (mcm) of natural gas extracted from underground reservoirs or deposits (Eurostat, n.d.-a).

We augment Kilian's (2009) model by introducing EU imports of natural gas from Russia as an additional variable to examine the impact of the EU's dependence on Russian gas. Upon our preliminary analysis of the data (Figure 4, Plot 1 and 4), we found it particularly interesting that the sudden decline in natural gas imports from Russia appears to coincide with the sharp increase in natural gas prices in the EU. This motivated our research question, where we aim to investigate the relationship between the two variables more closely. We collected monthly frequency data from Eurostat on the quantity of natural gas imports from Russia to the EU, measured in mcm. In the model, supply variables are expressed in log differences. See Appendix A10 for description of all the variables.

6 Empirical Results

In this section, we present the empirical results of our analysis, including impulse response functions (IRFs), forecast error variance decompositions (FEVDs), and the historical decomposition. Lastly, we conduct robustness tests to evaluate the validity and reliability of our model. Aligned with our research question, we assess the effects of the structural shocks, with a particular focus on their impact on the real price of gas. Through a discussion of these results, we aim to obtain a better understanding of the dynamics of the EU natural gas market. Specifically, we focus on understanding the price effect of Russian supply shocks. The analysis is based on a sample period spanning from 2014:01 to 2022:12. The reduced form structural VAR model is estimated using the least squares method with 19 lags.

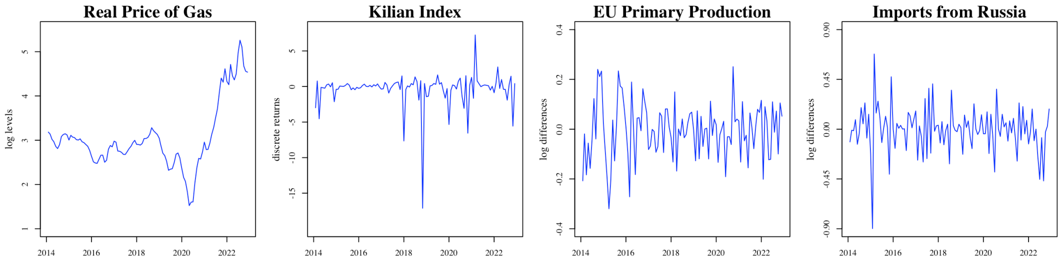

Figure 6: Plots of the time series used in our model. The real price of gas is expressed in log levels, Kilian's index is expressed in discrete returns, whereas the supply variables are expressed in log differences.

6.1 Impulse Response Functions

One of the key features of a structural VAR model is the ability to generate IRFs to estimate the effect of structural shocks imposed on the variables. This allows us to understand the dynamics of the system and how the shocks evolve over time. All shocks have been normalised such that an innovation intuitively leads to an increase in the real price of gas. This implies negative supply shocks and positive demand shocks. Additionally, we have accumulated the impulse responses for the variables expressed in returns. This enables us to assess the cumulative effect of the shocks over time, capturing the overall response and the persistence of the shocks' effect on the variables.

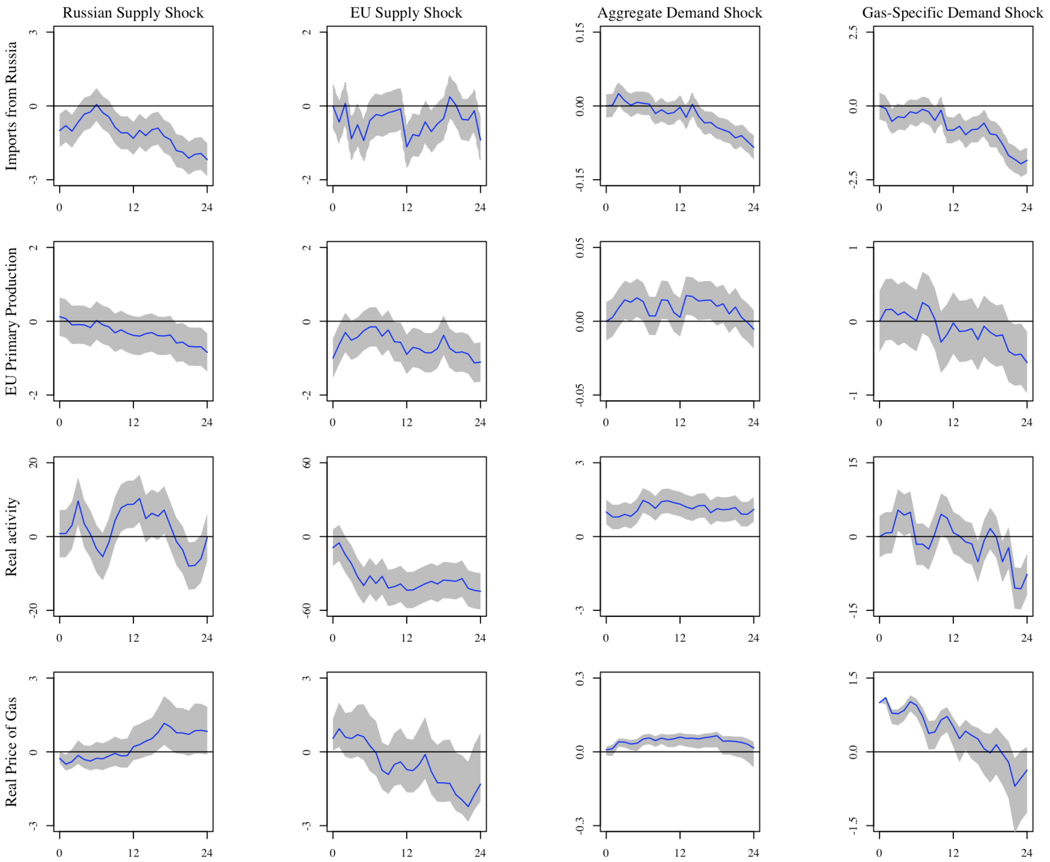

Figure 7: Impulse responses generated from the model described in Equation 6. The sample period is 2014:01 –2022:12. The responses are stated in levels of the variables. Shocks are normalised to unit shocks, such that the response of the variables equals one on impact. This implies 1% for Russian supply shocks, EU supply shocks and aggregate demand shocks, and one log unit for the real price of gas. Point estimates are indicated by solid lines, while the shaded area represents the upper and lower 68% confidence intervals, calculated using bootstrap with 10,000 draws.

In the figure above, each column represents a structural shock imposed on our variables of interest, whereas the rows illustrate the variables' responses to the structural shocks. The first and second column denote the effects of a 1% reduction in EU natural gas imports from Russia and EU primary production, respectively. In the third column, we examine the responses of a 1% increase in the Kilian index, whereas the fourth column represents the reaction to an increase of one log unit in the real price of gas. We comment on the responses of all the variables to gain insight about the overall dynamics of the EU natural gas market. We especially focus on the last row that illustrates the response of the real price of gas to the structural shocks.

First of all, we observe in the first row that the decline in imports of natural gas from Russia becomes more significant over time as Russian supply shocks materialise. Further, the imports decrease as a response to both positive aggregate and gas-specific demand shocks. These observations indicate that the imports decrease in response to shocks that intuitively should result in an increase in the real price of gas. This is consistent with the EU's actions to reduce its dependence on natural gas imports from Russia. Additionally, the finding supports that Russia utilises natural gas as a political weapon, since the country does not increase its exports when the price is high.

The second row shows the responses of the EU primary production to the respective structural shocks. The EU production does not increase in response to reduced supply from Russia nor positive gas-specific demand shocks. In addition, the effect of negative EU supply shocks leads to persistently lower domestic production over time. These responses suggest presence of capacity constraints or insufficient political involvement related to gas infrastructure in the EU. This may imply that the EU is already operating at maximum production capacity, making it challenging to increase production when there is a reduction in supply or increase in demand. This observation suggests that the EU's natural gas production is limited by existing infrastructure, hindering its ability to respond to external shocks.

Furthermore, in the third row, the impulse responses of the real economic activity indicate a persistently positive effect over time following positive aggregate demand shocks. This is expected because an increase in the overall demand for goods and services within an economy generally leads to an expansion of the economic activity. On the contrary, the economic activity is negatively affected by negative EU supply shocks. However, we exercise caution when claiming that the gas-specific variables directly affect the economic activity, because natural gas represents a small portion of the overall economy. This is consistent with Russian supply shocks and gas-specific demand shocks not exhibiting significant impacts on the economic activity.

In the last row, we review the responses of the real price of gas to structural innovations in the EU natural gas market. The value of the impulse response function can be interpreted as the cumulative percentage change in the real price of gas expressed in log levels, representing the deflated one-month futures contract. The sudden decline in imports from Russia causes an insignificant decrease in the real price of gas for the first year, before the shock materialises into a 1.16% increase in the real price of gas. The lagged effect may indicate that a reduction in supply from Russia can effectively be replaced in the short run. EU member countries have proactively been implementing measures that enables them to respond to unexpected declines in natural gas supply. This has been done by maintaining high inventory levels (Appendix A11) and diversifying their gas supply and energy sources. Additionally, policy measures, that are usually implemented by governments during external shocks, may also reduce the impact on the price in the short term. The long-term upward pressure on the real price of gas suggests that the EU's dependence on Russian gas makes it difficult to cope with the supply reduction in the long term. This can be attributed to depleted inventories and the substantial investments required in infrastructure for LNG and renewables. The short-term altering of market dynamics was observed in the beginning of 2023, when European gas prices experienced significant downward pressure despite the decline in imports from Russia. This can be explained by unseasonably mild weather conditions, strong LNG supply, and gas inventories well above historical averages (IEA, 2023). Our finding is consistent with our hypothesis that a reduction in EU natural gas imports from Russia has contributed to increasing prices over time.

An unexpected disruption in the EU primary production makes the real price of gas increase by ~1% upon impact. After seven months, the shock triggers a decline in the real price of gas. This effect may indicate that a decline in EU production does not necessarily lead to a reduction in total supply and higher prices, considering the EU's dependence on gas imports. Following positive aggregate demand shocks, the effect on the real price of gas is very persistent over time, leading to consistently higher prices. This is consistent with Kilian's (2009) findings for the effect on the real price of oil. However, the magnitude is not substantial (~0.05%). Lastly, positive gas-specific demand shocks in the EU leads to an immediate increase in the real price of gas. This effect persists for 19 months before it eventually dies out.

Focusing on the last column, gas-specific demand shocks tend to have more negative than positive impact on the variables of interest. This is in line with the empirical observation that higher prices generally have a negative impact (Nick & Thoenes, 2014). This negative impact coincides with lower economic activity and supply shortfall over time. This is consistent with a report by the European Commission that found that high gas prices can increase cost of production and transportation, leading to higher consumer prices and thus lower economic demand (Kuik et al., 2022).

6.2 Forecast Error Variance Decompositions

We continue our analysis by calculating the FEVDs. The decompositions provide insights into the contribution of each shock in explaining the variation in the variables. Throughout this section, we mainly focus on the real price of gas. The FEVDs of the other variables are outlined in Appendix A12. Table 1 represents the FEVD of the real price of gas, applied for the full sample period with forecast horizons of 1, 6, 12, 24, and 36 months[9].

h	Russian Supply Shock	EU Supply Shock	Aggregate Demand Shock	Gas-Specific Demand Shock
1	7.92	11.39	1.79	78.90
6	11.46	14.03	18.90	55.61
12	7.64	12.16	37.41	42.78
24	22.44	25.44	33.41	18.71
36	42.70	17.55	26.03	13.72

Table 1: FEVD of the real price of gas with a forecast horizon up to 36 months, representing the percent contribution of supply and demand shocks on the overall variability. The sum of the contribution of every shock adds up to 1 in every period.

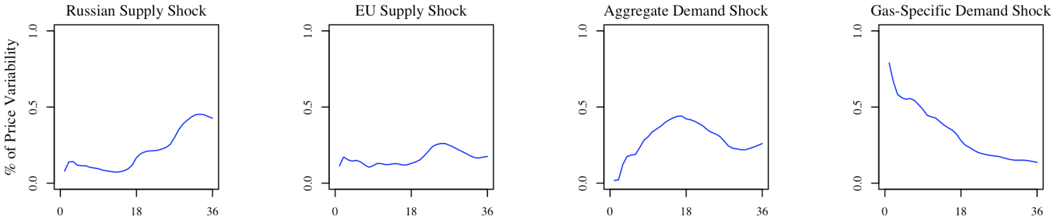

Figure 8: Graphical illustration of FEVD of the real price of gas with a forecast horizon up to 36 months.

The FEVD (Table 1 and Figure 8) shows the contribution of each structural shock in explaining the real price of gas. Our results indicate that in the first 18 months, the demand shocks play a bigger role than supply shocks in explaining the gas price variability. During this period, the supply shocks together account for 23.36%, while the demand shocks account for 76.64% of the variability on average. In the medium and long term, the supply shocks gain more explanatory power relative to the demand shocks, especially Russian supply shocks.

The contribution of Russian supply shocks is relatively stable for the first 18 months with an average contribution of ~10%. In the medium and long term, its explanatory power increases continuously. After 36 months, Russian supply shocks account for 42.70% of the fluctuation in the real price of gas. This finding is consistent with our hypothesis that a reduction in EU natural gas imports from Russia would have an increasing explanatory power on the real price of gas over

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[9] We refer to short-term effects as less than 12 months, medium-term effects as 12 to 24 months, and long-term effects as 24 months or more.

time. Repeating our arguments from Section 6.1, a supply reduction in the short term can be replaced by existing inventories or diversifying gas supply and energy sources. This may alter market dynamics in the short term and thus reduce the price effect of a supply shortfall. In the long run, however, our results indicate that it may be difficult to replace supply from Russia. Hence, the EU's dependence on Russian gas has long-term consequences for the real price of gas.

Focusing on the second plot in Figure 8, we see that the explanatory power of EU supply shocks on the real price of gas have the most stable contribution of the all the shocks over time. For the first 18 months, EU supply shocks have an average contribution of ~13%. Hereafter, the contribution peaks at ~26% on the 24-month horizon, before decreasing to ~18% on the 36-month horizon. The contribution of the supply shocks is not directly comparable to existing research since the specific angle is novel to our approach. However, other relevant papers also demonstrate upwards sloping curves for the supply shocks in their respective models. Rubaszek et al. (2020) show that U.S. natural gas dry production account for 6.4%, 9.1%, and 9.8% of the gas price variability in the short, medium, and long term, respectively. Similarly, Hailemariam & Smyth (2019) find that natural gas supply shocks in the U.S. has an increasing impact over time, although the contribution of these shocks is significantly smaller compared to our findings.

The contribution of aggregate demand shocks (Figure 8, third plot) is low in the first month, accounting for only 1.79% of the gas price variability. This short-term effect can be explained by a price adjustment lag arising from data processing time, expiration time on contracts, or renegotiation of terms. However, the importance of the aggregate demand shocks increases relatively fast and continuously up until 18 months, where the contribution is ~44%. In the medium to long term, the explanatory power decreases again to ~26%.

Lastly, as expected, we see that gas-specific demand shocks (Figure 8, fourth plot) have a high level of contribution to the variation in the real price of gas in the short run. These demand shocks represent the residual variation in natural gas prices that is not explained by other variables in the model. The strong short-run effect decreases as the forecast horizon increases, implying that the gas price is highly influenced by its own lags in the short term. In the long term, the contribution decreases as the other shocks gain more explanatory power on the real price of gas. This development is consistent with existing research on the U.S.

market. Jadidzadeh & Serletis (2017) show a contribution of "other shocks" to be 99.62% in the first period and decreasing to 61.71% in the 15th period. Hailemariam & Smyth (2019) show a contribution of 99.8%, 97.3%, and 97.2% in the 1st, 24th, and 60th period, respectively.

Overall, it is challenging to compare our findings with existing research, as most of the papers on structural VAR analyses on natural gas markets focus on the U.S. market. However, we can compare our results with the literature discussed in Section 3.3 on natural gas market dynamics. Hailemariam & Smyth (2019) argue that the fluctuations in natural gas prices are almost exclusively explained by its own lags. However, similar to our result, the paper shows an increasing contribution from supply shocks over time. Jadidzadeh & Serletis (2017) also argue that most of the gas price variability is attributed to gas-specific demand shocks in the short term, and that supply shocks have increasing explanatory power over time. In addition, the paper finds a concave development of aggregate demand shocks over time. The broad picture that emerges from this comparison is that our results demonstrate similar developments for supply, aggregate demand and gas-specific demand shocks over time.

6.3 Historical Decomposition

The historical decomposition shows the cumulative contribution of the structural shocks on the real price of gas over the sample period, allowing us to determine the cumulative effect of each structural shock at any point in time. This makes it easier to quantify the evolution of the response of the real price of gas to the structural shocks. Implied by our model, Figure 9 displays the accumulated effect of the structural shocks, while Figure 10 plots the time path of each structural shock. The plots start at the end of 2015, accounting for the 19 lags in our model.

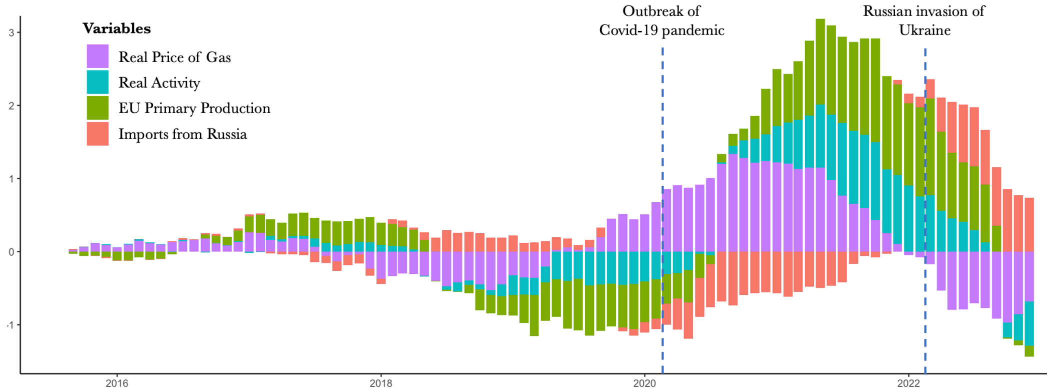

Figure 9: Historical decomposition of the real price of gas. The variables represent the historical contribution of gas-specific demand shocks, aggregate demand shocks, EU supply shocks, and Russian supply shocks in explaining the real price of gas.

The historical decomposition comprises several geopolitical events and recessions that have resulted in significant fluctuations in the real price of gas and the overall economic activity. Our research has been notably affected by the Covid-19 pandemic, spanning from 2020 to 2022, and the Russian invasion of Ukraine at the beginning of 2022 to present. To our knowledge, there are no similar papers investigating the same data period capturing these major events. The pandemic caused a global economic slowdown, surging inflation, and significant volatility in natural gas prices. The invasion contributed to another setback to the global economy, and significantly less imports of natural gas from Russia to the EU (International Monetary Fund, 2023). As a result of these events, Europe is experiencing an unprecedented energy crisis, with energy prices reaching all-time highs in 2022.

As depicted in Figure 9, the importance of the structural shocks in driving fluctuations in the real price of gas varies across the sample period. As expected, the impact was minuscule until the volatility of the price rose steeply in 2020. Towards the end of the sample period, we observe a negative combined effect on the real price of gas. These effects coincide with the observed fluctuations in natural gas prices.

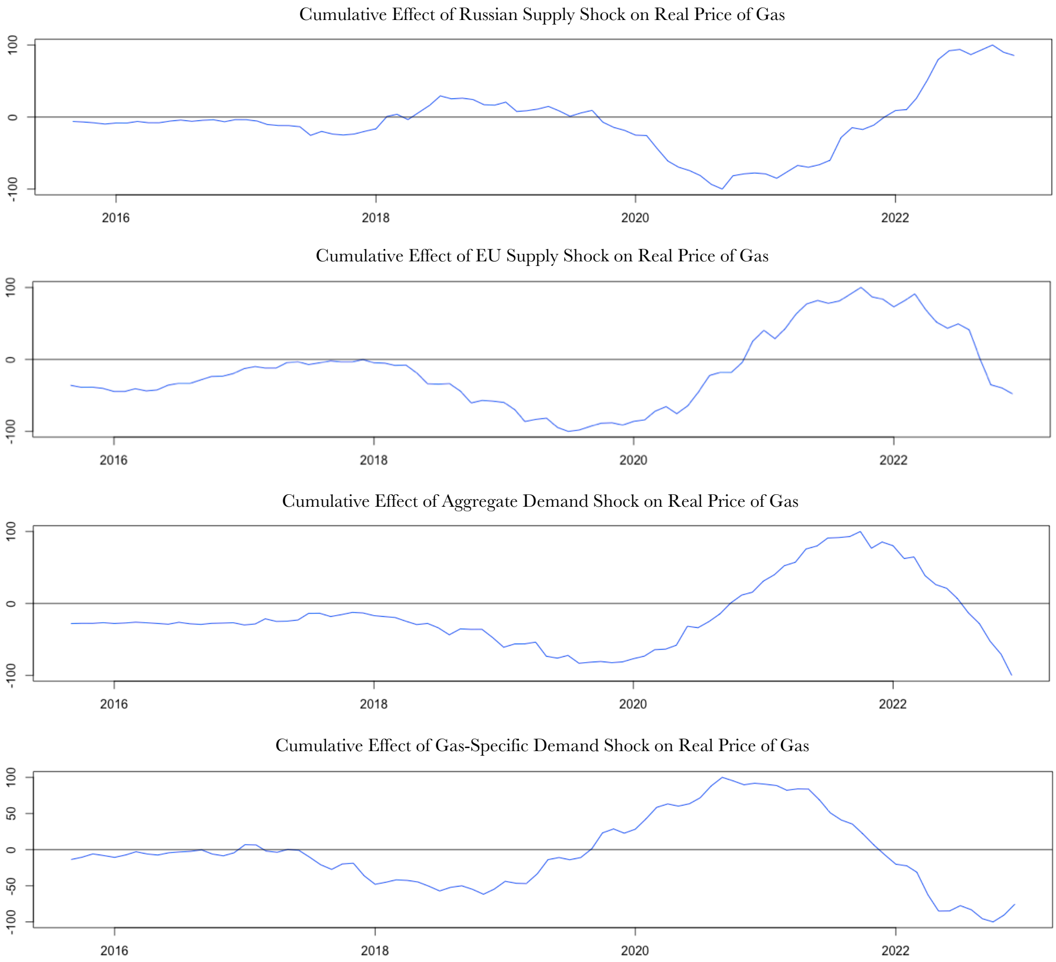

Figure 10: Cumulative effects of Russian supply shocks, EU supply shocks, aggregate demand shocks, and gas-specific demand shocks to the real price of gas based on a historical decomposition of the data.

The respective cumulative effects of the structural shocks on the real price of gas are illustrated in Figure 10. At first glance, the panels have similar patterns, with increasing impact towards the end of the sample period. The first panel illustrates the cumulative effect of Russian supply shocks on the real price of gas. Initially, the impact of the shocks is relatively insignificant, with only minor effects on the price. However, the impact turns negative in 2020, corresponding to a period with a steady increase of natural gas supply from Russia to the EU, despite the sharp drop in demand caused by the Covid-19 pandemic. Following Russia's invasion of Ukraine in 2022, the impact turns positive due to the significantly reduced gas supply from Russia to the EU at a time when the demand for natural gas was relatively high.

In the beginning of the sample period, the cumulative effect of EU supply shocks on the real price gas was the most significant compared to the other structural shocks. At this point in time, the production of natural gas in the EU was relatively high, thus affecting the price negatively. Similar to Russian supply shocks, EU supply shocks had a negative effect on prices in 2020, due to the decreased demand caused by the Covid-19 pandemic. However, the negative impact shifted to positive more quickly compared to the contribution of Russian supply shocks, probably because of the declining trend in the EU primary production.

The third panel illustrates the cumulative effect of aggregate demand shocks. The outbreak of the Covid-19 pandemic led to a drop in demand for natural gas, causing a subsequent negative effect on the real price of gas. However, as economic activity in the industrial commodity markets eventually stabilised at a high level, these shocks had a positive effect on the price. At the end of 2022, lower demand for industrial commodities resulted in a negative effect on the real price of gas. The final panel represents the cumulative effect of gas-specific demand shocks on the real price of gas. We observe that the impact across the sample period is similar to aggregate demand shocks. This is probably because the shocks are driven by similar factors.

To summarise the effect during our two most important events: After the outbreak of the Covid-19 pandemic, all of the structural shocks had negative effects on the real price of gas. This coincides with the steep decline in the real price of gas in 2020. Following the Russian invasion of Ukraine in 2022, the historical decomposition reveals that the decreased supply of natural gas from Russia to the EU contributes to elevated natural gas prices. However, the combined impact of the three other shocks, that contributes to lower prices, is more substantial. This explains the decrease in the real price of gas observed at the end of 2022.

6.4 Robustness Tests

To assess the robustness of our baseline model, we conduct three different robustness tests. In the first test, we employ an alternative proxy to represent the economic activity, while all other variables and the methodology remain the same. We substitute Kilian's index with EU industrial production. This substitution should better capture the local character of natural gas compared to oil. We observe relatively similar patterns when comparing the impulse responses of the real price of gas in our baseline model with those of the new model that incorporates EU industrial production. However, even though the main conclusions are the same, the short-term effect differs. In addition, the presence of more narrow confidence intervals suggests less uncertainty regarding the impact of positive demand shocks on the real price of gas. These disparities could be due to the appreciation of the USD towards the end of 2014 and the rapid expansion of manufacturing activities, which potentially invalidated the usage of the industrial production index as a measure of real economic activity (Wiggins & Etienne, 2017).

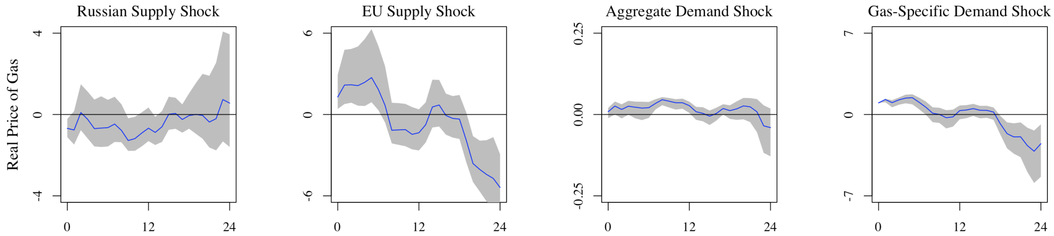

Figure 11: Impulse responses on the real price of gas for a structural VAR model with EU industrial production representing real economic activity. According to AIC, the model has 19 lags. The sample period is 2014:01 –2022:12. The responses are stated in levels of the variables and the shocks are normalised to unit shocks. The shaded area represents the upper and lower 68% confidence intervals, calculated using bootstrap with 10,000 draws.

The second robustness test implies rearranging the ordering of the variables, such that EU primary production is placed at the top and imports from Russia second. The results do not change compared to our baseline model results, indicating that the effects remain similar irrespective of the ordering of the variables. This implies that the model is robust, since the effects of the variables are not heavily influenced by their specific order.

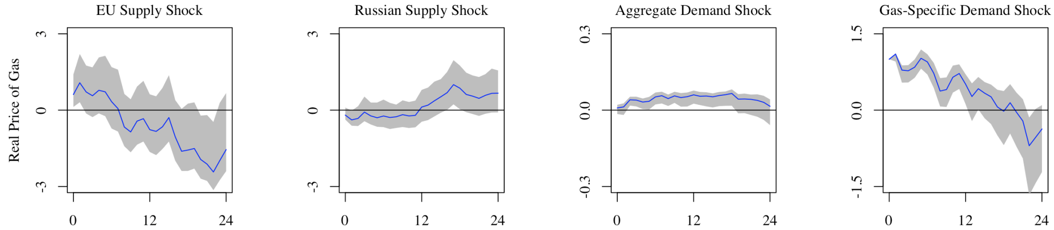

Figure 12: Impulse responses on the real price of gas for a structural VAR model with EU primary production placed above imports from Russia. According to AIC, the model has 19 lags. The sample period is 2014:01 –2022:12. The responses are stated in levels of the variables and the shocks are normalised to unit shocks. The shaded area represents the upper and lower 68% confidence intervals, calculated using bootstrap with 10,000 draws.

Lastly, we split our data period into two subsamples (2014:01 – 2018:12 and 2019:01 – 2022:12) and conduct the empirical analysis for each of the subsamples. The second subsample includes both the Covid-19 pandemic and the Russian invasion of Ukraine. This makes it possible to investigate whether the dynamics of the EU natural gas market have changed during our baseline sample period. We emphasise that shorter sample periods potentially limit the accuracy and reliability of the results. In addition, using fewer lags might make it hard to capture the full temporal dynamics of the system. This is because the lags account for delayed responses and allow to examine the interaction between the variables over time.

The empirical results from the first subsample are more in line with our initial expectations. The results indicate that a sudden decline in imports from Russia causes the real price of gas to stay at a consistently higher level, whereas the effect of EU supply shocks is harder to interpret. This is probably due to existing capacity constraints, as discussed in Section 6.1. Similar to the impulse responses of our baseline model, the effect of gas-specific demand shocks leads to an immediate increase in the real price of gas before it eventually dies out. However, we struggle to find the response to aggregate demand shocks intuitive.

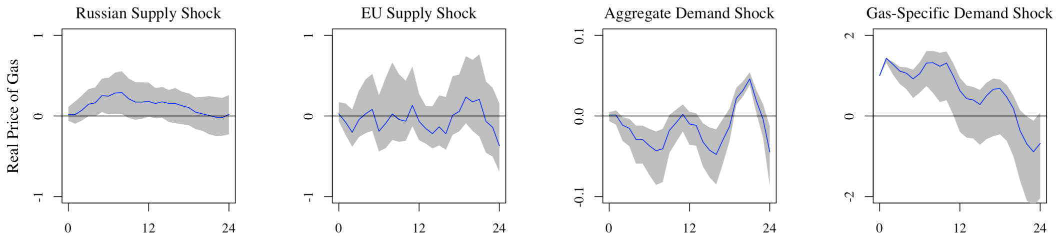

Figure 13: Impulse responses on the real price of gas for a structural VAR model with sample period 2014:01 –2018:12. According to AIC, the model has seven lags. The responses are stated in levels of the variables and the shocks are normalised to unit shocks. Point estimates are indicated by solid lines and the shaded area represents the upper and lower 68% confidence intervals, calculated using bootstrap with 10,000 draws.

We observe that the second subsample is more volatile, and that its short-run effects are similar to our baseline model results. Hence, we observe more complex responses to the negative supply shocks, and positive responses to the positive aggregate and gas-specific demand shocks. However, the short-run effect persists for a longer time horizon compared to our baseline model. Hence, it takes longer time for Russian supply shocks to materialise into higher natural gas prices. Similarly, EU supply shocks and gas-specific demand shocks cause the price to increase for a longer period, before the effects turn negative. These findings indicate that the dynamics of the EU natural gas market have to some extent changed after the Covid-19 pandemic and the Russian invasion of Ukraine. However, as mentioned above, we do realise that the two subsamples might respond to the structural shocks differently because the sample periods are shorter, and we use fewer lags in the structural VAR models.

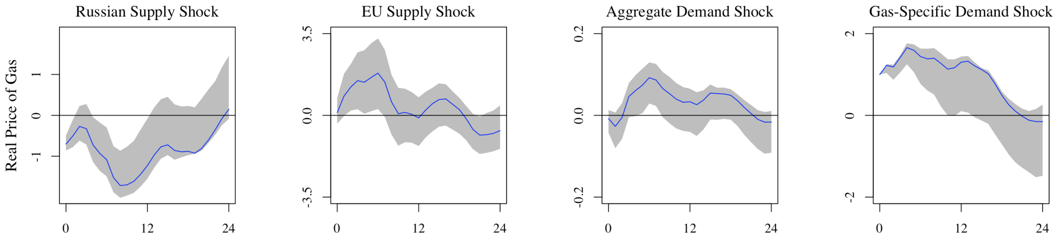

Figure 14: Impulse responses on the real price of gas for a structural VAR model with sample period 2019:01 –2022:12. According to AIC, the model has five lags. The responses are stated in levels of the variables and the shocks are normalised to unit shocks. Point estimates are indicated by solid lines and the shaded area represents the upper and lower 68% confidence intervals, calculated using bootstrap with 10,000 draws.

Upon conducting robustness tests, we conclude that our main results derived from the baseline model remain robust to the chosen identification strategy. This demonstrates the stability and consistency of our findings, making them valid and reliable.

7 Conclusion

In this thesis, we investigate the dynamics of the EU natural gas market by analysing the impact of supply and demand shocks on natural gas prices. Following the Russian invasion of Ukraine, which highlighted the EU's dependence on Russian gas, we became particularly interested in investigating the effect of Russian supply shocks. To do this, we employ a structural VAR model based on the methodology proposed by Kilian (2009), incorporating imports from Russia, EU production, real global activity, and the real price of gas as variables. To our knowledge, applying imports from Russia and EU production as supply variables in a structural VAR analysis of the EU natural gas market represents an innovative contribution to the existing literature.

Our analysis reveals that the response of natural gas prices to shocks in supply and demand variables varies over time. The positive responses to positive aggregate and gas-specific demand shocks are aligned with our expectations, while the interpretation of the responses to negative supply shocks is more comprehensive. Russian supply shocks are insignificant the first year, before the shocks materialise and cause the prices to increase by 1.16%. The lagged effect may indicate that the EU can substitute supply shortfalls in the short run by utilising inventories or alternative sources of gas and energy. An alternative reason may be policy measures that aims to reduce the impact of negative supply shocks on the prices in the short term. In the long term, the results reveal that the high dependence on Russian gas makes it difficult to cope with the supply reductions. This may be due to the large investments necessary to improve the infrastructure for LNG and renewables. Further, our results reveal that an unexpected decrease of 1% in the EU primary production makes the real price of gas increase by ~1% upon impact, before the shock triggers a significant decline. This effect may indicate that a decline in EU production does not necessarily lead to a reduction in total supply and higher prices, considering the EU's dependence on gas imports. We also provide evidence indicating that the EU's natural gas production is limited by existing infrastructure, hindering its ability to respond to external shocks.

The variation in the natural gas prices is mainly explained by demand shocks in the short to medium term. However, this contribution is continuously declining over time, as the supply shocks gain more explanatory power, particularly Russian supply shocks. Compared to existing research mentioned throughout the thesis, we find significantly higher impact from supply shocks over time. However, these papers are not directly comparable, since they investigate different markets and data periods. Finally, when decomposing the historical contribution of structural shocks, we observe that their impact on natural gas prices increases over the data period. This coincides with the increased volatility in natural gas prices after 2020. As a result, we conclude that our findings support our hypothesis that a decrease in EU natural gas imports from Russia has contributed to increasing prices, with increasing explanatory power over time.

To further examine the dynamics of the EU natural gas market, we propose to repeat our analysis when more data becomes available. We provide evidence that the dynamics of the EU natural gas market have to some extent changed during our sample period, making it interesting to incorporate more data that includes the current gas dispute between Russia and the EU. To take our analysis a step further, it would be interesting to empirically investigate why the effect of negative Russian supply shocks on natural gas prices requires one year to manifest in the form of higher prices. This analysis would imply including other supply variables in the model, such as EU inventory levels or LNG imports. Additionally, it would be interesting to examine the differentiation of the marginal cost of natural gas from other energy sources.

8 Bibliography

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Alquist, R., Bhattarai, S., & Coibion, O. (2020). Commodity-price comovement and global economic activity. *Journal of Monetary Economics*, *112*(C), 41–56.

Alquist, R., & Kilian, L. (2007). What Do We Learn from the Price of Crude Oil Futures? *CEPR Discussion Papers*, *25*. https://doi.org/10.2307/40607046

Arora, V., & Lieskovsky, J. (2014). Natural Gas and U.S. Economic Activity. *The Energy Journal*, *35*(3). https://doi.org/10.5547/01956574.35.3.8

Aruga, K. (2016). The U.S. shale gas revolution and its effect on international gas markets. *Journal of Unconventional Oil and Gas Resources*, *14*, 1–5. https://doi.org/10.1016/j.juogr.2015.11.002

Aruoba, S. B., Diebold, F. X., & Scotti, C. (2009). Real-Time Measurement of Business Conditions. *Journal of Business & Economic Statistics*, *27*(4), 417–427. https://doi.org/10.1198/jbes.2009.07205

Asche, F., Misund, B., & Sikveland, M. (2013). The relationship between spot and contract gas prices in Europe. *Energy Economics*, *38*, 212–217. https://doi.org/10.1016/j.eneco.2013.02.010

Baumeister, C., & Hamilton, J. D. (2019). Structural Interpretation of Vector Autoregressions with Incomplete Identification: Revisiting the Role of Oil Supply and Demand Shocks. *American Economic Review*, *109*(5), 1873–1910. https://doi.org/10.1257/aer.20151569

Baumeister, C., & Peersman, G. (2013). The Role of Time-Varying Price Elasticities in Accounting for Volatility Changes in the Crude Oil Market. *Journal of Applied Econometrics*, *28*(7), 1087–1109. https://doi.org/10.1002/jae.2283

Bennett, G. (2019). LNG trading, liquidity, and hedging: A new landscape for natural gas benchmarks. *The Oxford Institute for Energy Studies*, *119*, 29–33.

Bjørnland, H. C. (n.d.). PhD Course: Structural VAR models. Lecture II. Specification, estimation procedure and information content. *Norwegian School of Management* (BI).

Bjørnland, H. C., & Thorsrud, L. A. (2015). Applied time series for macroeconomics (2nd edition). *Gyldendal*. https://www.gyldendal.no/faglitteratur/e-boeker/oekonomi-og-administrasjon/applied-time-series-for-macroeconomics-e-bok/p-10024192-no/

Blanchard, O. J., & Quah, D. (1988). The Dynamic Effects of Aggregate Demand and Supply Disturbances. *National Bureau of Economic Research*. https://doi.org/10.3386/w2737

Bowen, A. S. (2022). Russian Military Buildup Along the Ukrainian Border. *Congressional Research Service*. https://crsreports.congress.gov/product/pdf/IN/IN11806

Braun, R. (2021). The importance of supply and demand for oil prices: Evidence from non-Gaussianity. *Bank of England Working Papers*, Article 957. https://ideas.repec.org//p/boe/boeewp/0957.html

Britannica. (n.d.). Natural gas - Composition and properties of natural gas. *Britannica.* Retrieved 24 April 2023, from https://www.britannica.com/science/natural-gas/Composition-and-properties-of-natural-gas

Brown, S., & Yücel, M. K. (2008). What Drives Natural Gas Prices? *The Energy Journal*, *Volume 29*, 45–60.

Byrne, J., Fazio, G., & Fiess, N. (2013). Primary commodity prices: Co-movements, common factors and fundamentals. *Journal of Development Economics*, *101*(C), 16–26.

Caldara, D., Cavallo, M., & Iacoviello, M. (2019). Oil price elasticities and oil price fluctuations. *Journal of Monetary Economics*, *103*, 1–20. https://doi.org/10.1016/j.jmoneco.2018.08.004

CNBC. (2022a, February 24). Russian forces invade Ukraine. *CNBC.* https://www.cnbc.com/2022/02/24/russian-forces-invade-ukraine.html

CNBC. (2022b, August 31). Russia halts gas flows to Europe via Nord Stream 1 for maintenance works. *CNBC.* https://www.cnbc.com/2022/08/31/russia-temporarily-halts-gas-flows-to-europe-via-nord-stream-1.html

Cooley, T., & LeRoy, S. (1985). Atheoretical macroeconometrics: A critique. *Journal of Monetary Economics*, *16*(3), 283–308.

Corboy, D., Courtney, W., & Yalowitz, K. (2014, November 6). Hitting the Pause Button: The 'Frozen Conflict' Dilemma in Ukraine. *The National Interest.* https://nationalinterest.org/feature/hitting-the-pause-button-the-frozen-conflict-dilemma-ukraine-11618

D'Anieri, P. (2019). Ukraine and Russia—From Civilized Divorce to Uncivil War (2nd edition). *Cambridge University Press.*

Delle Chiaie, S., Ferrara, L., & Giannone, D. (2017). Common factors of commodity prices (Working Paper Series No. 2112). *European Central Bank.* https://econpapers.repec.org/paper/ecbecbwps/20172112.htm

Deutsche Welle. (2022, January 12). EU tries to mitigate impact of gas shortages. *Deutche Welle.* https://www.dw.com/en/eu-prepares-for-russia-to-cut-off-gas-supply-over-sanctions/a-62493092

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the Estimators for Autoregressive Time Series With a Unit Root. *Journal of the American Statistical Association*, *74*(366), 427–431. https://doi.org/10.2307/2286348

EIA. (2022, December 27). Natural gas explained. *U.S. Energy Information Administration.* https://www.eia.gov/energyexplained/natural-gas/

Eiknes, M. (2021, January 26). How Does Regasification of LNG Work? *Econnect Energy.* https://www.econnectenergy.com/articles/how-does-regasification-of-lng-work

Energy Council. (2022, March). Global gas report – the effects of the Russo-Ukrainian War on global supply. *Energy Council.* https://energycouncil.com/articles/global-gas-report-the-effects-of-the-russo-ukrainian-war-on-global-supply/

Eur-Lex. (2023, February 5). Council Decision 2014/512/CFSP of 31 July 2014 concerning restrictive measures in view of Russia's actions destabilising the situation in Ukraine. *Eur-Lex.* http://data.europa.eu/eli/dec/2014/512/2023-02-05/eng

European Commission. (2022, November 22). Questions and Answers on the gas market correction mechanism. *European Commission.* https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_7066

European Commission. (2023, March 14). Reform of the EU electricity market design. *European Commission.* https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1591

European Council. (2022a, November 7). Where does the EU's gas come from? *European Council.* https://www.consilium.europa.eu/en/infographics/eu-gas-supply/

European Council. (2022b, December 20). Liquefied natural gas infrastructure in the EU. *European Council.* https://www.consilium.europa.eu/en/infographics/lng-infrastructure-in-the-eu/

European Union. (2021, February 25). Seven years since Russia's illegal annexation of Crimea. *EEAS.* https://www.eeas.europa.eu/eeas/seven-years-russia%E2%80%99s-illegal-annexation-crimea_en

Eurostat. (n.d.-a). Eurostat's Concepts and Definitions Database. *Eurostat.* Retrieved 4 April 2023, from https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=DSP_GLOSSARY_NOM_DTL_VIEW&StrNom=CODED2&StrLanguageCode=EN&IntKey=33013336&RdoSearch=&TxtSearch=&CboTheme=&IsTer=&ter_valid=0&IntCurrentPage=121

Eurostat. (n.d.-b). Statistics. *Eurostat.* Retrieved 4 April 2023, from https://ec.europa.eu/eurostat/databrowser/view/PRC_HICP_CIND__custom_5566073/default/table?lang=en

Eurostat. (2022, March 9). Energy statistics - An overview. *Eurostat.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview

Faust, J. (1998). The robustness of identified VAR conclusions about money. *Carnegie-Rochester Conference Series on Public Policy*, *Volume 49*, 207–244. https://doi.org/10.1016/S0167-2231(99)00009-3

Federal Reserve Bank of Dallas. (n.d.). Index of Global Real Economic Activity. *Federal Reserve Bank of Dallas*. Retrieved 4 April 2023, from https://www.dallasfed.org/research/igrea

Galí, J. (1999). Technology, Employment and the Business Cycle: Do Technology Shocks Explain Aggregate Fluctuations? *American Economic Review*, 249–271.

Global Witness. (2022, August 1). Loopholes undermine sanctions: The Russian Shipping Forecast. *Global Witness.* https:///en/campaigns/stop-russian-oil/loopholes-undermine-sanctions-regime-russian-shipping-forecast/

Gottschalk, J. (2001). An Introduction into the SVAR Methodology: Identification, Interpretation and Limitations of SVAR models. *Kiel Institute for the World Economy*. https://EconPapers.repec.org/RePEc:zbw:ifwkwp:1072.

Hailemariam, A., & Smyth, R. (2019). What drives volatility in natural gas prices? *Energy Economics*, *80*, 731–742. https://doi.org/10.1016/j.eneco.2019.02.011

Hamilton, J. D. (2003). What is an oil shock? *Journal of Econometrics, 113*(2), 363–398. https://doi.org/10.1016/S0304-4076(02)00207-5

Hartley, P., Medlock, K., & Rosthal, J. E. (2008). The Relationship of Natural Gas to Oil Prices. *The Energy Journal*, *Volume 29* (Number 3), 47–66.

Hou, C., & Nguyen, B. H. (2018). Understanding the US natural gas market: A Markov switching VAR approach. *Energy Economics*, *75*(C), 42–53.

IEA. (2019, July). The Role of Gas in Today's Energy Transitions – Analysis. *IEA.* https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions

IEA. (2020a). Europe – Countries & Regions. *IEA.* https://www.iea.org/regions/europe

IEA. (2020b, May). 2021-2025: Rebound and beyond – Gas 2020 – Analysis. *IEA.* https://www.iea.org/reports/gas-2020/2021-2025-rebound-and-beyond

IEA. (2023, May). Gas Market Report, Q2-2023 – Analysis. *IEA.* https://www.iea.org/reports/gas-market-report-q2-2023

International Monetary Fund. (2023, April). World Economic Outlook, April 2023: A Rocky Recovery. *IMF.* https://www.imf.org/en/Publications/WEO/Issues/2023/04/11/world-economic-outlook-april-2023

Ivanov, V., & Kilian, L. (2007). A Practitioner's Guide to Lag Order Selection for VAR Impulse Response Analysis. *Studies in Nonlinear Dynamics & Econometrics*, *9*, 1219–1219. https://doi.org/10.2202/1558-3708.1219

Jacks, D. S., & Stuermer, M. (2020). What drives commodity price booms and busts? *Energy Economics*, *85*, 104035. https://doi.org/10.1016/j.eneco.2018.05.023

Jadidzadeh, A., & Serletis, A. (2017). How does the U.S. natural gas market react to demand and supply shocks in the crude oil market? *Energy Economics*, *63*, 66–74. https://doi.org/10.1016/j.eneco.2017.01.007

Kilian, L. (2008). Exogenous Oil Supply Shocks: How Big Are They and How Much Do They Matter for the U.S. Economy? *The Review of Economics and Statistics*, *90*(2), 216–240.

Kilian, L. (2009). Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market. *American Economic Review*, *99*(3), 1053–1069. https://doi.org/10.1257/aer.99.3.1053

Kilian, L. (2011). Structural Vector Autoregressions. *SSRN* (Scholarly Paper No. 1908563). https://papers.ssrn.com/abstract=1908563

Kilian, L., & Murphy, D. P. (2012). Why Agnostic Sign Restrictions Are Not Enough: Understanding The Dynamics Of Oil Market Var Models. *Journal of the European Economic Association*, *10*(5), 1166–1188.

Kilian, L., & Murphy, D. P. (2014). The Role of Inventories and Speculative Trading in the Global Market for Crude Oil. *Journal of Applied Econometrics*, *29*(3), 454–478. https://doi.org/10.1002/jae.2322

Kotzé, K. (n.d.). Vector Autoregression Models. *Economodel.* Retrieved 26 June 2023, from https://www.economodel.com/time-series-analysis-2019

Kuik, F., Adolfsen, J. F., Meyler, A., & Lis, E. (2022). Energy price developments in and out of the COVID-19 pandemic – from commodity prices to consumer prices. *ECB Economic Bulletin*, *4/2022*. https://www.ecb.europa.eu/pub/economic-bulletin/articles/2022/html/ecb.ebart202204_01~7b32d31b29.en.html

Kwiatkowski, D., Phillips, P. C. B., Schmidt, P., & Shin, Y. (1992). Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? *Journal of Econometrics*, *54*(1), 159–178. https://doi.org/10.1016/0304-4076(92)90104-Y

Lütkepohl, H. (2005). New introduction to multiple time series analysis. *Springer Berlin, Heidelberg.* https://doi.org/10.1007/978-3-540-27752-1

Mertens, K., & Ravn, M. O. (2019). The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States: Reply. *The American Economic Review*, *109*(7), 2679–2691.

Misund, B., & Øglend, A. (2016). Supply and demand determinants of natural gas price volatility in the U.K.: A vector autoregression approach. *Energy (2016). 178-189*. https://doi.org/10.1016/j.energy.2016.05.124

Molnar, G. (2022). Economics of Gas Transportation by Pipeline and LNG. In M. Hafner & G. Luciani (Eds.), *The Palgrave Handbook of International Energy Economics* (pp. 23–57). https://doi.org/10.1007/978-3-030-86884-0_2

Nick, S., & Thoenes, S. (2014). What Drives Natural Gas Prices? – A Structural VAR Approach. *Energy Economics*, *45(*C), 517–527. https://doi.org/10.1016/j.eneco.2014.08.010

Norwegian Petroleum Directorate. (2022, September 22). The oil and gas pipeline system. *Norsk Petroleum.* https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/

Pirani, S. (2007). Ukraine's Gas Sector. *Oxford Institute for Energy Studies*. https://www.oxfordenergy.org/publications/ukraines-gas-sector/

Pirani, S., Stern, J., & Yafimava, K. (2009). The Russo-Ukrainian gas dispute of January 2009: A comprehensive assessment. *Oxford Institute for Energy Studies.*

Planete Energies. (2022, April 25). Gas pipelines between Europe, Russia and Caucasia. *Planete Energies.* https://www.planete-energies.com/en/media/infographic/gas-pipelines-between-europe-russia-and-caucasia

Reuters. (2009, January 7). 18 countries affected by Russia-Ukraine gas row. *Reuters*. https://www.reuters.com/article/uk-russia-ukraine-gas-factbox-idUKTRE5062Q520090107

Rubaszek, M., Uddin, G. S., & Szafrane, K. (2020). The role of underground storage in the dynamics of the US natural gas market: A threshold model analysis. *Energy Economics*, *87*(C). https://ideas.repec.org//a/eee/eneeco/v87y2020ics0140988320300529.html

Sims, C. A. (1980). Macroeconomics and Reality. *Econometrica*, *48*(1), 1–48. https://doi.org/10.2307/1912017

Speight, J. G. (2007). Natural Gas: A Basic Handbook. Chapter 4 - Recovery, Storage, and Transportation. (pp. 87–111). *Gulf Publishing Company.* https://doi.org/10.1016/B978-1-933762-14-2.50009-1

Stock, J., & Watson, M. W. (2012). Disentangling the Channels of the 2007-2009 Recession. *Brookings*, 81–156. https://www.brookings.edu/bpea-articles/disentangling-the-channels-of-the-2007-2009-recession/

Strauss Center. (n.d.). Natural Gas vs. Oil. *The Strauss Center.* Retrieved 16 March 2023, from https://www.strausscenter.org/energy-and-security-project/gas-vs-oil/

Wiggins, S., & Etienne, X. L. (2017). Turbulent times: Uncovering the origins of US natural gas price fluctuations since deregulation. *Energy Economics*, *64*, 196–205. https://doi.org/10.1016/j.eneco.2017.03.015

A. Appendix

A1. Timeline of Political Events

Year	Event
February 1954	Under the government of Nikita Khrushcev, Crimea was transferred from the Russian Soviet Federative Socialist Republic (RSFSR), to the Ukrainian Soviet Socialist Republic (SSR).
December 1991	Declaration of Independence of Ukraine and the dissolution of the Soviet Union (USSR) after a referendum. Leonid Kravchuk (Political party: independent) was elected president. Independent Ukraine originally maintained strong ties with Russia, which led to an integration of their economies.
1990s	Gas disputes of the 1990s: Immediately after the collapse of the Soviet Union, gas depts and non-payment issues emerged, resulting in Russia suspending natural gas export several times.
June 1994	The Partnership and Co-operation Agreement (PCA) between the EU and Ukraine was signed. The agreement established a framework for political, economic, and democratic cooperation between the two countries, aiming to integrate Ukraine into the EU and global economy.
July 1994	Leonid Kuchma (Political party: independent) was elected as president.
September 1997	The first EU-Ukraine summit took place in Kyiv.
March 1998	The PCA that was signed in 1994 entered in to force and would last through 2008.
October 1998	The second EU-Ukraine summit took place in Vienna. Ukraine declared its desire to acquire associate membership in the EU.
November 2004	The Orange Revolution in Ukraine, a sequence of protests and political events following the run-off vote of the 2004 Ukrainian presidential election. These events were prompted by allegations of widespread corruption, voter intimidation, and electoral fraud.
January 2005	Viktor Yushchenko (Political party: Our Ukraine) was elected as president after the Orange Revolution
March 2005	Gas dispute of 2005-2006: Russia accuses Ukraine of not paying for gas and retaining gas intended for Europe. Preliminary agreement was reached in January 2006, and the situation calmed.
December 2005	The ninth EU-Ukraine summit in Kyiv. This is believed to be one of the most successfull ones in developing EU-Ukraine relations. The recently elected Yushchenko had a high level of trust within the
October 2007	Gas dispute of 2007-2008: Dispute arose due to Ukraine's outstanding gas debt. Disagreements on quantities, outstanding payment of gas delivered and pre-payment, led to drastic supply cuts from Russia.
December 2008	Gas dispute of 2008-2009: Russia and Ukraine once again fail to reach an agreement on gas prices and supplies for 2009. European gas supplies from Russia through Ukraine are highlt affected.
February 2010	Viktor Yanukovych (Political party: Party of Regions) was elected as president
April 2010	Closing agreement on the 2009 gas dispute was reached to reduce the price of Russian gas exports to Ukraine by 30 percent.
November 2013	Ukrainian president Viktor Yanukovych abandons an agreement with the EU in favour of closer ties with Russia and the Eurasian Economic Union. This sudden decision sparked major protests in Ukraine, also known as Euromaidan.
February 2014	The Ukrainian Revolution took place as a result of the deadly Euromaidan protests that ended with the ousting of Yanukovych. Himself and the parliamentary opposition signed an agreement for an interim government to take power on 21 February, and he went into exile the same evening. Oleksandr Turchynov (Political party: Fatherland) served as president for 115 days.
February 2014	Russia annexed Crimea in response to Ukraine's political changes. While the unmarked Russian occupants had control over the parliament building, the parliament held an emergency session voting to terminate the Crimean government and replace the current prime minister with one of the Russian Unity
February 2014	Gas dispute of 2014: Ukraine's oil and gas company Naftogaz sued the Crimean Chernomorneftegaz, over which the self-proclaimed authorities of Crimea had established control. Based on the documents, Naftogaz is requesting Chernomorneftegaz to repay the loans that were extended to the Crimean company between 2009 and 2012.
June 2014	Petro Poroshenko (Political party: European Solidarity) was elected as president.
June 2014	Gas dispute of 2014: Negotiations betweeen Ukraine and Russia again failed to reach an agreement. As a result, Gazprom cut gas supplies to Ukraine also leading to reduced supply in Europe. A deal was launced in October in which Ukraine agreed to pay in advance and with the EU acting as a guarantor of Ukraine's gas purchases from Russia.
November 2015	Gas dispute of 2015: Gas flows from Russia to the EU was significantly reduced. Gazprom claimed they halted supply because of lacking pre-payment while Naftogaz claimed they had stopped purchasing from Gazprom because Ukraine could buy cheaper from other suppliers. In 2018, the SCC Arbitration Institute ordered Gazprom to pay Naftogaz $2.5bn for failing to ship certain volumes. Gazprom disputed this order and tried to fight it in several European courts.
May 2019	Volodymyr Selensky was elected as president (Political party: Servant of the People).
February 2022	Putin declares a "special military operation" to "demilitarize and denazify" Ukraine, followed by missile strikes, airstrikes, and ground invasion. War between Russia and Ukraine begins.
Februray 2022	Ukraine applied for EU membership.

Table 2: Timeline of political events relevant for our thesis.
Source: "Russia and Ukraine – from civilized divorce to uncivil war" by Paul (D'Anieri, 2023)

A2. Coal Final Consumption by type in Europe

There has been a drastic decrease in coal consumption in Europe over the last decades, mainly due to increased focus on reducing greenhouse gas emissions. This has contributed to a high dependency on natural gas.

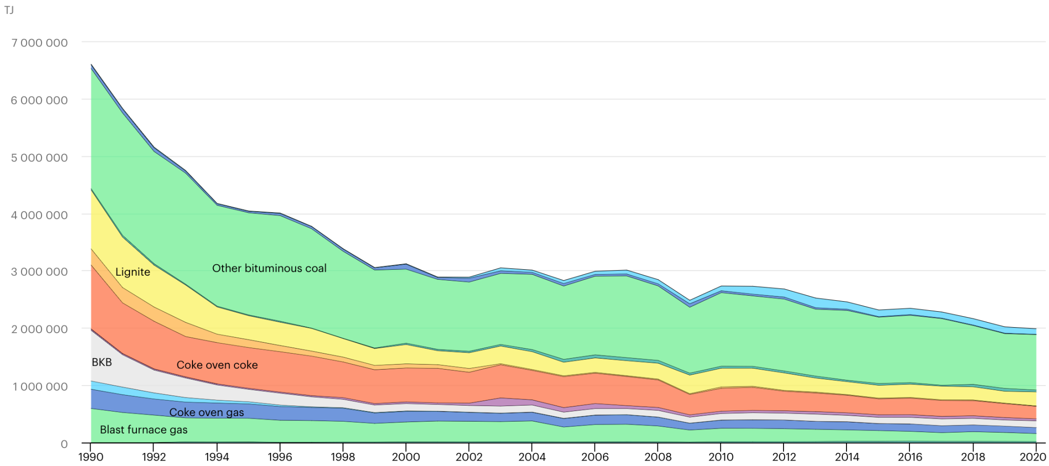

Figure 15: Coal Final Consumption by type, Europe 1990-2020
Source: IEA

A3. Share of LNG Imports in EU's Total Natural Gas Imports

Recognising the need to reduce dependence on major suppliers and meet increasing energy demand, the EU has increased LNG imports by prompting investments in LNG infrastructure, such as import terminals and storage facilities.

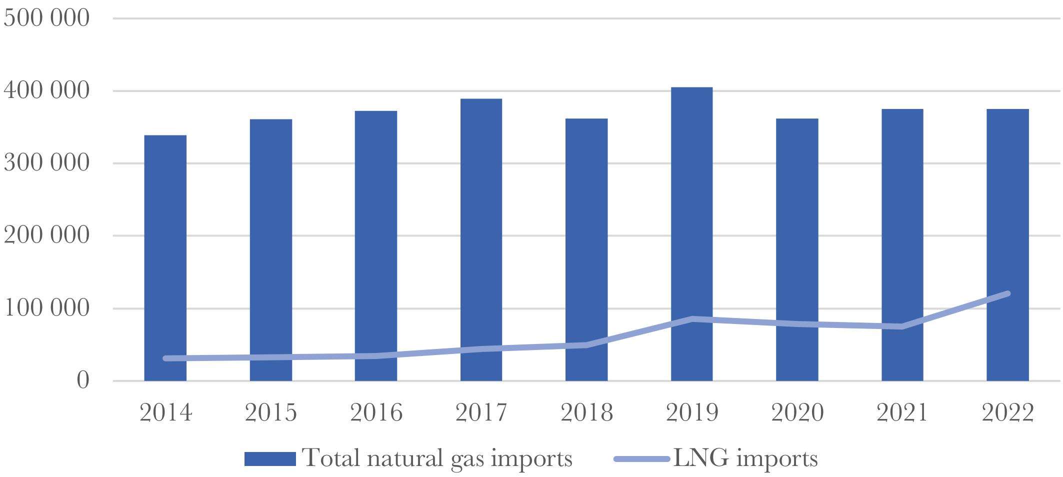

Figure 16: LNG imports represents an increasing share of total natural gas imports in the EU.
Source: Eurostat

A4. LNG Infrastructure in Europe

The figure below shows that the access to LNG infrastructure is uneven in Europe.

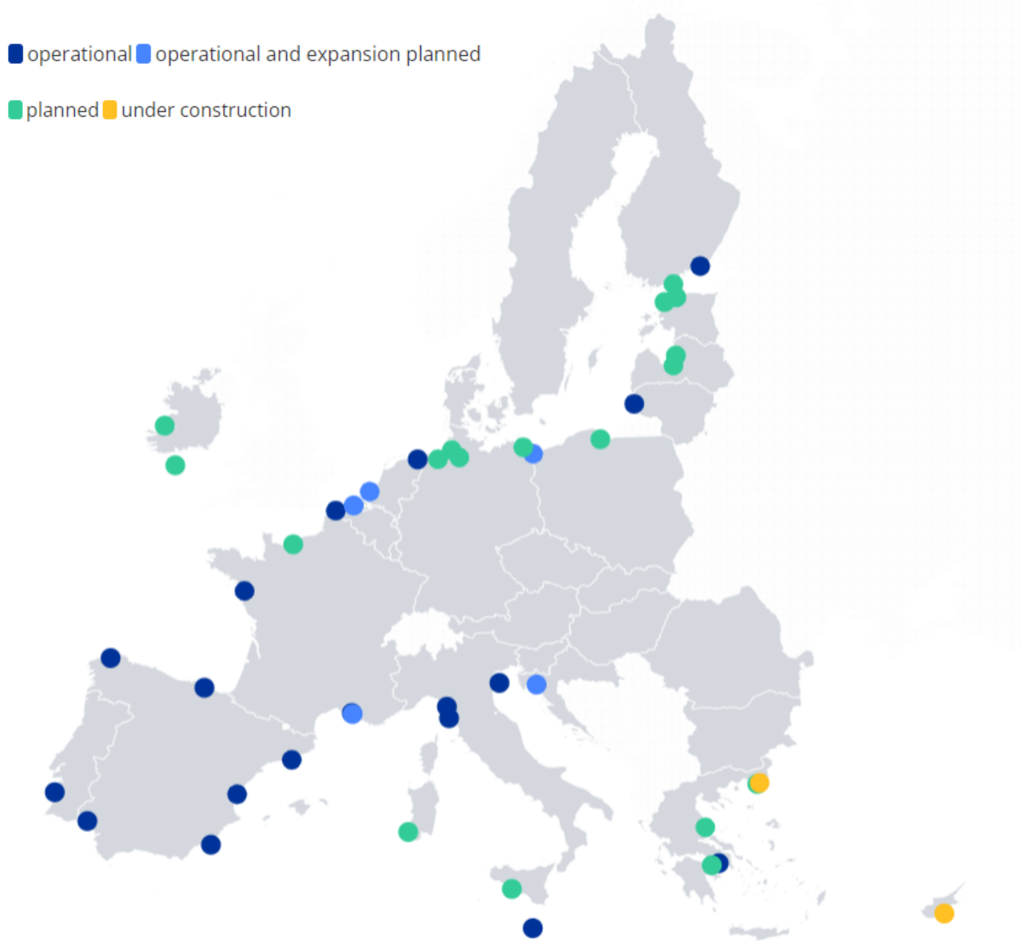

Figure 17: Map of Europe illustrating LNG terminals that are operational, planned or under construction. Source: European Commission, Gas Infrastructure Europe

A5. Testing for Stability

Before modelling the system, it is important to assess the stability of our model as it directly impacts the model's utilisation and, consequently, the feasibility of our analysis. The effect of the structural shocks (ε) must die out over time for the VAR model to be covariance stationary. We test for stability using an OLS-CUSUM stability test. This implies calculating the eigenvalues of the companion form matrix (A) in the reduced form VAR. The resulting eigenvalues must be less than one ($\lambda < 0$) in absolute value for the model to be stable (Bjørnland & Thorsrud, 2015). The test shows evidence that the system is stable as there are no points that exceeds the red lines.

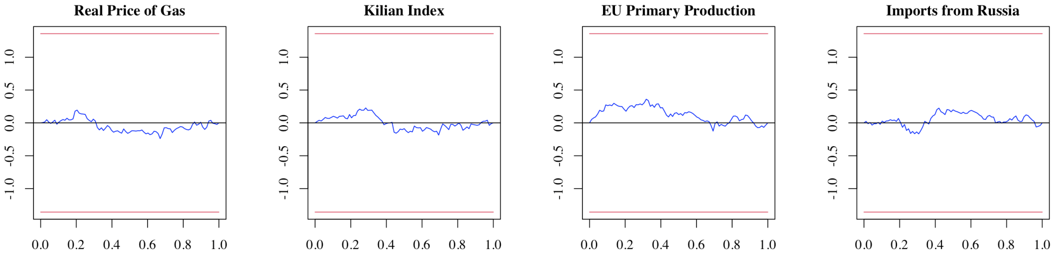

Figure 18: Result of the OLS-CUSUM stability test showing the empirical fluctuation process of each variable

A6. Cholesky Decomposition

We employ the Cholesky decomposition to identify matrix S. This identification scheme postulates that a positive definite symmetric matrix can be expressed as the product of a lower triangular matrix with positive diagonal elements and its conjugate transpose (Bjørnland & Thorsrud, 2015).

The reduced form can be written as:

$$Y_t = \alpha \; + A(L)^{-1} * S * S^{-1} * e_t$$

$$Y_t = \alpha \; + \theta(\mathrm{L}) * S^{-1} * e_t$$

where $A(L)^{-1} * S = \theta(\mathrm{L})$. By defining $S^{-1} * e_t = \varepsilon_t$, we prove that the shocks in ε_t is uncorrelated and of unit variance if S is lower triangular:

$$E[\varepsilon_t, \varepsilon_t'] = S^{-1} * E[e_t, e_t'] * (S^{-1})' = S^{-1} * (SS') * (S^{-1})' = I$$

A7. Testing for Stationarity

Stationarity is a crucial concept in the analysis of time series. A process for y_t is considered covariance stationary if its mean and covariance are both independent of time (Bjørnland & Thorsrud, 2015). To achieve covariance stationarity, the following conditions must hold for all time periods and lags:

$$E[y_t] = \mu$$

$$E(y_t - \mu)(y_{t-1} - \mu) = Cov(y_t, t_{t-j}) = \gamma(j)$$

Previous studies have found evidence that the majority of commodity prices are non-stationary, and the time series often exhibit the characteristics of one unit root (Byrne et al., 2013). Hence, we expect to encounter non-stationarity in some of our time series. We perform a unit root test – ADF test – to decide the number of unit roots (Dickey & Fuller, 1979). The test takes the autocorrelation into account and requires the optimal lag length since the error terms do not represent white noise. We can apply different information criteria to find the most suitable model specification, representing the number of lags that minimises the information criterion. In our thesis, we minimise the AIC:

$$AIC = \log(\hat{\sigma}^2) + \frac{2k}{T}$$

A common approach to convert non-stationary models to stationary models in the stochastic non-stationary case is incorporating first differences equivalent to the number of unit roots.

Cointegration is another potential consequence when including non-stationary variables. The property implies that there is a long-term relationship between the variables because they share the same trend. In addition, a non-stationary model has infinite persistence of shocks. Hence, the regression can become spurious and give a misleading result with high explanatory power even though the variables are not related at all. In addition, the inclusion of non-stationary variables creates problems for hypothesis tests as the t-ratios will not follow a t-distribution. It is common to handle the deterministic non-stationary case by looking at the estimated residuals, which should be stationary. We investigate the presence of cointegration by comparing the ADF test with a stationarity test – KPSS test – and check whether the tests give a conclusive result (Kwiatkowski et al., 1992). We need to use the error correction model to avoid spurious results if cointegration is present in the time series. The results of our stationarity tests are illustrated below:

Real Price of Gas

Variable	**ADF**	**KPSS**	**Conclusive result**
rpg	-1.8631	1.9176	Non-stationary
log(rpg)	-0.9937	1.4051	Non-stationary
Δrpg	-9.2290	0.0991	Stationary

Figure 19: ADF and KPSS tests of the real price of gas yield conclusive results

In line with previous research, we find a conclusive result that the real price of natural gas is non-stationary and contains one unit root. We use the real price of gas expressed in logs in our analysis even though the time series contain one unit root – $I(1)$. This is possible because model stability, which is confirmed in Appendix A5, is more important than stability in the individual time series.

Real Economic Activity

Variable	**ADF**	**KPSS**	**Conclusive result**
Kilian Index	-2.6828	2.4408	Non-stationary
rea	-7.0612	0.2440	Stationary

Figure 20: ADF and KPSS tests of the real economic activity variable yield conclusive results.

We use Kilian's index for global real economic activity in discrete returns in our analysis. The time series is stationary – $I(0)$.

EU Primary Production

Variable	**ADF**	**KPSS**	**Conclusive result**
Δprod	-6.043	0.0348	Stationary

Figure 21: ADF and KPSS tests of EU primary production yield conclusive results.

We use the production of natural gas in the EU in log differences in our analysis. The time series is stationary – $I(0)$.

EU imports from Russia

Variable	**ADF**	**KPSS**	**Conclusive result**
Δruexp	-8.4453	0.1551	Stationary

Figure 22: ADF and KPSS tests of EU imports of natural gas from Russia yield conclusive results.

We use the EU imports of natural gas from Russia in log differences in our analysis. The time series is stationary – $I(0)$.

A8. Lag Selection using Information Criteria

To find the most suitable model specification, we can employ different information criteria to determine the optimal number of lags. These information criteria serve as quantitative measures to evaluate the goodness of fit while considering the complexity of the model. By assessing the values of these criteria for varying lag lengths, we can identify the model specification that minimises the respective information criterion. This approach enables us to select the most appropriate number of lags for our analysis, ensuring an effective representation of the underlying temporal dependencies and dynamics in the data. The figure below illustrates the appropriate number of lags for our structural VAR model using different information criteria. We use the Akaike Information Criterion (AIC).

Information criteria	**# lags**
AIC	19
HQ	19
SC	19
FPE	20

Table 3: Number of appropriate lags according to the Akaike Information Criterion (AIC), Hannan-Quinn Criterion (HQ), Schwarz Criterion (SC), and Final Prediction Error Criterion (FPE).

A9. Descriptive Statistics

The table below contains the descriptive statistics of the daily TTF prices:

Observations	2305
Min	4.59
Max	192.48
Mean	29.83
Standard deviation	33.59

Table 4: Descriptive statistics of the daily TTF natural gas prices.

A10. Description of Data

Variable	Description	Unit	Data Code	Source
rpg	Dutch TTF natural gas one-month futures contract deflated with the HICP to get the price in real terms. The real price of gas is expressed in log levels in our model.	EUR/MWh	TTFG1MON Index	Bloomberg (ICE Endex)
rea	Kilian's index used as a proxy for global real economic activity in the industrial commodity markets. The index is expressed in discrete returns in our model.	Indexed value	IGREA	Federal Reserve Bank of Dallas
Δprod	EU primary production in million cubic meters per month. The variable is expressed in log differences in our model.	mcm	NRG_CB_GASM	Eurostat
Δimp_ru	EU imports of natural gas from Russia in million cubic meters per month. The variable is expressed in log differences in our model.	mcm	NRG_TI_GASM	Eurostat

Table 5: Information on our data set. All variables are in monthly frequency.

A11. EU Inventory Levels

The EU has maintained high inventory levels. This may alter market dynamics in the short run, in the sense that a cut in supply can be replaced by inventories.

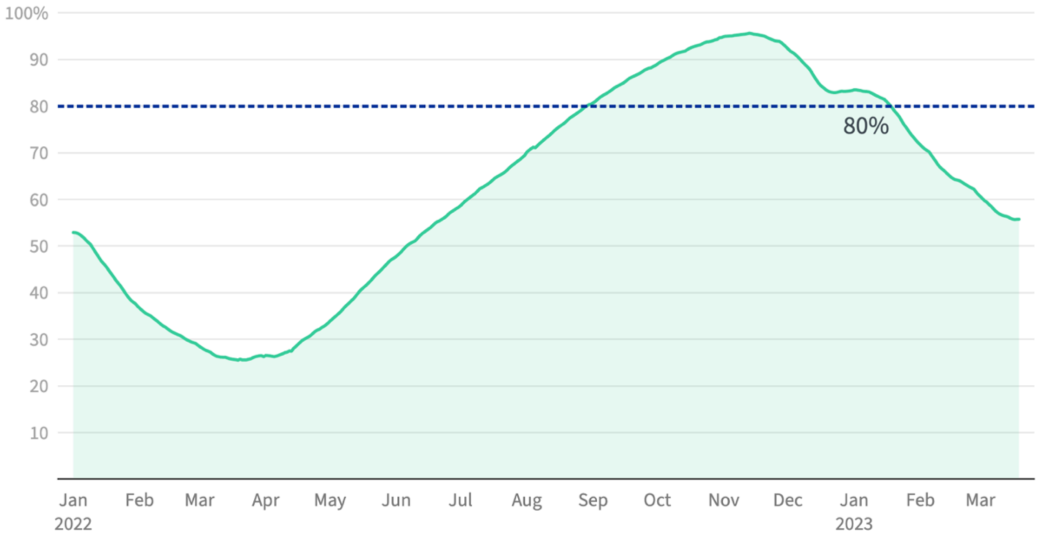

Figure 23: EU gas storage filling level.
Source: Gas Infrastructure Europe, Council of the European Union (2023)

A12. Forecast Error Variance Decomposition for All Variables

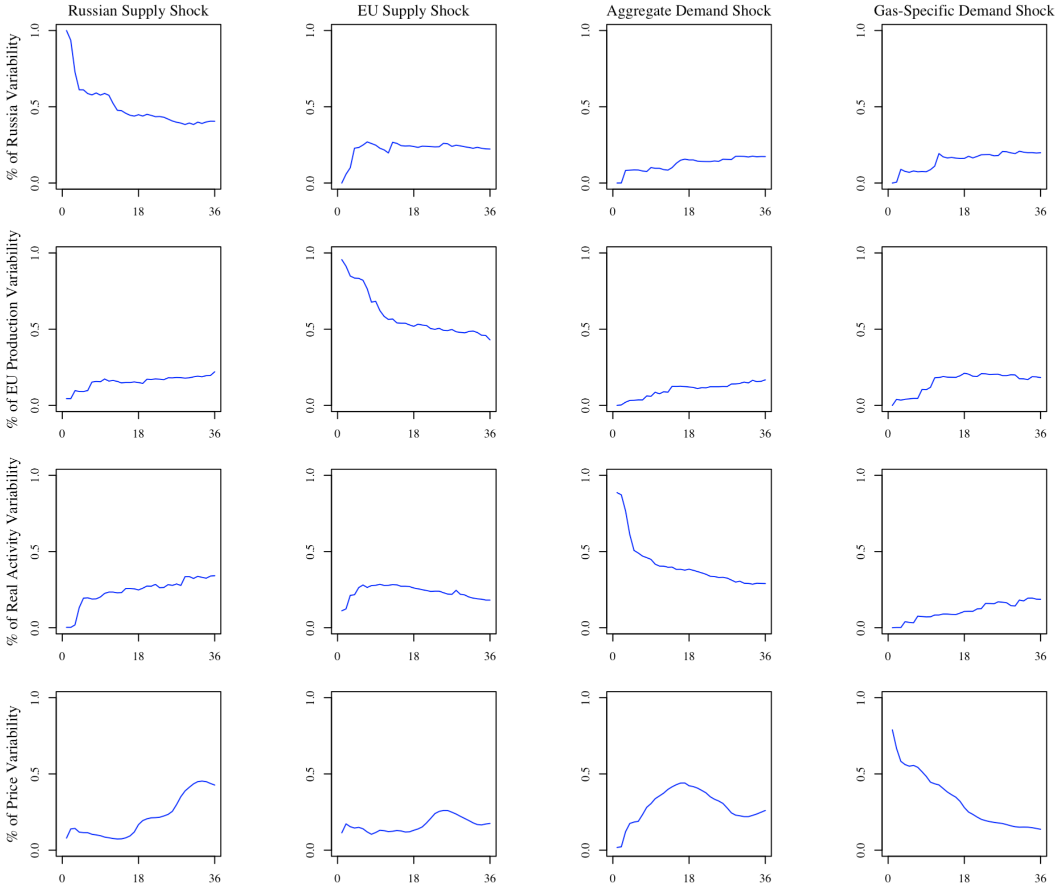

Figure 24: FEVDs of Russian imports to the EU, EU primary production, real economic activity, and the real price of gas with a forecast horizon up to 36 months.

In general, the plots show that all of the variables are primarily influenced by their own shocks in the short term. However, the impact of these shocks decreases over time as the other variables gain explanatory power. We discuss the FEVD of the real price of gas more thoroughly in Section 6.2.