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What Drives Natural Gas Prices? – A Structural VAR Approach[☆]

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Abstract

In this study, we develop a structural vector autoregressive model (VAR) for the German natural gas market. Our setup allows us to analyze the determinants of the natural gas price in a comprehensive framework. In particular, we illustrate the usefulness of our approach by disentangling the effects of different fundamental influences on gas prices during three recent supply interruptions: The Russian-Ukrainian gas dispute of January 2009, the Libyan civil war in 2011 and the withheld Russian exports in February 2012. Our results show that the natural gas price is affected by temperature, storage and supply shortfalls in the short term, while the long-term development is closely tied to both crude oil and coal prices, capturing the economic climate and the energy specific demand.

Keywords: natural gas, structural vector autoregression, SVAR, supply interruption, security of supply

JEL classification: Q41

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1. Introduction

The price of natural gas is of significant economic interest for various stakeholders. Not only does gas play a crucial role as a primary fuel in the residential and commercial heating market, but it also serves as an important input for industrial applications and electricity generation. Consequently, understanding the drivers of natural gas prices is relevant from both a macro and firm-specific perspective. However, the price formation at liberalized natural gas hubs is complex, since these markets are faced with a variety of fundamental demand and supply influences such as meteorological conditions, business cycles, international trade flows and substitution effects among energy commodities. Moreover, unforeseen disruptions in gas supply may induce significant repercussions in these markets. This holds true especially for the continental European natural gas market, which recently has been exposed to supply disruptions due to the Russian-Ukrainian gas transit dispute of January 2009, production outages caused by the Libyan civil war in the spring of 2011 and the cut in Russian gas deliveries in February 2012.

In this study, we focus on Germany, one of the largest European natural gas markets, which is heavily dependent on natural gas imports via pipelines and therefore provides an interesting setting for the investigation of the impact of supply disruptions on the gas price. For this purpose, we develop a structural vector autoregressive model (VAR) to investigate the effects of various fundamental variables on gas prices. The natural gas-related variables analyzed in this study include gas supply disruptions, weather conditions, storage activity and imports of liquefied natural gas (LNG). Moreover, the model yields insights into the relationship of the natural gas price and the prices of coal and crude oil, which we use as proxies for the energy specific demand.

The impulse responses provided by the VAR are consistent with economic theory and suggest that the natural gas price reacts to the underlying supply and demand characteristics. The natural gas price rises in reaction to supply interruptions and due to extraordinary cold temperatures increasing the heating demand. The response to structural shocks of storage follows with the idea that storage flows either serve as additional demand or additional supply in the respective period. Whereas coal prices have an immediate and persistent impact on natural gas prices, the crude oil price only affects natural gas prices after a substantial delay. The decomposition of the forecast error variance of the natural gas price highlights that supply disruptions and unexpected meteorological conditions have an important, but transitory, effect on gas prices. For medium- and long-term horizons, gas prices are mainly affected by both coal and crude oil prices.

To better understand the effects of natural gas supply interruptions, we use our VAR model to disentangle the historical structural shocks affecting the German gas market during the three recent supply shortfalls. Our results show that the positive price impact of the Russian-Ukrainian transit dispute of January 2009 was partly offset by the negative price pressure of the coinciding financial crisis and economic slowdown. The structural effects on gas prices during the Libyan civil war suggest that the increase of German wholesale gas prices was rather induced by precautionary demand of storages than by the actual supply shortfall to the European gas market. Furthermore, the sharp price spike in February 2012 was affected to a greater extent by the extremely low temperatures compared to the sudden shortfalls in Russian supply.

To our knowledge, we are the first to pursue an econometric analysis of the impact of supply shortfalls within the German gas market. A major contribution of our research is the identification of the distinct influences that affect gas prices in critical market situations. By disentangling the respective structural shocks, we are able to infer how the main fundamental variables interact in case of supply interruptions. Hence, we can distinguish the contribution of the different variables on gas prices. This is especially valuable since the observed natural gas price increases are caused not only by the supply shock, but also by various coinciding exogenous shocks of all variables. The proposed model therefore helps to provide new empirical insights into the security of supply for the European natural gas market. In this context, the relationship between Russia as a natural gas exporter and the European Union as an importer has attracted a substantial amount of research, such as the studies by Finon and Locatelli (2008), Goldthau (2008), Sagen and Tsygankova (2008) and Spanjer (2007). Morbee and Proost (2010) provide a theoretical framework for the relationship between European importers and Russia. Also related to the security of gas supply, Giulietti et al. (2012) analyze how the outage of a major storage facility affects the natural gas market in the UK.

Our finding that coal prices have a significant impact on the natural gas market challenges the exclusive focus on crude oil as an explanatory variable for cross-commodity effects on gas prices, which is common in most of the empirical gas market research. For example, Hartley et al. (2008), Panagiotidis and Rutledge (2007) as well as Brown and Yücel (2008) use a cointegration framework and specify error correction models to capture the mechanisms among the markets for natural gas and crude oil both in the short run and the long run. However, the stability of the cointegration relationship has been questioned as there seems to be a decoupling of oil and gas prices as outlined by Ramberg and Parsons (2012), who find that the cointegration relationship between oil and gas prices in the United States is not stable over time. They also argue that the price of oil has only weak explanatory power for short-term gas price fluctuations. Economic reasons for a decoupling of oil and gas prices could be the increasing production of shale gas in the United States or the rise of liquid spot markets in Europe fostering gas-to-gas competition and therefore a slow but steady decline in oil-indexed contracts.

We also add to the literature in that our structural VAR approach allows for endogeneity of fundamental gas market variables, such as storage and LNG supplies. Most approaches, such as for example Brown and Yücel (2008), Mu (2007) or Ramberg and Parsons (2012), treat gas inventories as exogenous with respect to gas prices and do not account for the role of LNG. One exception is the study of Maxwell and Zhu (2011), which employs a reduced-form VAR and Granger causality tests to investigate the interdependency of LNG imports and the US gas market. The assumption of exogenous gas inventories implies that storage operators do not adjust flows according to market prices, which is a restrictive assumption for liberalized and efficient gas markets.

The remainder of this study is structured as follows: Section 2 describes the data used for our analysis. The structural VAR framework and the identification of our model are given in Section 3. The results of the impulse response analysis as well as the decomposition of forecast error variance are presented and discussed in Section 4. Section 5 provides a brief overview of the three recent gas supply interruptions affecting the German natural gas market and also contains the event studies of these situations. Section 6 concludes.

2. Data

Our data set comprises weekly data within the period from January 2008 to June 2012.[1] It consists of the NetConnect Germany (NCG) natural gas price, the Brent crude oil price, the North-Western-European coal price, the deviation from historical average heating degree days in Germany, German natural gas storage data, shortfalls of natural gas supplies to the European market and European LNG import data.[2] Figure A.6 in the Appendix displays all time series used for the analysis and Table 1 summarizes the definition of the variables used in this study. In the following, detailed descriptions concerning data sources and the construction of variables are provided.

The data set for the econometric analysis is rather comprehensive with seven variables included. The decision of variable selection is justified by the diversity of fundamental

[1] The first observation is the week ending on Friday February 1st, 2008 and the last observation is the week ending on Friday June 1st, 2012.

[2] For cases in which time series are available on a daily level, we generally construct five-, respectivly seven- day averages (depending on the number of trading days per week).

Table 1: Variable Definitions

Variable	Description	Unit	Source
Heating degree days deviation (Temperature)	Deviation from historical heating degree days during the respective week	Degrees celsius	Deutscher Wetterdienst (DWD), German Meteorological Service
Supply Shortfall	Missing natural gas supply volumes due to specific events	Billion cubic meters (bcm)	Own estimates based on various sources
Price of Brent crude oil	Europe Brent spot crude oil price	Euro per barrel	Energy Information Administration (EIA)
Price of coal	Coal price for North-Western-Europe	Euro per ton	McCloskey
LNG imports to EU-27	Linearly detrended LNG import volumes for all EU-27 countries	Million cubic meters (mcm)	Eurostat
Storage	Difference between historical and actual weekly changes in the German natural gas storage utilization rate	Percentage points	Gas Infrastructure Europe (GIE)
Natural gas price	NetConnect Germany (NCG) day-ahead natural gas price	Euro per Megawatt hour	European Energy Exchange (EEX)

Notes: All time series are transformed to weekly data within the period from January 2008 to June 2012

impacts on gas prices, which do not allow a more parsimonious model specification. As reference prices for the German gas market, we use day-ahead prices of the market area NCG quoted at the European Energy Exchange (EEX).[3] We rely on spot prices as we expect that some short-term impacts of crucial interest for our research question, such as temperature induced demand spikes or unexpected supply shortfalls, are reflected to a greater extent in the day-ahead than in the futures market. We focus on spot prices at NCG rather than at Gaspool because liquidity within the NCG-market area is higher and therefore prices in this market should represent more valid signals.[4]

[3] Available at `http://www.eex.com/en/Download/Market%20Data/Natural%20Gas%20-%20EEX`

[4] In March 2012, the trading volume for H-gas was approximately 85,500 gigawatt hours (GWh) at the Gaspool Hub, while approximately 116,600 GWh were traded at NCG in the same period. The respective churn rates were 3.02 for Gaspool and 3.51 for NCG. This data is available at `http://www.gaspool.`

We specify our model in weekly frequency since this allows both for an inclusion of storage data, which is only available on weekly frequency before 2011, while still enabling the modeling of rather short-term meteorological conditions. The choice of an appropriate frequency, with respect to weather and storage activity, has the consequence that we cannot rely on data of industrial production or gross domestic product as an approximation for the business cycle. However, spot prices of Brent crude oil, which capture the substitution relationship of oil and gas in the residential heating market as well as the still prevailing oil indexation of German gas imports, may also partly reflect the macroeconomic environment in the long-run as outlined by He et al. (2010).[5] Spot prices of coal for delivery in North-Western-Europe, as published by McCloskey, are used in the model. These values are included to capture the interaction of gas and coal within the electricity sector and therefore represent cross-commodity effects related to fuel substitution.[6] The natural gas, crude oil and coal price time series are transformed into their natural logarithms. As commonly done in the macroeconomic literature, for example in Kim and Roubini (2000), we estimate the VAR with log-level price data because we are not interested in any possible stationarity or cointegration properties itself, but rather on the economic relationships within the natural gas market. We do not make any further assumptions and proceed with a consistently estimated VAR in log-levels. This practice is supported by Sims et al. (1990) and Toda and Yamamoto (1995).

We also account for the fact that gas demand, especially in the residential space heating sector, is highly sensitive to temperature. However, in a liberalized gas market, storage operators are expected to exploit predictable seasonal demand variations. Therefore, only unexpected shifts in gas demand, which are caused by extraordinary short-term weather

de/hub_handelsvolumina.htmland http://datenservice.net-connect-germany.de/Handelsvolumen.aspx?MandantId=Mandant_Ncg

[5]The oil price data is available at http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=D

[6]Available at http://cr.mccloskeycoal.com/story.asp?sectioncode=164&storyCode=34769

conditions, are expected to be relevant for the gas price formation. Consequently, we focus on deviations from the normal seasonal meteorological pattern as a determinant of gas prices. Thus, in a first step, we construct the historical average seasonal series of heating degree days (HDD) using temperature data from the German Weather Service for Frankfurt am Main during 1949-1999.[7] In a second step, we calculate the deviations of observed HDD and their historical averages in order to estimate the effects of unexpected temperature conditions on gas prices.

We include storage data because storage operators are both part of the supply side (storage withdrawal) and the demand side (storage injection). Existing German underground gas storage sites can be split into two categories[8]: On the one hand, pore storages balance out the seasonal divergence of supply and demand during winter and summer months. Due to technical restrictions, they are rather inflexible in their operation and hence many of them may be unable to respond to short-term price signals. On the other hand, more flexible cavern storages offset short-term imbalances between gas supply and demand. The most straightforward modeling approach would be to only consider flows of sufficiently flexible storages, which can quickly adapt their withdrawal and injection activity according to price fluctuations. Unfortunately, storage flow data are neither available on a site-specific nor on a category-specific level for Germany, as only aggregated storage data is published. Therefore, we take an intuitive approach to separate the two aforementioned categories: Accounting for the fact that inflexible storages follow a rather strict seasonal pattern, whereas flexible storages do not, we first construct an average seasonal pattern of storage utilization based on data published by Gas Storage Europe.[9] We consider utilization rates instead of absolute volumes to control for changes in the total storage capacity. In a second step, we take the

[7]Available at `http://www.dwd.de/bvbw/appmanager/bvbw/`

[8]In addition to underground gas storages, many above ground gas storages exist in Germany. However, since the working gas volume is comparably small, they are of less importance compared to underground gas storage facilities.

[9]Available at `https://transparency.gie.eu.com/`

first differences of the average weekly utilization. These values are the changes in average utilization for each calender week (measured in percentage points of total storage volume) and represent the seasonal storage flows. Finally, we take the difference between these average seasonal changes in utilization and the actual change in each week as a proxy for the flows related to flexible storages. It is reasonable to assume that these storages create the deviation from the seasonal storage utilization pattern.

As the supply side is concerned, natural gas production data with monthly or weekly frequencies is not available. However, we account for the gas supplies with a supply shortfall variable, which represents gas volumes that are unexpectedly not delivered to the continental European market. Thus, the variable is equal to zero when no supply interruption occurs and amounts to the missing volumes, measured in billion cubic meters (bcm), during periods of supply shocks. We consider the impact of the Russian-Ukrainian transit dispute of 2009, the supply shortfalls caused by the civil war in Libya in 2011 and the lack of Russian gas supplies in February 2012.[10]

Beyond capturing supply interruptions via the supply shortfall approach presented above, we also draw upon the EU-27 LNG-imports provided by Eurostat as an indicator of current supply conditions.[11] Unfortunately, the import data is only available on a monthly frequency. Therefore, we apply linear interpolation to the data as we argue that any resulting errors from this procedure are expected to be rather small compared to the benefit of modeling LNG volumes entering the European gas market. Since the EU-27 LNG-imports exhibit a significant growth over time, we linearly detrend the variable by regressing the interpolated series against time.

The major European gas markets are highly interdependent, as shown by Robinson (2007) and Growitsch et al. (2012). Based on the empirical findings of these studies, we

[10] Details about the crises and the calculation of the missing supply volumes are given in Section 5.

[11] Available at `http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_124m&lang=en`

conclude that changes in supply volumes, no matter in which market area they originally occur, induce repercussions in other continental European gas markets. Therefore, we refer to supply shortfalls and LNG-imports on a European rather than only on a national level.

3. A Structural VAR for the German Natural Gas Market

We employ a structural vector autoregression for modeling the interdependencies between the main gas market fundamentals in order to explicitly examine the relevant transmission channels affecting the natural gas price. Accounting the exogeneity of some variables, we constrain certain feedback-effects by restricting their coefficients to zero.

The model in its reduced-form representation can be written as

$$y_t = v + A_1 y_{t-1} + \ldots + A_p y_{t-p} + u_t \tag{1}$$

where $y_t = (y_{1t}, \ldots, y_{Kt})'$ is a vector of K endogenous variables and p is the number of lags included in the model. The vector v is an intercept vector with K rows and the A's are $K \times K$ coefficient matrices. Furthermore $u_t = (u_{1t}, \ldots, u_{Kt})$ is a K-dimensional vector of reduced-form errors with the properties $E(u_t) = 0$, $E(u_t u_s') = \Sigma_u$ and $E(u_t u_s') = 0$ for $s \neq t$, where Σ_u is an invertible $K \times K$ variance-covariance matrix. We specify the VAR model to have a lag length of two lags as indicated by the Schwarz Information Criterion.

However, since u_t reflects the instantaneous causality among the variables not accounted for in the reduced-form model, this representation does not allow an economic interpretation of the error term. For this purpose, the structural model has to be identified. The structural VAR has the representation

$$Ay_t = A_1^* y_{t-1} + \ldots + A_p^* y_{t-p} + \epsilon_t \tag{2}$$

or equivalently, adding $(I_k - A)y_t$ to both sides of the equation,

$$y_t = (I_K - A)y_t + A_1^* y_{t-1} + \ldots + A_p^* y_{t-p} + \epsilon_t \tag{3}$$

where I_K represents the identity matrix of order K, A is an $K \times K$ matrix of instantaneous interaction among the variables and A_i^* is equal to AA_i for $i = 0, \ldots, p$. Moreover, $\epsilon_t = (\epsilon_{1t}, \ldots, \epsilon_{Kt})'$ is a row-vector of dimension K representing structural errors with variance-covariance matrix Σ_ϵ. As the instantaneous causality of the variables is captured by A, Σ_ϵ is diagonal. Hence, the errors of the structural representation can be assigned to a single variable and therefore be interpreted in terms of economic theory. The identification of the structural form is based on restrictions placed on the instantaneous coefficient matrix A. To derive the structural representation, a total of $K(K+1)/2$ restrictions must be imposed.

We choose a recursive identification structure as the starting point for our model. However, in case the recursive identification diverges from our economic expectations, we deviate from the recursive ordering and impose restrictions that are more appealing from an economic point of view. The instantaneous restrictions imposed for the identification of the structural VAR model are summarized in Table 2.

Table 2: Identification of the Contemporaneous Matrix

	Temperature	Supply Shortfall	Crude Price	Coal Price	LNG	Storage	Gas Price
Heating degree days deviation	⋆	0	0	0	0	0	0
Supply Shortfall	⋆	⋆	0	0	0	0	0
Price of Brent crude oil	⋆	⋆	⋆	0	0	0	0
Price of coal	⋆	0	⋆	⋆	0	0	⋆
LNG imports to EU-27	⋆	⋆	0	0	⋆	⋆	⋆
Storage	⋆	⋆	⋆	⋆	0	⋆	⋆
Natural gas price	⋆	⋆	⋆	⋆	⋆	⋆	⋆

Notes: Each row of this table indicates an equation in the VAR model with the respective dependent variable. Each column indicates the instantaneous impact of a variable in each equation. The ⋆ denotes that a parameter is estimated from the data and that the model allows for an instantaneous relationship, whereas a 0 indicates that the according parameter is restricted to zero.

Since weather is apparently exogenous with respect to the other included variables, deviations from historical heating degree day averages are ordered first within the matrix of instantaneous interaction.

The supply shortfall variable, accounting for absent gas deliveries to the European market, also exhibits exogenous character. However, historical evidence suggests that supply shortfalls of Russian gas are more likely during peak demand periods.[12] Consequently, we leave the instantaneous influence of temperature deviations on supply shortfalls unrestricted.

As the price of crude oil is concerned, it appears intuitive to let it instantaneously react to the supply shortfall variable as gas supply disruptions frequently go hand in hand with a shortened supply of crude oil. A recent example of this phenomenon is the case of the civil war in Libya in 2011, which affected both natural gas and crude oil production. Furthermore, extraordinary cold weather periods increase the demand for heating oil in Europe and possibly increase the price of Brent crude oil through this channel. Therefore, we do not restrict the impact of heating degree days on the crude oil price.

The price of coal is assumed to be instantaneously affected by weather conditions (via an increase in power demand). Additionally, accounting for the role of crude oil as a global benchmark commodity and the character of gas as a substitute for coal, it seems reasonable to assume a contemporaneous impact of oil and gas prices on the price of coal.

The first variable directly related to the German gas market is the EU-27 import of LNG. Unexpected weather conditions as well as supply shocks are likely to evoke significant changes in natural gas market fundamentals and hence the demand for LNG volumes. Therefore, we do not place any restrictions on the respective coefficients. Furthermore, LNG imports are expected to be affected by gas prices and storage flows. Regarding the necessary restrictions for identifying this equation, we argue that the instantaneous impact of coal and oil prices are of less, if any, relevance. Hence we restrict these coefficients to zero.

It is necessary to account for the endogeneity of storage flows with respect to changes

[12]The experienced shortfalls of Russian gas supply to Western Europe in 2009 and 2012 both occurred during extraordinary cold weather conditions. This may be a consequence of Gazprom's priority to satisfy domestic demand.

in gas prices. Gas storages are likely to react instantaneously to changes in gas prices since inter-temporal price arbitrage is the economic rationale of any commercial storage operator. Additionally, storage flows are expected to balance temporary divergence of supply and demand caused by any unforeseen shifts in market conditions (i.e. weather, supply surprises or cross-commodity effects). Thus, we allow for the direct effects of gas prices, coal prices, oil prices, unexpected temperatures and supply shortfalls on storage flows. Finally, since the German gas price is of main interest to our research, no restrictions are placed on the equation of this variable. This allows for a comprehensive analysis of the instantaneous impacts of all variables considered in the model on the price of natural gas.

As the instantaneous restrictions required for identification are based on economic theory, we use them also for lagged relationships with the following exceptions: First, the supply shortfall variable is set to be strictly exogenous, i.e. not affected by lagged temperature changes. Second, we allow for cross-commodity price effects in all directions because, from our perspective, there is no need to impose strict exogeneity to crude oil prices a priori. Third, the process of heating degree days is modeled as a first-order autoregressive process and has no lagged influence on crude oil and coal prices. We argue that temperature effects on commodity prices exhibit short-term character. Additionally, we allow LNG imports, storage and natural gas prices to depend on lags of all other variables. Table 3 summarizes the parameter restrictions on the lagged relationships.

The restrictions placed on lagged relationships imply different regressors within the VAR-framework. The existence of different explanatory variables makes the ordinary least squares estimator inefficient, as pointed out by Zellner (1962), since the error term of the reduced-form representation contains instantaneous correlation among the variables. Accordingly, we explicitly account for the correlation between the variables when estimating the reduced-form model using feasible generalized least squares (FGLS). The estimation of the structural model in the second step is based on the variance-covariance matrix of the reduced-form

Table 3: Lag Restrictions in the VAR Model

	Temp-erature	Supply Shortfall	Crude Price	Coal Price	LNG	Storage	Gas Price
Heating degree days deviation	$\star$/0	0	0	0	0	0	0
Supply Shortfall	0	0	0	0	0	0	0
Price of Brent crude oil	0	$\star$	$\star$	$\star$	0	0	$\star$
Price of coal	0	0	$\star$	$\star$	0	0	$\star$
LNG imports to EU-27	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
Storage	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
Natural gas price	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$

Notes: Each row of this table indicates an equation in the VAR model with the respective dependent variable. Each column indicates a lagged impact of a variable in each equation. The $\star$ denotes that a parameter is estimated from the data, whereas a 0 indicates that the according parameter is restricted to zero.

residuals estimated via FGLS. The structural-form parameters are nonlinear with respect to the reduced-form parameters and therefore only iterative algorithms, instead of a closed-form solution, can be applied. Hence, we estimate the structural-form parameters using the scoring algorithm of Amisano and Giannini (1997), as proposed by Lütkepohl (2005).

4. Results

The structural moving average (MA) representation of our model can be used to infer impulse response functions. Dropping the intercept term, as it is of no interest for the analysis, allows the structural MA-form to be written as

$$y_t = \sum_{i=0}^{\infty} \Theta_i \epsilon_{t-i} \tag{4}$$

where ϵ has the properties as described in Section 3. The Θ_i-matrices can be calculated using the previously estimated structural coefficient matrices and contain the dynamic multipliers within the system. Hence, the response of variable j, i periods after an impulse of variable k is reflected in $\theta_{jk,i}$, the jk-th element of Θ_i. The impulses have the size of one standard deviation as we use the square roots of the estimated structural variance-covariance matrix for the calculation of responses. Following Lütkepohl (2005), who emphasizes the problematic finite sample properties of asymptotic confidence intervals for impulse responses, we rely on numerical resampling methods to derive error bands. We refer to Hall's 95-percentage bootstrap intervals using 1000 draws (see Hall (1995)). We generate responses of the natural gas price on impulses of all other variables, thus exploring the dynamic effects of gas market fundamentals on the price development. Figure 1 presents the estimated impulse response functions for the natural gas price.

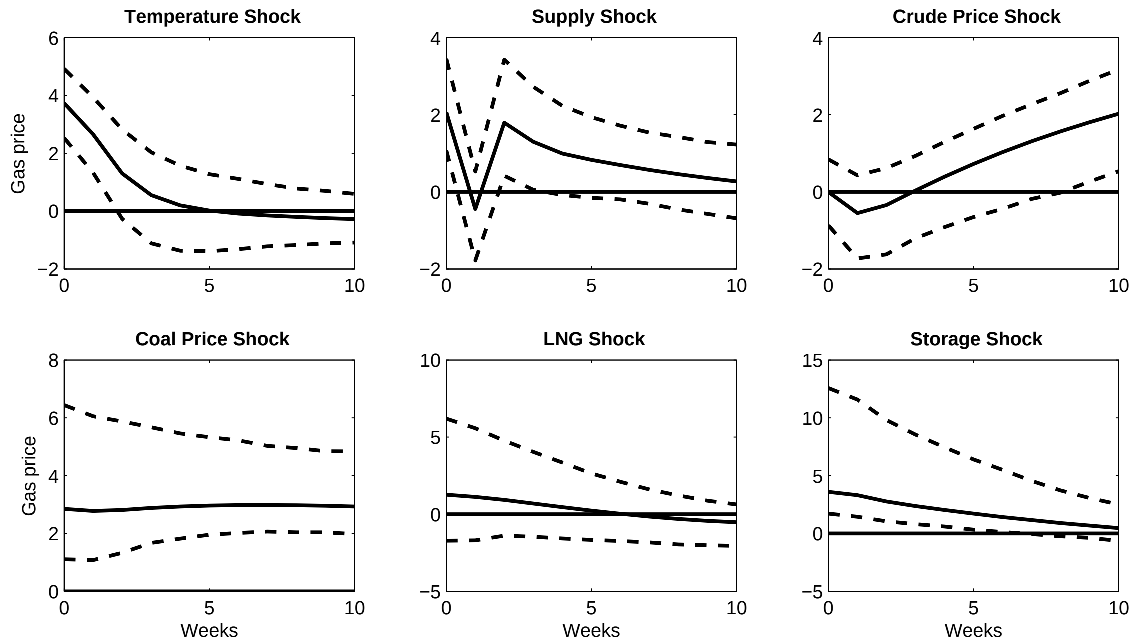

Figure 1: Responses of the Natural Gas Price

Notes: The impulse responses (solid lines) are based on one standard deviation of the respective structural shock. They can be interpreted as the percentage change in the natural gas price as a reaction to a standardized shock of the respective variable. Confidence intervals (dashed lines) are bootstrapped as Hall's 95-percentage bootstrap interval using 1000 draws.

The impulse responses of the natural gas price are consistent with economic reasoning. Extraordinary cold weather results in an immediate and strong increase in the natural gas price. This increase is significant but lasts only for two weeks, indicating that temperature deviations have rather short-term effects on gas prices. Supply disruptions, approximated by the structural innovations of the supply shortfall variable, also cause a rise in the natural gas price. This result is consistent with both historical market conditions, e.g. the price spikes in January 2009 and February 2012, and economic theory. The missing volumes are replaced by more expensive sources of supply to satisfy the rather price-inelastic gas demand. Furthermore, the impact on the natural gas price could also be attributed to the uncertainty of future supply conditions resulting in spot purchases (e.g. storage injection as a consequence of anticipated price increases).

The derived structural response functions of the natural gas price, with respect to oil and coal prices, provide evidence of significant interdependencies among energy commodities. The price of gas responds positively to shocks of both oil and coal prices. However, the pattern with which oil and coal influence the natural gas prices is fundamentally different. The impact of coal prices on gas prices occurs instantly and remains stable over time. In contrast, oil prices only affect natural gas prices after a substantial time delay.[13]

The strong interdependency of coal and gas prices can be attributed to different features of European energy markets. First, the fuel-competition of the primary energy carriers gas and coal in the electricity sector may induce a positive cross-price elasticity of these commodities. Consequently, a rise in coal prices implies an increased demand for gas and therefore a resulting price increase. Second, since the spot prices used in this study comprise the North-Western European coal price and the German natural gas price, they reflect the same regional economic dynamics. Therefore, they are both economically and geographically closely related to one another.

In contrast, the physical link of crude oil and natural gas exhibits rather long-term character, since direct substitution is effectively limited to the residential heating sector. However, in the long run, as oil-indexed long-term contracts still prevail in German gas imports, a certain degree of long-run correlation between these two commodity prices seems

[13]This finding is also supported by the correlations of price returns. While the returns of gas and coal prices have a correlation coefficient of 0.2088, the correlation of oil and gas returns is 0.0486 and insignificant. The two-tailed 5% critical value is 0.1305 for 226 observations.

plausible.

Next, the influence of the endogenous gas market variables on the natural gas price is discussed. There is no clear effect of a LNG import shock on the natural gas price, which may be caused by the use of interpolated monthly LNG import data. A positive structural shock of storage contributes to rising gas prices, as the injected volumes increase the spot market demand. Intuitively, a positive structural shock of storage can be interpreted as an abnormal storage injection or as a storage withdrawal that is smaller than presumed from the current market situation.

Although our focus is on the determinants of the natural gas price, we briefly discuss the structural responses of LNG imports and storage, since they are a novelty in econometric research on European gas markets. The respective impulse responses are presented in Figure A.7 in the Appendix. The impulse response analysis shows that extraordinary low temperatures lead to storage withdrawals. This mechanism is caused by an increase in the temperature-sensitive natural gas demand in the residential and commercial heating sector. The additional demand has to be satisfied by gas withdrawal from storage facilities. The reaction of storage flows to supply disruptions is rather volatile and does not reveal a clear pattern. The response of storage flows to structural shocks in the natural gas price is consistent with the economic objectives of storage operators because higher natural gas prices intuitively incentivize storage operators to withdraw natural gas. The determinants of LNG imports are estimated with large error bands. Thus, there seems to be no clear pattern how the included fundamental gas market variables influence the amount of imported LNG.

In the following discussion, we return to the investigation on the impact of different fundamental influences on the natural gas price. In order to analyze the relative contribution of the variables considered in the modeling framework, we perform a forecast error variance decomposition using the results of the estimated structural VAR model. Based on the structural MA-representation of the VAR model, the contribution of innovations in variable

k to the error variance of an h-step forecast of variable j can be written as

$$\omega_{jk,h} = \sum_{i=0}^{h-1} e_j' \theta_i^2 e_k / MSE[y_{j,t}(h)] \tag{5}$$

with

$$MSE[y_{j,t}(h)] = \sum_{i=0}^{h-1} \sum_{k=1}^{K} \theta_{jk,i}^2 \tag{6}$$

as the mean squared error (MSE) of h-step forecasts for variable j and e_k as the k-th column of an identity matrix of order K. Consequently, in our model framework, $\omega_{7k,h}$ represents the fraction of gas price variance that can by explained by the structural innovations of another variable included in the model.

Table 4: Forecast Error Variance Decomposition for the Natural Gas Price

Forecast Horizon	Temp -erature	Supply Shortfall	Crude Price	Coal Price	LNG	Storage	Gas Price
1	0.26	0.08	0.00	0.15	0.03	0.24	0.24
2	0.23	0.05	0.00	0.17	0.03	0.26	0.25
4	0.16	0.07	0.00	0.22	0.03	0.26	0.26
8	0.11	0.06	0.02	0.33	0.02	0.23	0.23
12	0.09	0.05	0.07	0.39	0.02	0.19	0.19
26	0.05	0.02	0.30	0.37	0.02	0.12	0.12
52	0.04	0.02	0.39	0.26	0.01	0.14	0.14

Table 4 shows the estimated shares of the variance of the natural gas price accounted for by the structural innovations of each variable. The results are both intuitive and consistent with the economic arguments provided above. In the short run, supply disruptions and unexpected temperature deviations are of major importance for the natural gas price and explain 34% of its fluctuation. However, the impact of these effects is rather short lived and hence, their influence diminishes over time. For longer horizons, the forecast errors of gas prices can be explained more precisely by developments related to the coal and oil markets. The variation in coal prices reaches its maximum explanatory power in medium-term horizons (12 to 26 weeks), while the long-term gas price development (up to 52 weeks) is heavily affected by variations in oil prices. With a forecast horizon of half a year, the aggregated effects of changes in coal and oil prices account for 67% of the gas price variance. Furthermore, our results indicate that storage flows have an important short-term influence on gas prices, a finding that is consistent with the fact that storage facilities balance the occuring demand and supply fluctuations in the natural gas market. In contrast, the explanatory power of LNG imports on the gas price is weak for all time horizons.

Both the impulse response analysis and the decomposition of the forecast error variance indicate that coal prices are more relevant than crude oil prices in explaining the natural gas price in the short term. While recent literature, for example Brown and Yücel (2008), Ramberg and Parsons (2012) and Hartley et al. (2008), focuses on the relationship between crude oil and natural gas prices, our results highlight that for an improved understanding of gas price dynamics, attention should also be paid to the interdependencies of gas and coal markets.

5. Event Studies of Supply Interruptions: Historical Decomposition of Structural Shocks

In this section, we examine the price impact of the three major interruptions in gas supply since the year 2008. First, we analyze the import disturbances from Russia in January 2009, which were caused by a dispute between Russia and Ukraine about the conditions of gas transit. Second, the Libyan production outage in the spring of 2011 due to a civil war is investigated. Third, we explore the withheld exports by Russia in February 2012.

Two difficulties regarding our analysis are that the nature of these supply shocks is not perfectly equivalent and that the gas infrastructure also changes over time. For example, the Russian-Ukrainian gas transit dispute could have a different impact if it occurred after the commissioning of the Nord Stream pipeline.[14]

In order to harmonize the impact of these different disruptions, we attempt to objectify the magnitude by calculating approximative values for the volumes of supply shortfall. Taking into account the high degree of integration among European national gas markets, as shown by Robinson (2007), Renou-Maissant (2012) and Growitsch et al. (2012), we argue that one unit of production or import shortfall to the European market results in similar economic effects for all cases and locations of the gas shortage. The method has the advantage that the estimated effect of supply shocks, as derived from our model, has a generalizable interpretation. This property is desirable because future supply shocks are inherently uncertain with respect to the time and location of their occurrence.

While the three supply disruptions analyzed in this study are of political nature, technical defects could also potentially lead to supply disruptions from politically stable exporters. An illustrative example for such a major technical malfunction is the fire at the Rough gas storage facility, which prevented access to 80% of the total UK storage capacity in the year 2006 and was analyzed in detail by Giulietti et al. (2012).

The proposed structural VAR model is able to disentangle the different fundamental effects during the supply disruptions described above. The technical procedure of our analysis is generally the same for all three event studies of the respective supply shocks. We determine the first week in which the specific situation begins and calculate the impact of the relevant structural shocks on the natural gas price. For this purpose, we do not only use the shock in the first week, which would be similar to an impulse-response analysis, but extract the actual sequence of the relevant structural shocks to infer the accumulated impact in each period. As an indicative benchmark, we also show the actual development

[14]The Nord Stream pipeline directly connects Russia with Germany through the Baltic Sea and therefore bypasses the transit route of the Ukrainian corridor. Thereby, Russia increases its own bargaining position towards transit countries as pointed out by Hubert and Ikonnikova (2011).

of the natural gas price in each plot.[15]

5.1. The Russian-Ukrainian Gas Conflict of 2009

The Russian-Ukrainian gas dispute of 2009 is one of the most prominent examples of political supply risks related to natural gas imports from Russia. In January 2009, natural gas transits from Russia into Western Europe were disrupted for about two weeks as Russia and the Ukraine could not find an agreement on transit charges. According to Lochner (2011), who analyzes this crisis in detail, Russia at this time accounted for 25% of the natural gas supplies to the European Union, 65% of which were transported through Ukraine. Our estimates of the supply shortfalls during this crisis are based on the supply statistics of Naftogaz Ukrainy reprinted in Pirani et al. (2009). The transit volumes declined from 318.4 million cubic meters (mcm) on January 1st, 2009 to a complete stop on January 7th. The gas flows were interrupted until January 20th and regained normal levels on January 22nd. In order to calculate the volume of missing deliveries, we take the volume of gas transported on January 1st as a reference case and consider volumes below that level as supply shortfall. To measure losses between January 20th and January 22nd, we linearly interpolate to the pre-crisis volumes to be reached on January 22nd.

Following this procedure, the calculated lacking transit volumes amount to 4932.1 mcm in total. To test for robustness, we compare this estimate with the Eurostat Russian natural gas exports to EU-27 countries. The exports reported in January 2009 are 4585.9 mcm lower than in January 2008, 4793.7 mcm lower than in January 2010 and 5119.2 mcm lower than in January 2011. This comparison indicates that our estimates are of meaningful magnitudes. As a second robustness test of our approach, we compare our estimates of lacking deliveries

[15]The actual change in the natural gas price also depends on structural shocks before the time period analyzed. However, in the historical decomposition of the event studies, these shocks prior to the event are not included in the relative contribution of each influence during the specific event considered. Therefore, the relative influences during the crisis itself do not necessarily provide an optimal fit of the actual change in the natural gas price, which is therefore only included for illustrative purposes.

with the simulation-based estimate derived by Lochner (2011). According to that analysis, the affected daily gas transits via Ukraine account to 303.5 mcm on a normal winter day, which is close to the value found in our methodology.

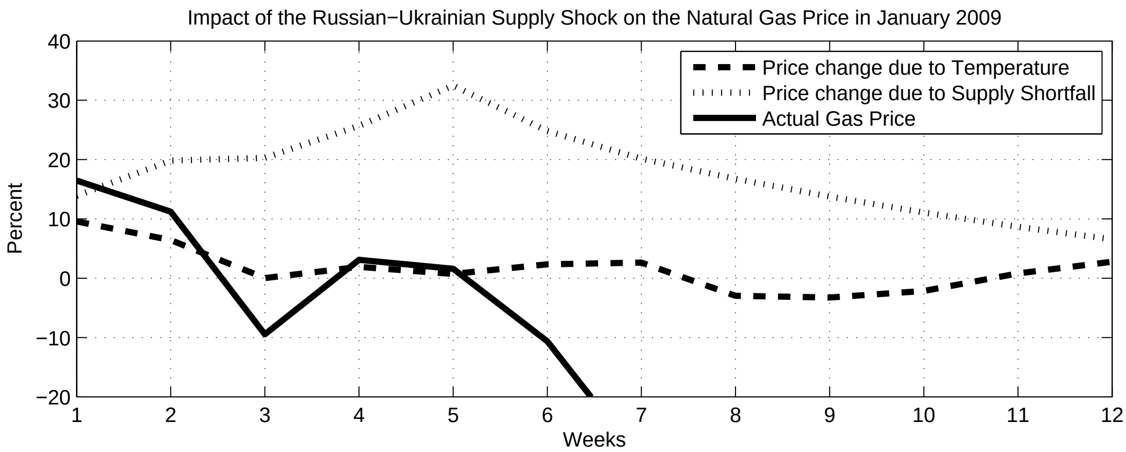

Figure 2: Historical Decomposition of Structural Influences During the Russian-Ukrainian Gas Dispute of January 2009

Notes: Week 1 refers to the week ending on Friday January 9$^{\text{th}}$, 2009

Figure 2 shows the fundamental drivers of gas prices during the Russian-Ukrainian dispute of January 2009 and for a period of 12 weeks. The shortfall of natural gas supplies accounts for an increase in the gas price of more than 30% and is therefore the main driver of the observed price spike. Increased demand due to unusually low temperatures accounts for 10% of the price increases and is especially of importance during the first two weeks. To summarize, the natural gas price follows the fundamental signals both from supply (interruption of imports) and demand (extraordinary low temperatures) closely.

However, the actual increase in the gas price was less than what would have been implied by the sudden supply shortfall and extreme temperature when setting all other influences to zero. This is due to the fact that the Russian-Ukrainian gas dispute occurred during the financial crisis and the natural gas price was already following a negative trend. During this time, the financial crisis and the global economic downturn constituted a distinctive influence on all commodity markets.

Therefore, we investigate the price impact during a longer period surrounding the supply disruption. Figure 3 shows the weekly development of the natural gas price for the six months after the bankruptcy of Lehman Brothers on September 15$^{\text{th}}$, 2008. In this figure, the spike in natural gas price in week 17 is driven by the start of the Russian-Ukrainian dispute in January 2009. The extended time window illustrates that while the short-term impact of the supply shock is substantial, it only had a short-lived impact on the overall downward sloping trend of the natural gas price. The results of this event study confirm our previous finding that the long-term development of the natural gas price crucially depends on the economic climate and closely follows the benchmark commodity prices of oil and coal.

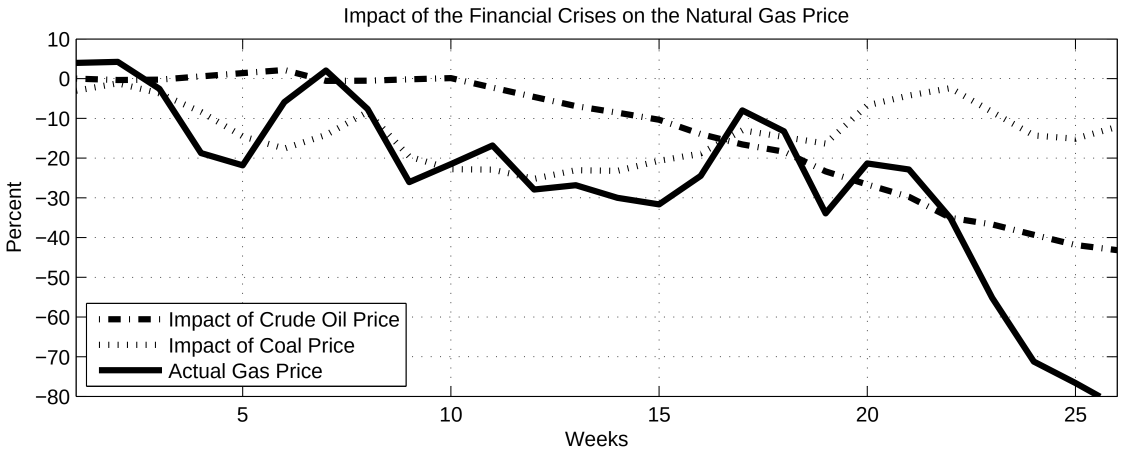

Figure 3: Historical Decomposition of Structural Influences During the Financial Crisis Following the Bankruptcy of Lehman Brothers on September 15$^{\text{th}}$, 2008

Notes: Week 1 refers to the week ending on Friday September 19$^{\text{th}}$, 2008. The price increase in week 17 reflects the beginning of the Russian-Ukrainian gas dispute of January 2009.

5.2. The "Arab Spring" and the Civil War in Libya 2011

In February 2011, the civil unrest of the so-called "Arab Spring" spread to Libya and resulted in a civil war with foreign military intervention. This turmoil lead to an interruption of natural gas production in Libya. Although Germany does not directly import natural gas from Libya, the shortfall of Libyan exports also indirectly affected the market. Lochner and Dieckhöner (2012) point out that Italy compensated for the Libyan imports by using storage withdrawals and additional imports via Austria and Switzerland, highlighting the integration of European natural gas markets. The shortfall of Libyan production therefore indirectly affects the German natural gas market because natural gas flows from Russia were diverted to Southern Europe and could consequently not be delivered to German consumers.

In order to estimate the supply shortfall, we use monthly Eurostat export data from Libya to Italy, which is Libya's main customer in the EU. We linearly interpolate from monthly to weekly frequency and define the supply shortfall as the difference between the actual exports and the exports before the interruption. According to Lochner and Dieckhöner (2012), delivery via the Greenstream pipeline to Italy was interrupted from February 22$^{\text{nd}}$ to October 13$^{\text{rd}}$, 2011. This period is consistent with Eurostat data indicating no exports to the EU between March and September 2011. As Italy was able to compensate the Libyan supply shortfalls by additional imports from Russia, we only consider the missing Libyan gas volumes until the mid of April 2011 as a shock.[16]

In addition to the actual supply shortfall, there were also other indirect effects on the natural gas market. First, there was an additional risk that the Arab Spring could spread to Algeria and thus disrupt the Algerian natural gas production. In this case, as Lochner and Dieckhöner (2012) point out, the consequences for the European natural gas market would have been more severe. Second, the Arab Spring also affected the crude oil market both directly and indirectly. Libya is a relevant crude oil exporter and the market, according to news coverage, accounted for the risk that the Arab Spring could spread to other more important crude oil producers in the Middle East. Baumeister and Kilian (2012) discuss

[16] Lochner and Dieckhöner (2012) argue that the lack of imports from Libya were mainly compensated by increased imports via the Austrian TAG pipeline carrying Russian natural gas deliveries. However, as it takes approximately two weeks for Russian gas to be physically transported to Italy, the compensation mechanism of delivering additional gas via pipelines from Russia was mainly relevant after the first few weeks of the interruption.

how the negative supply shock in Libya, as well as a precautionary demand shock driven by the political unrest resulting in a stocking up of crude oil, contributed to the increase in the real price of oil.

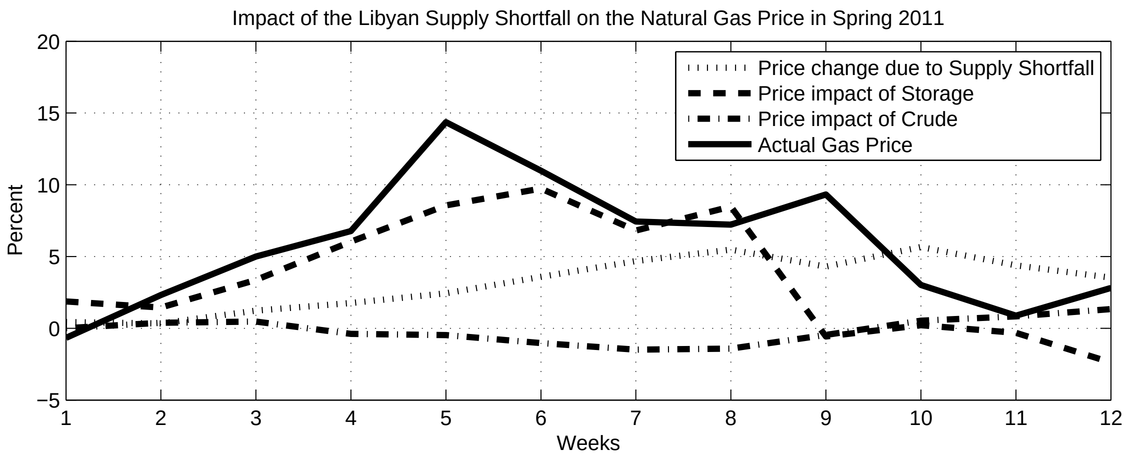

Figure 4: Historical Decomposition of Structural Influences During the Supply Shortfall After the Libyan Civil War in the Spring of 2011

Notes: Week 1 refers to the week ending on Friday February, 18^{th}, 2011

Figure 4 shows the impact of the Libyan supply shortfalls in Spring 2011. Due to the relatively small amount of supply shortfalls, the direct impact on the gas price is rather weak. Furthermore, our analysis indicates that the development of the crude oil price does not seem to be a major explanatory factor for the German gas price increase during the Libyan civil war in 2011. Yet, due to the political instability and risks associated with Algeria as a larger natural gas exporter, the increased precautionary demand for storage leads to increased gas prices. Such behavior is typical for energy markets during situations of uncertainty or turmoil in supplying countries, as shown by Kilian and Murphy (2010) using the Iranian Revolution in the year 1979 as one example.

5.3. Supply Interruptions of Russian Natural Gas Deliveries in February 2012

In late January 2012, unusually low temperatures increased the domestic Russian gas demand for a sustained period of time. As the cold weather spread to Central and Western

Europe, Russia found itself unable to meet its export commitments and thereby induced supply shortages and price spikes at various European gas hubs. However, there is a lack of quantitative estimates regarding the amount of the shortfall of supply during February 2012. In order to calculate a reasonable estimate, we draw upon different sources including the Dow Jones TradeNews Energy, the ICIS Heren European Gas Markets report and a report by Henderson and Heather (2012). Details regarding the information in these sources is given in Table A.5 in the Appendix. The estimates of supply interruptions are mostly in the range of 10 and 30%, but vary depending on the date, geography or company considered. Given this wide range of estimates, we assume a shortfall of 20% in the first two weeks of February 2011 and assume a normal weekly delivery volume of 2.5 bcm to the EU as indicated by Eurostat data.

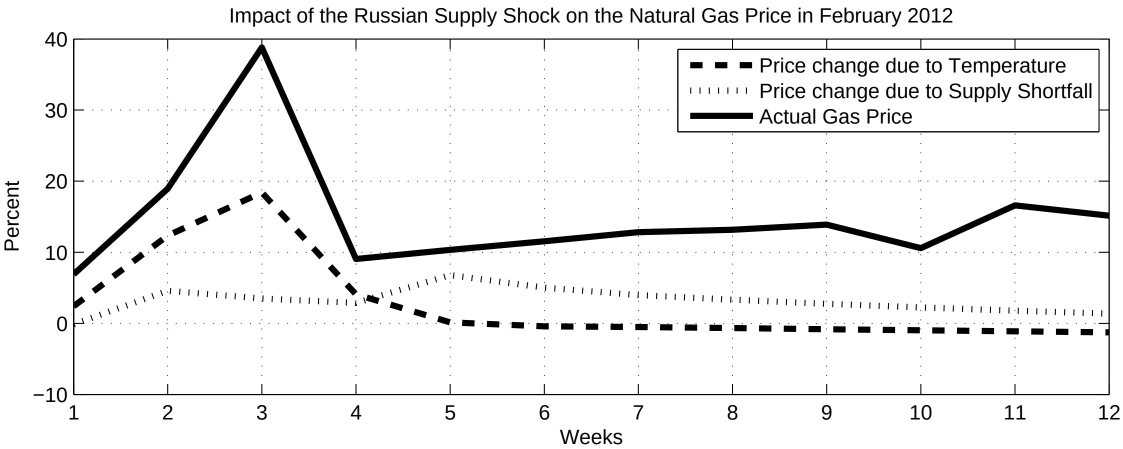

Figure 5: Historical Decomposition of Structural Influences During the Russian Supply Shortfall in February 2012

Notes: Week 1 refers to the week ending on Friday January 27$^{\text{th}}$, 2012

In Figure 5, we analyze the period of reduced Russian supplies in February 2012 coinciding with extraordinary cold temperatures. Our results indicate that the abnormally low temperatures can explain a bigger share of the actual price increase than the relatively small amount of supply shortfall. Consequently, we conclude that the price increase was rather driven by a positive demand shock than by the temporary cut in gas supplies.

6. Conclusion

In this study, we introduce a novel approach to model the economics of natural gas prices. Our structural model allows us to appropriately account for the dynamics within the natural gas market as well as for the relationship to other commodity markets. The empirical results for Germany show that abnormal temperatures and supply shocks only affect the natural gas price in the short term. However, in the long term, the price development is closely tied to crude oil and coal prices, indicating a high importance of cross-commodity effects.

The structural model allows us to perform a historical decomposition of the shocks affecting the natural gas price. We focus on the three major recent supply interruptions, namely the Russian-Ukrainian gas dispute of 2009, the Libyan supply shortfall in the spring of 2011 and the withheld Russian exports in February 2012. We explicitly analyze the specific contribution of the main fundamental variables on gas price development in these periods. Our findings can be used to draw conclusions about how the security of gas supply can be improved by different measures. The results of our structural model indicate that while supply shortfalls have a significant impact on the German gas market, their effect on gas prices may be overestimated since some of the discussed shortfalls occurred simultaneously with extraordinary demand conditions. These conditions comprise both extremely low temperatures and precautionary demand resulting from the anticipation of further supply interruptions, as pointed out in Section 5.

Consequently, the objective to improve the security of German gas supplies should not only focus on supply-sided measures such as a diversification of gas imports, but could also address flexibility options on the demand side of the market. A further extension of temperature-indexed interruptible contracts for industrial customers could be a conceivable measure to target demand flexibility. Modifications in the current market design for gas storages could keep these facilities available despite narrowing seasonal price spreads.

Our model provides a comprehensive and innovative framework for further research on more specific economic mechanisms within gas markets. Additionally, it could be easily extended to a European scope or other geographical regions. However, the current application is still restricted by the limited data available for the European gas markets.

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Appendix A. Supplementary Material

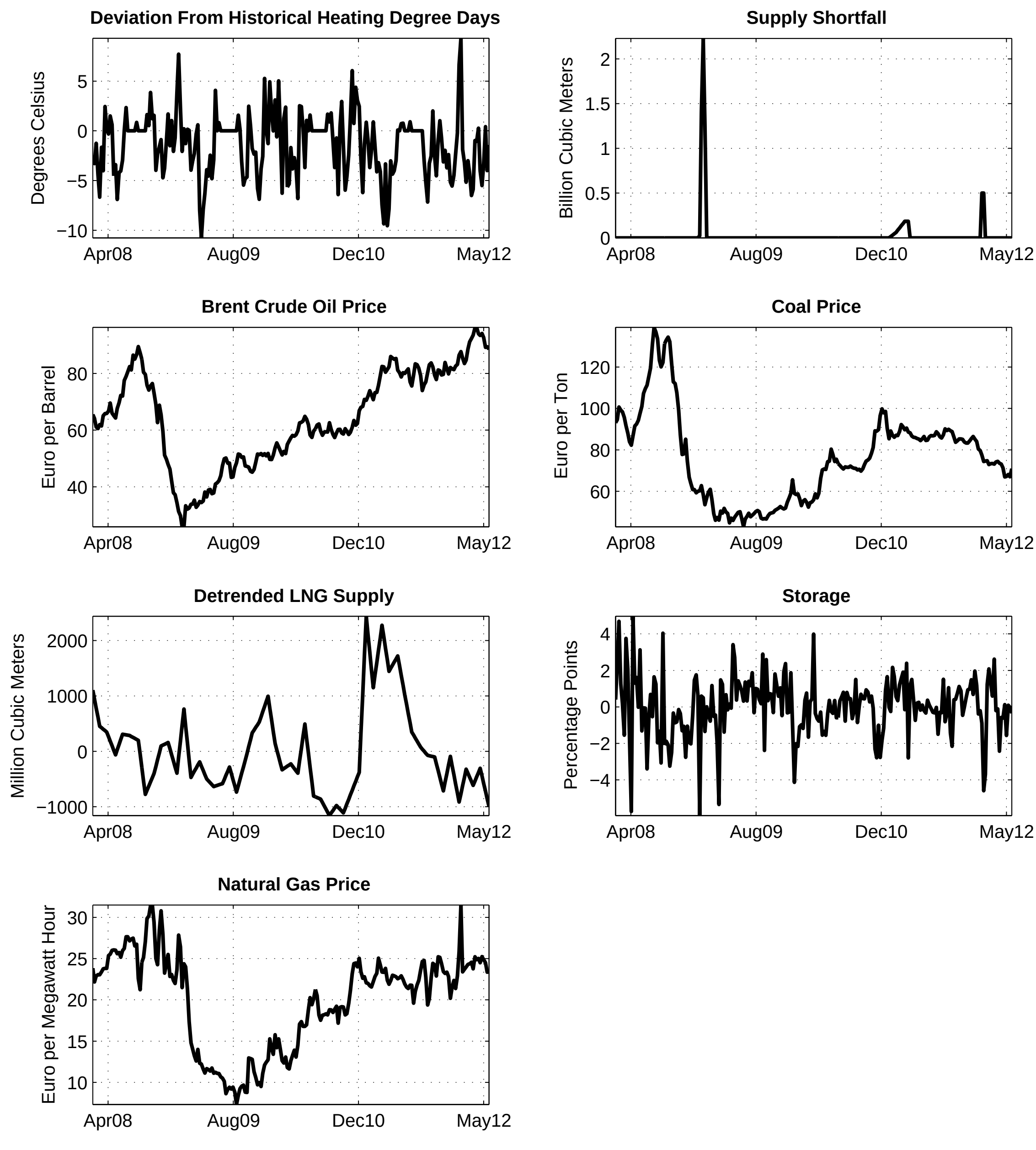

Figure A.6: Plots of the Time Series Used for the Analysis

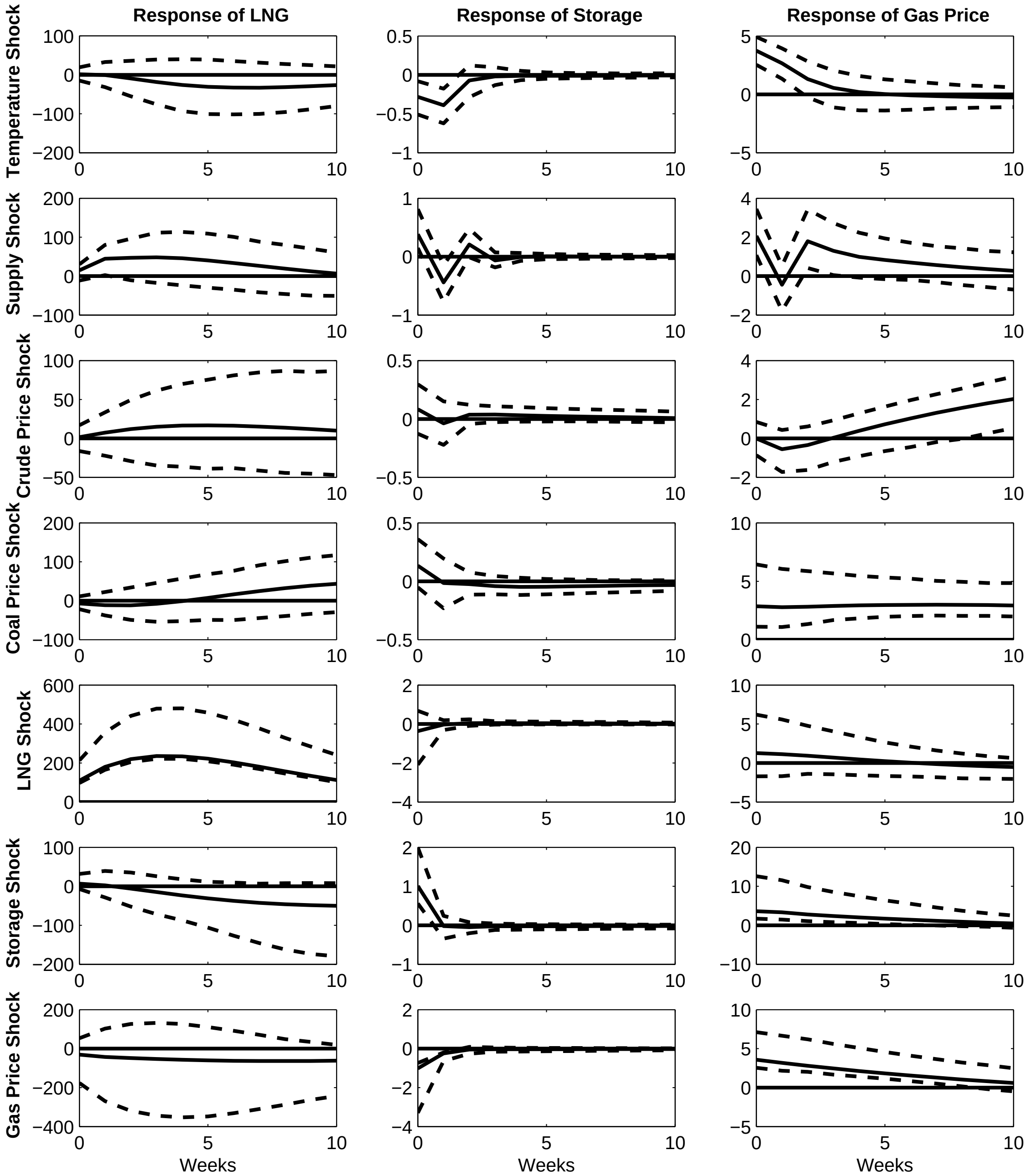

Figure A.7: Responses of LNG, Storage and the Natural Gas Price

Notes: The impulse responses (solid lines) are based on one standard deviation of the respective structural shock. The response of LNG is measured in million cubic meters (mcm), the response of deseasonalized storage utilization is measured in percentage points and the response of the natural gas price is measured in percent. Confidence intervals (dashed lines) are bootstrapped following Hall's 95-percentage bootstrap interval using 1000 draws.

Table A.5: Summary of Sources, Russian Supply Shortfall of February 2012

Source	Publication Date	Time Period	Affected Location	Supply Disruption	Original Source
DJ Tradenews	02/02/12	01/31/12	Europe	1.5% less	Gazprom Employee
DJ Tradenews	02/03/12		E.ON Ruhrgas, Germany	None	Company
DJ Tradenews	02/03/12		Italy	11.6% less	
DJ Tradenews	02/03/12		Italy, Poland, Slovakia	8% to 10% less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/03/12		Hungary, Czech Republic	Less	
DJ Tradenews	02/03/12		RWE Supply & Trading, Germany	30% less	Company
DJ Tradenews	02/03/12		Wingas, Germany	Less	Company
DJ Tradenews	02/03/12		OMV, Hub Baumgarten, Austria	30% less expected	Company
DJ Tradenews	02/06/12		PGNiG, Poland	7% less	Company
DJ Tradenews	02/06/12		E.ON Ruhrgas, Germany	Approximately one third less	Company
DJ Tradenews	02/06/12	02/02/12	Austria	30% less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/06/12	02/02/12	Italy	24% less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/06/12	02/02/12	Poland	8% less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/06/12	Currently	Italy, Greece, Austria, Poland, Slovakia, Hungary, Bulgaria, Romania	Less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/07/12		Germany, Romania, Italy	Less	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/07/12		Bulgaria, Slovakia, Hungary, Poland, Austria, Greece	No disruptions	Speaker of Günther Oettinger, European Comission
DJ Tradenews	02/08/12	Previous week	Europe	15% less	Alexander Medvedev, Gazprom
DJ Tradenews	02/13/12		E.ON Ruhrgas, RWE and Wingas, Germany	Less deliveries, but rising	Company
ICIS Heren EGM	02/15/12		Europe	About 10% below contractual levels	Gazprom
ICIS Heren EGM	02/15/12	Beginning of February	GDF Suez, France	30% less	Company
ICIS Heren EGM	02/15/12	02/06/12	GDF Suez, France	20% less	Company
ICIS Heren EGM	02/15/12	01/31/12	Slovakia	8% to 10% less	
ICIS Heren EGM	02/15/12	02/02/12	SPP, Slovakia	36% less	Company
DJ Tradenews	02/21/12		Europe	No disruptions anymore	Alexander Medvedev, Gazprom
Henderson and Heather (2012)	April 2012	02/02/12 to 02/07/12	Italy	11% - 29% less	Snam Rete Gas

Notes: DJ Tradenews refers to the Dow Jones TradeNews Energy publication available at `http://www.djnewsletters.de/produkte/commodities/energie/dow-jones-tradenews-energy.html`. ICIS Heren EGM refers to the ICIS Heren European Gas Market report available at `http://www.icis.com/energy/gas/europe/`.