CESifo WORKING PAPERS

11191
2024

June 2024

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Jochen Güntner, Magnus Reif, Maik Wolters

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp

CESifo *Working Paper No. 11191*

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Abstract

We use a structural VAR model to study the German natural gas market and investigate the impact of the 2022 Russian supply stop on the German economy. Combining conventional and narrative sign restrictions, we find that gas supply and demand shocks have large and persistent price effects, while output effects tend to be moderate. The 2022 natural gas price spike was driven by adverse supply shocks and positive storage demand shocks, as Germany filled its inventories before the winter. Counterfactual simulations of an embargo on natural gas imports from Russia indicate similar positive price and negative output effects compared to what we observe in the data.

JEL-Codes: E320, F510, Q410, Q430, Q480.

Keywords: energy crisis, German natural gas market, narrative sign restrictions, natural gas price, structural scenario analysis, vector-autoregression.

*Jochen Güntner**
JKU Linz
Altenberger Str. 69
Austria – 4040 Linz
jochen.guentner@jku.at

Magnus Reif
German Federal Bank
Frankfurt / Germany
reif@bundesbank.de

Maik Wolters
University of Kiel / Germany
wolters@economics.uni-kiel.de

*corresponding author

25h June 2024
This paper expresses the authors’ personal opinions and does not necessarily reflect the views of the Deutsche Bundesbank or the Eurosystem. We thank Marco del Negro and three anonymous referees for their insightful comments and suggestions. We also thank seminar participants at CESifo Munich, Deutsche Bundesbank, Karlsruhe Institute of Technology, and the University of Magdeburg as well as conference participants at Universidad de Alicante, Free University of Bolzano, and IWH for helpful comments. Declarations of interest: none.

1 Introduction

Natural gas prices in the European Union started to surge in the summer of 2021, ending a two-decade period of low and stable prices. Demand pressures attributed to the economic recovery following the COVID-19 pandemic and supply disruptions related to the Russian invasion of Ukraine alike arguably contributed to this unexpected development. At the peak of the crisis, the price of one-month ahead natural gas futures for the European market (TTF) had risen by a factor of twelve relative to its 2019 average (see Figure 1). Although natural gas import prices, which are more relevant for industry, do not co-move perfectly with gas futures prices, they also started to increase substantially in Germany as of 2021.

To investigate the drivers and economic consequences of this surge in natural gas prices, we draw on the extensive literature on SVAR models of the global oil market and estimate a model for the regionally fragmented natural gas market. We focus on the case of Germany and distinguish between structural natural gas supply and demand shocks by imposing sign restrictions on impulse response functions. To sharpen inference, we complement these assumptions with additional narrative restrictions on the sign, size, or effects of shocks during well-documented episodes in 2022 and an earlier natural gas supply shock associated with the Russia-Ukraine gas transit dispute in 2009. Our econometric framework thus allows us to quantify the contribution of each of these shocks to fluctuations in domestic natural gas prices and economic activity — both on average over the sample period and during the recent natural gas price surge.

We find that supply and demand shocks in the German natural gas market have large and persistent price effects, but moderate output effects. During the 2022 energy crisis, adverse supply and gas-specific demand shocks related to the rapid filling of natural gas storage facilities before the next winter contributed disproportionately to the surge of natural gas import prices between February and August of 2022.[1] Despite these supply shocks, German industrial production remained fairly robust. After the natural gas price

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[1] Figure A.1 in the Appendix illustrates the successful efforts by the German government to ramp up gas inventories, following exceptionally low levels in March 2022. The political aim to increase the level of gas inventories to 90% by November was already reached in October 2022.

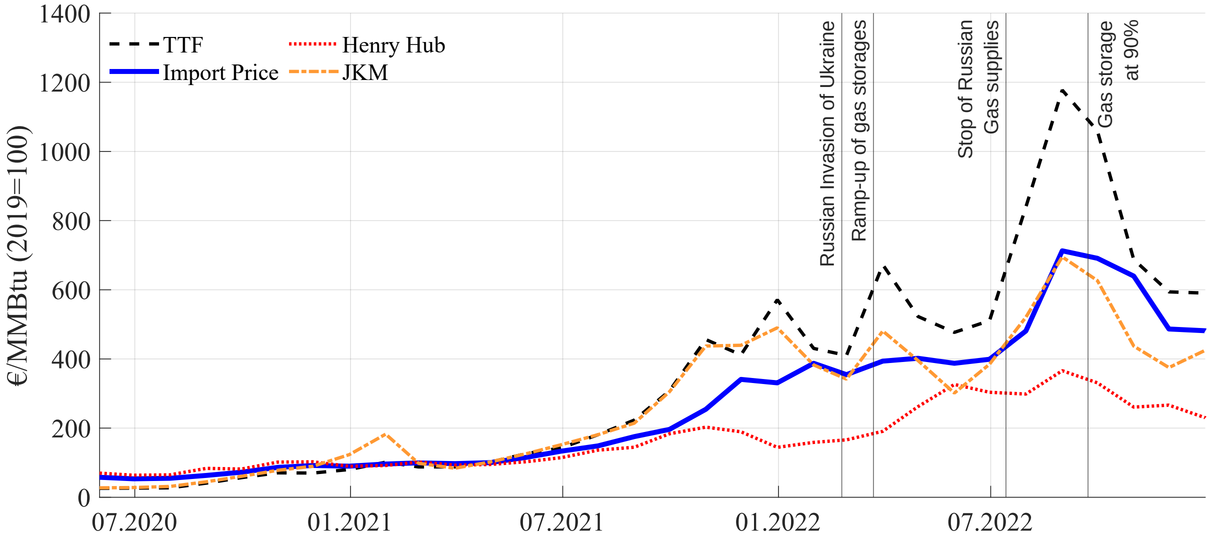

Figure 1: German natural gas import price and one-month ahead natural gas futures for Europe (TTF), the US (Henry Hub), and northeast Asia (JKM)

spike in the summer of 2022, the relatively mild winter that followed led to an easing of domestic prices and about 20% higher natural gas inventories compared to what would have been expected during a harsh winter. This easing of the natural gas market occurred despite lower natural gas imports, as increases in imports from Norway, Belgium, and the Netherlands did not fully compensate for the shortfall of imports from Russia.

According to our model, an immediate disruption of gas imports from Russia in April 2022 — for example due to a German embargo on Russia called for by some politicians and economists — would likely have led to only moderately and temporarily higher gas import prices compared to the actual scenario, in which flows through the Nord Stream 1 pipeline connecting Russia and Germany were reduced to zero in three steps between June and September of 2022. A hypothetical disruption of natural gas flows through Europipe 1 and 2, which transport natural gas from Norway to Germany and accounted for 36% of German imports between July and December of 2022, is predicted to have comparable effects on natural gas import prices and aggregate economic activity.[2] An assumption inherent in these counterfactual simulations is that substitution patterns remain similar to those observed in the summer of 2022. The effects should therefore be interpreted as a lower bound. Given that Germany currently relies on only three main natural gas

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[2] Europipe 1 and 2 deliver natural gas from the Norwegian Draupner E platform to Dornum and from Kårstø in Norway to Emden in Germany, respectively. Along the German coast, the two pipelines run next to each other in shallow water, making them susceptible to targeted disruptions.

suppliers — Norway, Belgium, and the Netherlands — the loss of another supplier could be more difficult to compensate, as many pipelines to Germany are operating at close-to-full capacity. Although Germany has recently commissioned LNG terminals, the amount of natural gas imported via these terminals has so far been negligible and is unlikely to significantly increase the scope for substitution, at least in the short term.

Our work relates to several strands of the literature studying the macroeconomic effects of energy price shocks and contributes to the recent policy debate on the economic consequences of the natural gas price surge in import-dependent economies, such as Germany, where predictions of the potential output losses from an embargo against natural gas imports from Russia were far from unanimous. (see, e.g., Bachmann et al., 2022; German Council of Economic Experts, 2022; Krebs, 2022).

Methodologically, we build on the extensive SVAR literature studying the market for crude oil. Starting with Kilian (2009), numerous contributions have disentangled the effects of supply and demand shocks in the global oil market on the price of crude oil and thus on economic conditions in the US and abroad.[3] Using an SVAR model and identifying strategies that are well established in the oil-market literature, we disentangle the effects of supply and demand shocks in the German natural gas market.[4] While analyzing price dynamics in regional natural gas markets helps us to better understand the cause of regional business cycles, in contrast to relevant studies of the global market for crude oil, our approach necessarily remains in partial equilibrium.

The use of a structural empirical framework and state-of-the-art identifying strategies allows us to run scenario analyses and reconsider, for example, the theoretical model-based prediction of Bachmann et al. (2022) that a natural gas embargo on Russia in early 2022 would have done moderate harm — in terms of forgone GDP growth — to the German

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[3] See, in particular, Kilian and Murphy (2012, 2014), Baumeister and Peersman (2013), Baumeister and Hamilton (2019), and Kilian and Zhou (2020).

[4] Nick and Thoenes (2014) also use a VAR model to study the German natural gas market. Given that they orthogonalize the reduced-form residuals by Cholesky decomposition, their shocks have an ambiguous economic interpretation. Moreover, their sample lacks the recent energy crisis for identification. Böck and Zörner (2023) focus on the role of inflation expectations for the propagation of natural gas price shocks in the euro area. Adolfsen et al. (2024) use a SVAR similar to ours to investigate the impact of natural gas price shocks on euro area inflation without distinguishing between different types of gas-specific demand shocks.

economy.[5] Using a empirical approach, we obtain qualitatively and quantitatively similar results, namely that the output losses of an embargo would likely have been moderate.

The rest of this article is structured as follows. Section 2 discusses the institutional background. Section 3 presents the SVAR model, the data, and the identifying assumptions as well as the importance of narrative sign restrictions. Section 4 shows our baseline results. Section 5 conducts scenario analyses to quantify the effects of a hypothetical Russian gas embargo and different temperature paths during 2022. Section 6 presents further analysis and robustness checks, while Section 7 concludes.

2 Institutional Background

The structure of the natural gas market resembles that of the market for crude oil, with many globally distributed consumers and producers that differ in their production capacities, market shares, and market power. Accordingly, the price of natural gas reflects the interplay of supply and demand in the corresponding market (Kilian, 2009).

With few exceptions, such as the US, spatial distances between petroleum production, refining, and consumption required the establishment of a global network of shipping routes and pipelines, which promoted a virtually integrated world market for crude oil. While the maritime transport of crude oil and petroleum products dates back to its modern commercial exploitation and export from Burma — then a British colony — in the 19th century, and despite the recent commercialization of LNG for transport using maritime vessels, regional gas markets remain comparatively fragmented, with pipeline transport as the dominant mode of transportation.[6]

Figure 1 highlights this fragmentation. While natural gas prices surged in Europe, they exhibited a much smaller increase in East Asia (JKM) and remained relatively stable in the US (Henry Hub). Despite recent political attempts to launch LNG terminals (e.g. along the German coastline), time to build and limited global capacity of maritime vessels

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[5] German chancellor Olaf Scholz's reaction to the findings in Bachmann et al. (2022) in a live interview was: "The scientists see this wrong. It is irresponsible to add up any mathematical models, which then don't really work" (translated from the German original quote in the newspaper NZZ).

[6] For a detailed analysis of the obstacles to natural gas trade, see Barbe and Riker (2015).

suggests that regional natural gas markets are likely to remain less integrated than the global market for crude oil.

Moreover, while crude oil is primarily used as an input in the refinery production process, natural gas can be used without further processing for heat generation in the residential and industrial sector as well as for electricity generation.[7] In its efforts to phase out coal and nuclear energy from its energy mix, Germany decided to rely predominantly on natural gas, 95% of which was imported in 2021, until renewable energy sources are sufficient to cover domestic demand (see Federal Statistical Office, 2023). Natural gas accounted for 31.2% of the energy consumed by German industry in 2020, 41.2% of energy consumed by German households for residential heating in 2019, and 13.8% of the electricity produced domestically in 2022 (Federal Statistical Office, 2022). Moreover, the German economy is characterized by a comparatively high value-added share of industry, a significant fraction of which may be classified as energy-intensive.[8] For these reasons, the analysis in this paper focuses on the natural gas market of Germany — the world's fourth largest economy, which appears to be particularly vulnerable to disruptions in the European natural gas market.

Due to an extensive network of pipelines, Germany previously relied on natural gas imports from Russia mainly through the Jamal, Transgas, and Nord Stream 1 pipelines (see Figure A.3 in the Appendix), thus benefiting from comparatively low and stable natural gas prices.[9] Until 2022, more than half of Germany's supply of natural gas was provided by Russia, indicating a strong import dependency. During January and May 2022, Russia still provided for 35% of German natural gas imports (see Bundesnetzagentur, 2024). Already prior to the invasion of Ukraine, Russia started to reduce gas flows through the Jamal and Transgas pipelines crossing Poland, Slovakia, and Ukraine (Figure A.3 in the online Appendix), foreshadowing the complete suspension of gas exports

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[7] In 2022, the industrial, residential, and electricity sector accounted for 31%, 35%, and 14%, respectively, of German natural gas use (Federal Ministry of Economic Affairs and Climate Action (BMWK), 2022).

[8] In 2022, the value-added share of German industry was 25%, 16% of which was classified as energy-intensive.

[9] During 1999:1–2019:12 (i.e. prior to the start of the COVID-19 pandemic and the Russian invasion of Ukraine), the standard deviation of month-on-month percent changes in the natural gas import price was 4.8%, whereas that of the Brent crude spot price was 8.9% both expressed in US dollars and euros.

to Germany and the EU in September 2022. Since then, Germany has been effectively relying on natural gas imports from Belgium, the Netherlands, and Norway, while *direct* imports of LNG via the newly built Wilhelmshaven terminal started on December 21, 2022 and accounted for 7.5% of German natural gas imports in 2023.

3 Empirical Methodology

In this section we present the econometric model, the time series used for estimation, and our identifying assumptions.

3.1 Model

We model the dynamics of the German market for natural gas using a four-variable SVAR:

$$A_0 y_t = c + \sum_{l=1}^{12} A_l y_{t-l} + \sum_{i=1}^{11} \gamma_i s_i + \sum_{j=0}^{11} \delta_j x_{t-j} + \chi_t \epsilon_t, \qquad \epsilon_t \sim N(0, I_n), \tag{1}$$

where the $n \times 1$ vector of endogenous variables y_t contains log differences of the sum of net natural gas imports and a (small) amount of domestic gas production, an indicator of real economic activity, and the real natural gas price as well as the change in domestic natural gas inventories in month t. We account for seasonal variation in the seasonally unadjusted time series by including monthly dummies s_i, which equal one for the respective month and zero otherwise. Moreover, we include the contemporaneous value and eleven lags of the average monthly temperature as exogenous regressors x_t to control for temperature-related natural gas demand, in particular for consumption in gas-heating systems. We also include an entire year of lags of the endogenous variables to allow for persistent cycles in the German natural gas market.

To account for the unprecedented volatility in the German natural gas market in 2022, we follow Lenza and Primiceri (2022) and multiply the residual covariance matrix by a factor χ_t, which may take on non-unit values during three consecutive months at the peak of the energy crisis and decays at rate ρ_χ afterwards. Specifically, $\chi_t = 1$ prior to June 2022, which we denote by χ_{t^*}. We then set $\chi_{t^*} = \overline{\chi}_0$, $\chi_{t^*+1} = \overline{\chi}_1$, $\chi_{t^*+2} = \overline{\chi}_2$, in

July, August, and September, respectively, while $\chi_{t^*+j} = 1 + (\overline{\chi}_2 - 1)\rho_\chi^{j-2}$ from October 2022 onwards.

Given that $u_t = A_0^{-1}\epsilon_t$, where u_t denotes the reduced-form VAR residuals, knowledge about the structural impact multipliers in A_0^{-1} is sufficient for recovering the structural objects of interest. We use Bayesian estimation techniques and impose Minnesota-style Normal-Wishart priors as in Kadiyala and Karlsson (1997). The overall tightness (λ), the scaling factors ($\overline{\chi}_0, \overline{\chi}_1, \overline{\chi}_2$), and the rate of decay (ρ_χ) are estimated using the procedure of Giannone, Lenza, and Primiceri (2015) with the modification proposed by Lenza and Primiceri (2022), where the degrees of freedom parameter is set to $n + 2$.[10]

In light of a growing literature emphasizing that solely the joint distribution is able to correctly capture the shape and comovement of impulse responses and the uncertainty surrounding them (see, e.g., Lütkepohl, Staszewska-Bystrova, and Winker, 2015; Bruder and Wolf, 2018; Montiel Olea and Plagborg-Møller, 2019; Inoue and Kilian, 2022), we evaluate the joint distribution of all admissible impulse response functions under additively separable absolute loss, as suggested by Inoue and Kilian (2022).[11] Specifically, we obtain the Bayes estimator by stacking impulse response functions and minimizing the above loss function. The forecast error variance and historical decompositions are then evaluated based on the same estimator.

3.2 Data

We estimate the reduced-form representation of the model outlined above using monthly time series for Germany covering the period 1999:1–2022:12. Data on domestic natural gas quantities, cross-border prices, and inventories are obtained from the Federal Office for Economic Affairs and Export Control (BAFA). We define net natural gas imports as the sum of imports and (a small amount of) domestically produced natural gas less exports.

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[10] The posterior distributions for the scaling factors and the decay coefficient are provided in the online Appendix and indicate that the shocks indeed originate from another distribution during this episode, though the change in volatility is rather modest.

[11] Inoue and Kilian (2022) show that oft-used pointwise posterior statistics, such as the posterior mean or median, are not necessarily equal to the Bayes estimator and may imply impulse response functions that are incompatible with any admissible model. Moreover, pointwise posterior bands may understate the true estimation uncertainty by neglecting the mutual dependence between impulse responses.

As a measure of real domestic activity, we use the German industrial production (IP) index excluding construction activity. The real gas price corresponds to the cross-border price of natural gas deflated by the German consumer price index (CPI). Following Kilian and Murphy (2014), natural gas inventories enter the model in terms of changes relative to the previous month.[12] Average monthly temperatures for Germany are obtained from the German Weather Service (DWD).

3.3 Identification

Our goal is to identify four structural disturbances in the German natural gas market: a flow supply shock, a flow demand shock, a storage demand shock, and a gas preference shock. Each shock is normalized such that it raises the real price of natural gas. We achieve set-identification by imposing sign restrictions on the impulse response functions of the endogenous variables along the lines of Kilian and Murphy (2014). These restrictions are summarized in Table 1.

Following the oil market literature, a flow supply shock is assumed to move German net natural gas import growth and economic activity in the same direction, whereas the natural gas price moves in the opposite direction.[13] A flow demand shock instead moves net natural gas imports, economic activity, and the real gas price in the same direction. As stressed by Kilian and Murphy (2014), the response of inventories to either of these shocks is ex ante ambiguous. On the one hand, both adverse flow supply and expansionary flow demand shocks may cause a reduction of natural gas inventories. On the other hand, the anticipation of higher natural gas prices in the future may increase the demand for inventories already today. Accordingly, we abstain from restricting the impact response of natural gas inventories to these two shocks.

We distinguish between two natural gas-specific demand shocks — a storage demand and a gas preference shock. Following either shock, net gas imports and the real gas price

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[12] Figure A.2 in the online Appendix plots the time series of the endogenous variables, as they enter the SVAR model in Equation (1).

[13] We adopt the terminology of Kilian and Murphy (2014) and others from the literature on SVAR models of the global market for crude oil, who define “flow supply shocks” as sudden exogenous political events in oil-producing countries, unexpected politically motivated supply decisions by oil exporting countries, and other shocks to oil supply.

Table 1: Sign restrictions on impact responses

	Flow supply shock	**Flow demand shock**	**Storage demand shock**	**Gas preference shock**
Net gas import growth	−	+	+	+
Industrial production growth	−	+	−	−
Real gas price growth	+	+	+	+
Gas inventories			+	−

Notes: + and − indicates a positive and negative response, respectively. Missing entries mean that no sign restriction is imposed. All sign restrictions are imposed as weak inequality constraints on impulse response functions in the period of the shock

move in the same direction, whereas economic activity moves in the opposite direction. This guarantees that an exogenous increase in gas-specific demand is not conflated with an exogenous disruption of natural gas supply (i.e. an adverse flow supply shock) or an exogenous reduction of economic activity (i.e. an adverse flow demand shock). We disentangle the storage demand shock from the gas preference shock by assuming that the former raises, whereas the latter induces a draw-down of natural gas inventories. Hence, the storage demand shock is associated with exogenous changes in expectations about *future* natural gas supply or demand, while the gas preference shock captures sudden changes in the *current* demand for natural gas, driven by technological progress or shifts in preferences (e.g. voluntary or mandatory efforts to save natural gas). By imposing weak inequality constraints on the impact responses, we explicitly allow for zero responses and encompass thus a wide range of price elasticities of natural gas supply and demand.

While each admissible model satisfies by construction the sign restrictions in Table 1, not all set-identified models are equally plausible from an economic perspective. To narrow down the set of admissible models, we impose a small number of so-called narrative sign restrictions (NSRs), as proposed by Kilian and Murphy (2014) and formalized by Antolín-Díaz and Rubio-Ramírez (2018). The idea is to select the economically most plausible candidate models by restricting the sign of a given structural shock or its contribution to the historical decomposition of the endogenous variables during selected episodes in line with a widely accepted narrative. In addition to the sign restrictions in Table 1, we therefore require that admissible models must satisfy the following NSRs:

1. An *adverse flow supply shock* occurred in January 2009, when the Russia-Ukraine transit dispute led to an unexpected halt of natural gas flows through Transgas between January 7 and January 20 (see, e.g., Nick and Thoenes, 2014).

2. *Adverse flow supply shocks* occurred in June and July 2022, when Russia unexpectedly reduced natural gas flow through the Nord Stream 1 pipeline to 50% and zero, respectively (see Figure figure:flows in the online Appendix).

3. For the periods specified in NSR 2 above, flow supply shocks are the *overwhelming contributor* to unexpected fluctuations in net gas import growth, reflecting the widespread perception that — while certainly present — the effects of other structural shocks did not match those of the disruption of natural gas imports from Russia.[14]

4. The flow demand shock is the *overwhelming contributor* to the unexpected drop in German IP in April 2020. NSR 4 reflects two considerations. First, widespread lockdowns were imposed in major trading partners of Germany in April. As a result, merchandise exports to these economies dropped substantially, while imports from China, for example, were already recovering.[15] Second, both natural gas imports and inventories were not subject to pandemic-related restrictions or supply-chain disruptions. Hence, it seems implausible that flow supply and gas-specific demand shocks outweighed the cumulative effects of adverse flow demand shocks. Finally, these considerations are consistent with the findings in Balleer et al. (2022), who use German firm-level data to show that demand shortages dominated at the early stage of the pandemic.

In light of a wide consensus in the *oil market* literature that the short-run price elasticity of oil supply is very low (see, e.g., Kilian, 2009), Kilian and Murphy (2014) recommend to further sharpen inference by imposing upper bounds on supply and demand

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[14] Following Antolín-Díaz and Rubio-Ramírez (2018), a shock is "overwhelming", if its contribution to the unexplained variance of the restricted variable(s) in a given period is larger than the sum of the contributions of the remaining shocks.

[15] In April 2020, merchandise exports to France, Italy, and the US dropped by 35%, 28%, and 30%, respectively. Kilian, Nomikos, and Zhou (2023) find that the initial drop in US industrial production was largely due to falling domestic demand.

Table 2: Rejection rates for narrative restrictions

Restrictions	**NSR 1**	**NSR 2 & 3**	**NSR 4**	**NSRs in row**
Signs of shocks	3.38	2.14	–	5.42
Historical decompositions	–	0.78	28.0	28.6
Joint restrictions	3.38	2.92	28.0	32.0

Notes: Rejection rates in % of models identified based on sign restrictions for each narrative restriction (NSR) imposed individually and for (sub-)sets of NSRs imposed jointly.

elasticities. We refrain from imposing such restrictions, as there is no empirical evidence on short-run supply and demand elasticities for the German natural gas market, which is arguably very different from the global oil market. Moreover, existing estimates for the US, such as in Hausman and Kellogg (2015), might not be directly applicable. On the supply side, the US is a net exporter of natural gas that has strongly expanded its production during our sample period through "fracking", whereas Germany has negligible domestic production and depends thus on natural gas imports. On the demand side, the German residential sector heavily relies on natural gas for heating purposes, suggesting a lower demand elasticity than in the US, where natural gas is primarily used for (marginal) energy production and energy-intensive industrial production.

We obtain model draws satisfying both sign and narrative restrictions using the rejection sampler of Rubio-Ramírez, Waggoner, and Zha (2010) as well as the importance sampler of Antolín-Díaz and Rubio-Ramírez (2018).[16]

3.4 Importance of narrative restrictions

To assess the relevance of each narrative restriction, we follow Antolín-Díaz and Rubio-Ramírez (2018) and report rejection rates both individually and jointly in Table 2. It is important to note that a high rejection rate should not be interpreted as evidence against

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[16] As stressed by, for example, Baumeister and Hamilton (2019), the prior on the orthogonal rotation matrix, which is commonly imposed in SVARs with sign restrictions (see, e.g., Uhlig, 2005; Rubio-Ramírez et al., 2010; Arias, Rubio-Ramírez, and Waggoner, 2018), may be unintentionally informative. Whether this concern is empirically relevant is an ongoing debate, though. Inoue and Kilian (2021) show that, in models with multiple sign restrictions and further restrictions, such as narrative restriction, the impact of the prior tends to be small. Arias, Rubio-Ramírez, and Waggoner (2023) further alleviate this concern by showing that the standard approach in fact induces uniform joint posterior distributions over the identified set for the vector of impulse responses. Thus, we follow the standard approach of Rubio-Ramírez et al. (2010).

the plausibility of a particular NSR. Instead, it suggests that the baseline specification encompasses structural parameters that are at odds with the narrative evidence during this particular episode.

The restrictions on the signs of gas supply shocks in January 2009 (NSR 1) and mid-2022 (NSR 2) are only mildly informative. About 3.4% and 2.1% of the models identified based on conventional sign restrictions do not satisfy them individually, while 5.4% do not satisfy them jointly, suggesting that both restrictions add independent information. As a result, most model draws satisfying the sign restrictions in Table 1 are also consistent with NSRs 1 and 2. The restriction on the contribution to the historical decomposition in June and July 2022 (NSR 3) adds very little information to NSR 2, whereas the quantitative restriction in April 2020 (NSR 4) has substantially more bite. About 0.8% and 28% of the candidate models do not satisfy NSR 3 and NSR 4, respectively. Imposing them jointly shrinks the set of admissible models by 28.6% of the models identified by conventional sign restrictions alone, suggesting again that both NSRs carry orthogonal information.

While NSR 4 appears to be most informative above and beyond the conventional sign restrictions, it is important to note that the restrictions on the historical decomposition overlap with those on the signs of shocks, as adding the latter increases the joint rejection rate by less than 5.4%. In total, the results suggest that the narrative restrictions add valuable information to the identification process and eliminate about one third of the model draws that entail arguably implausible structural parameters.

4 Baseline Results

In this section, we investigate the effects of the identified structural shocks. We start by analyzing the impulse responses of the endogenous variables to each of the shocks. We then discuss their contributions to the forecast error variance in the long run. Finally, we quantify their contributions to the historical decomposition of the endogenous variables.

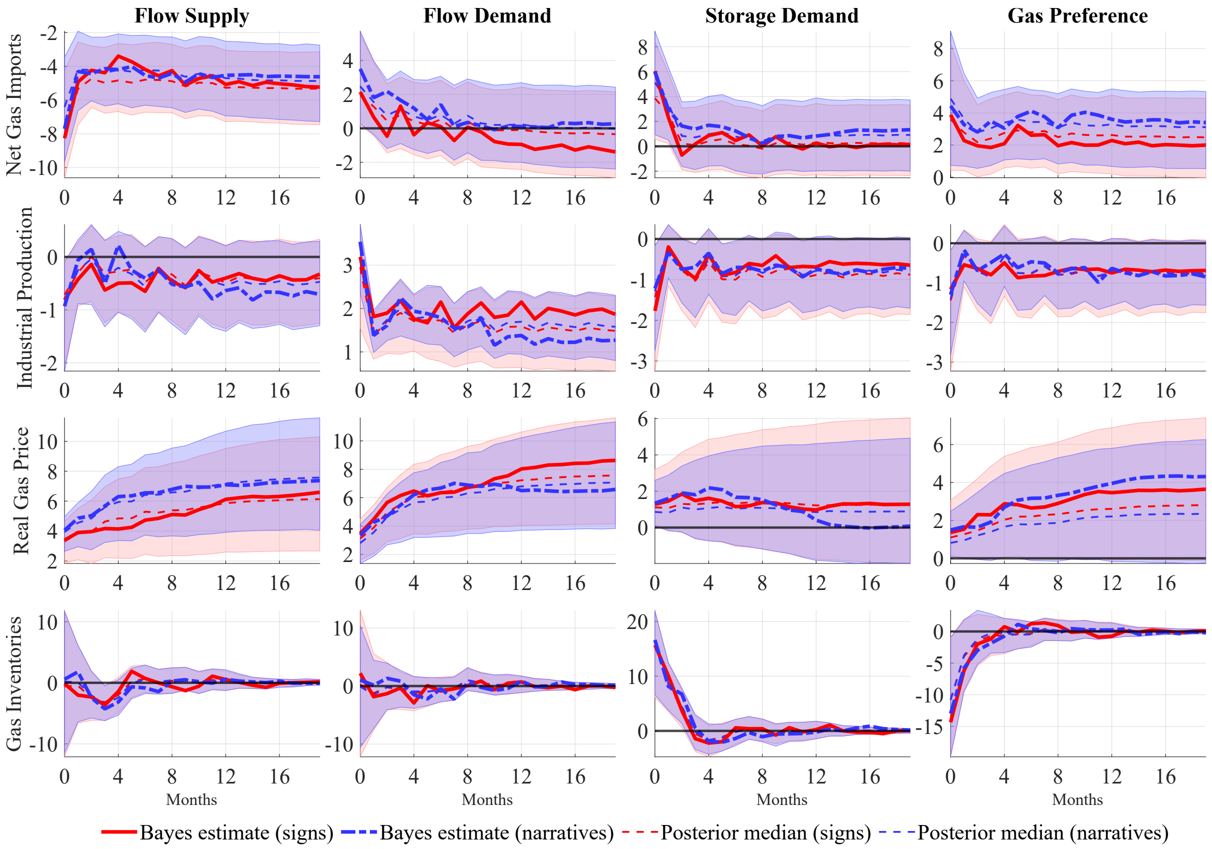

Figure 2: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions.

4.1 Impulse response analysis

As a starting point, Figure 2 plots Bayes estimators together with pointwise medians and 68% simultaneous confidence (sup-t) bands of the impulse response functions (IRFs) for the SVAR models identified only by conventional sign restrictions (in red) and the SVAR models identified by conventional and narrative sign restrictions (in blue).[17] The IRFs of net gas imports growth, industrial production growth, and real gas price growth are accumulated and reported in levels, whereas the change in gas inventories is not.

First, consider the IRFs to a flow supply shock in the left-most column. For either identification scheme, an adverse flow supply shock leads to persistently lower net natural gas imports and a persistently higher real natural gas price. The increase in natural gas

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[17] Bayesian sup-t bands equal the Cartesian product of the pointwise equal-tailed posterior interval, where the tail probability is calibrated to obtain a target simultaneous credibility. As shown by Montiel Olea and Plagborg-Møller (2019), the sup-t band is appealing because it is substantially narrower than, for example, the Bonferroni band.

prices leads to a permanent reduction in German industrial production (IP). Natural gas inventories, which were left unrestricted, decrease for about four months, as inventories are drawn down, and hover around zero afterwards. While the IRFs are qualitatively robust to the identification scheme, the SVAR models identified by conventional *and* narrative sign restrictions suggest that an adverse flow supply shock of similar magnitude induces a larger increase in the real natural gas price and, in the short run, a slightly smaller reduction of German IP. Intuitively, the narrative sign restrictions are consistent with model draws that imply a smaller elasticity between natural gas prices and economic activity. For example, the gas supply cuts in June and July 2022 captured by NSR 2 were followed by large price increases but a moderate response of IP.

In the second column, an expansionary flow demand shock leads to persistently higher economic activity, which remains significantly above steady state for at least two years. The increase in IP goes along with a short-lived increase in net natural gas imports. The real price of natural gas also increases for about eight months before settling in at a new steady state. Natural gas inventories do not respond systematically in either direction. When adding narrative restrictions, the impact on both net natural gas imports and IP is somewhat larger on impact, while the real price of natural gas increases by less.

Both gas-specific demand shocks (third and fourth columns) exert similar responses, except for the opposite effect on natural gas inventories that is inherent in our identifying assumptions. Specifically, both shocks induce persistently higher levels of net natural gas imports and real gas prices. Economic activity drops strongly on impact and remains below steady state for the rest of the impulse response horizon. The dynamics of IP are similar to those following an adverse flow supply shock. However, net natural gas imports drop after the supply-side shock, whereas they increase following either of the demand-side disturbances. Moreover, the real gas price increases considerably more after the supply-induced shock. Nevertheless, both gas-specific demand shocks exert persistent downward pressure on German economic activity. The impulse responses to a gas preference shock are hardly affected by the narrative restrictions. For sudden shifts in storage demand, including narrative restrictions leads to less persistent effects on the natural gas price.

Table 3: Contribution of structural shocks to FEVD (in %)

	Flow supply shock	**Flow demand shock**	**Storage demand shock**	**Gas preference shock**
Gas net import growth	44.2	11.7	29.4	14.7
	[5.9, 85.6]	[0.6, 44.8]	[1.6, 83.8]	[0.8, 80.6]
Industrial production growth	11.3	64.5	10.6	13.6
	[0.7, 55.2]	[18.5, 90.9]	[0.6, 70.2]	[0.4, 69.1]
Real gas price growth	47.7	36.4	7.4	8.6
	[0.7, 55.2]	[18.5, 73.1]	[0.6, 43.0]	[0.3, 43.0]
Gas inventories	6.2	2.8	59.1	32.0
	[1.3, 48.8]	[0.6, 43.4]	[6.8, 95.5]	[0.4, 84.6]

Notes: Variance decomposition based on Bayes estimator of impulse response functions in Figure 2 for models satisfying both conventional and narrative sign restrictions with 68% error bands in brackets. Unconditional variances are approximated by setting the forecast horizon to $h = 100$ months.

According to Figure 2, imposing narrative restrictions primarily affects the IRF of the real natural gas price to each of the structural shocks. Without narrative restrictions, its response to an adverse flow supply and an expansionary flow demand shock is of the same order of magnitude. With narrative restrictions, the price response to a negative flow supply shock is both stronger on impact and more persistent. In light of the recent turmoil in the German natural gas market, the latter result appears much more plausible.

4.2 What drives dynamics in the German natural gas market?

Next, we assess the contribution of each structural shock to the variance of the endogenous variables on average over the sample period. Table 3 reports the Bayes estimator of the forecast error variance decomposition (FEVD) after 100 periods, which approximates the unconditional variance.

Note that 29% of the unconditional variance of net gas import growth is explained by storage demand shocks, suggesting that natural gas inventories are used for speculative trading or that German storage capacity might be too low, requiring frequent sizeable changes in natural gas imports. More than 44% of the variance is accounted for by flow supply shocks, whereas flow demand shocks contribute about 12% to the FEVD of net gas import growth. This finding may be rationalized by the fact that the importance of natural gas for the German economy has increased over time, acting as a “pull factor” for net natural gas imports. While IP growth is mainly explained by flow demand shocks, flow supply shocks are also important, explaining about 11% of the unconditional variance of IP growth. This reflects again the importance of natural gas imports for the German economy.

Flow supply and demand shocks account for 84% of the unconditional variance of real gas price growth, with almost 48% attributed to flow supply shocks, in line with the importance of flow supply shocks for net gas imports. Storage demand and gas preference shocks together explain about 16% of the unconditional variance of real gas price growth, suggesting that gas-specific demand shocks may be important drivers of gas price volatility at least occasionally. Consistently, close to 60% of the unconditional variance of natural gas inventories is due to storage demand shocks, while 32% are attributed to gas preference shocks. The latter comprise efforts to save natural gas by German industry and households as well as non-economic factors, such as geo-strategic or political considerations. By contrast, flow supply and flow demand shocks together account for a mere 9% of the unconditional variance of natural gas inventories.

4.3 Historical decomposition

The contributions to the unconditional FEVD in Table 3 indicate that natural gas supply and demand shocks are important drivers of fluctuations in the German natural gas market. At the same time, they are mute about their importance during selected episodes. Beyond their contribution on average over the sample period, we are interested in how each shock contributed to fluctuations of the endogenous variables over time and, in particular, during the recent turmoil in the German natural gas market. In a first step, we therefore follow Kilian and Lee (2014) and compute the cumulative effect of each of the structural shocks on the four endogenous variables during two sub-sample periods — 2000–2019 and 2021–2022.[18] We then zoom in on the energy crisis at the end of our sample period.

In Figure 3, dark bars depict the net cumulative change in the endogenous variable due

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[18] We deliberately exclude 2020 from this analysis, as the extraordinary shifts in energy demand and economic activity during the COVID-19 pandemic may offset the effects in 2021 and 2022.

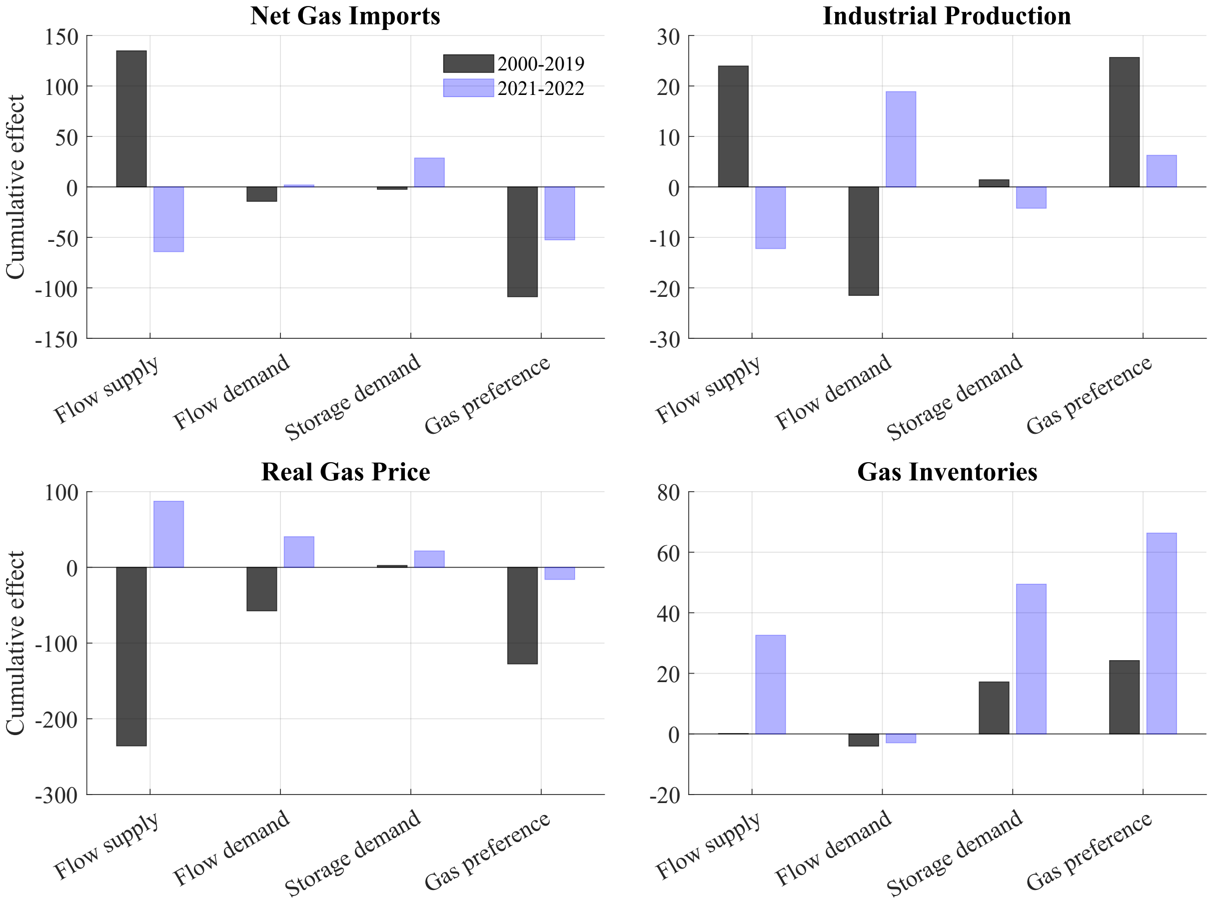

Figure 3: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and 2021–2022, respectively. Decomposition is based on Bayes estimator of impulse response functions in Figure 2.

to a given structural shock during 2000–2019, while light bars depict the net cumulative change during 2021–2022. In 2000–2019, most of the cumulative increase in net natural gas imports is attributed to favorable flow supply shocks, reflecting the political decision to enhance the role of natural gas as an energy carrier in Germany. The pronounced expansion of net natural gas imports goes along with a strong positive contribution of favorable flow supply shocks to IP growth and a markedly negative contribution to real gas price growth during the same period, in line with the narrative that German industry took advantage of low natural gas prices before the post-COVID-19 economic recovery and before the Russian invasion of Ukraine. For IP, the strong positive contribution of flow supply shocks is largely offset by the cumulative contribution of adverse flow demand shocks. For real gas prices, the cumulative contribution of favorable flow supply shocks is instead amplified by the negative effect of flow demand shocks. The cumulative change in natural gas inventories during 2000–2019 is mostly attributed to storage demand and gas preference shocks.

In 2021–2022, cumulative contributions switch signs in many cases, suggesting that the war in Ukraine and the subsequent suspension of Russian natural gas exports to Germany reversed the dynamics in the German natural gas market. For instance, adverse flow supply shocks contribute negatively to the cumulative change in net natural gas imports and IP, while inducing higher real gas prices. For natural gas inventories, the positive cumulative contributions of storage demand and gas preference shocks become much more pronounced, as inventories were at historically low levels before the start of the war in Ukraine. Russia arguably exerted strategic influence on German natural gas inventories prior to its invasion of Ukraine. For example, Gazprom Germania took over the largest domestic underground storage facility in Rehden in 2015 and let it run idle from mid-2021 onwards (see Figure A.1 in the Appendix).

In the aftermath of the Russian invasion of Ukraine, Germany experienced a dramatic surge of energy prices (see Figure 1). Below, we assess the structural drivers of fluctuations in the German natural gas market during this episode. Figure 4 depicts the historical decomposition of the endogenous variables based on the Bayes estimator of the SVAR models identified by conventional and narrative sign restrictions for 2020:1–2022:12.

In the top left panel, it is visible that net gas import growth fluctuated around zero with no obvious trend between early 2020 and early 2022, when Russia started to reduce natural gas flows to Germany. From April 2022 onward, net gas import growth remained below its deterministic trend for several months, mainly due to the contribution of adverse flow supply shocks. In September and October of 2022, the cumulative effect of flow supply shocks reversed, as the disruption of natural gas imports from Russia was offset by higher imports especially from Norway (see Figure A.3 in the online Appendix).

In the bottom left panel, we show that adverse flow supply shocks strongly contributed to real gas price growth during most months in 2020–2022. It is important to recall that NSR 3 only requires that flow supply shocks are the dominant driver of real gas price

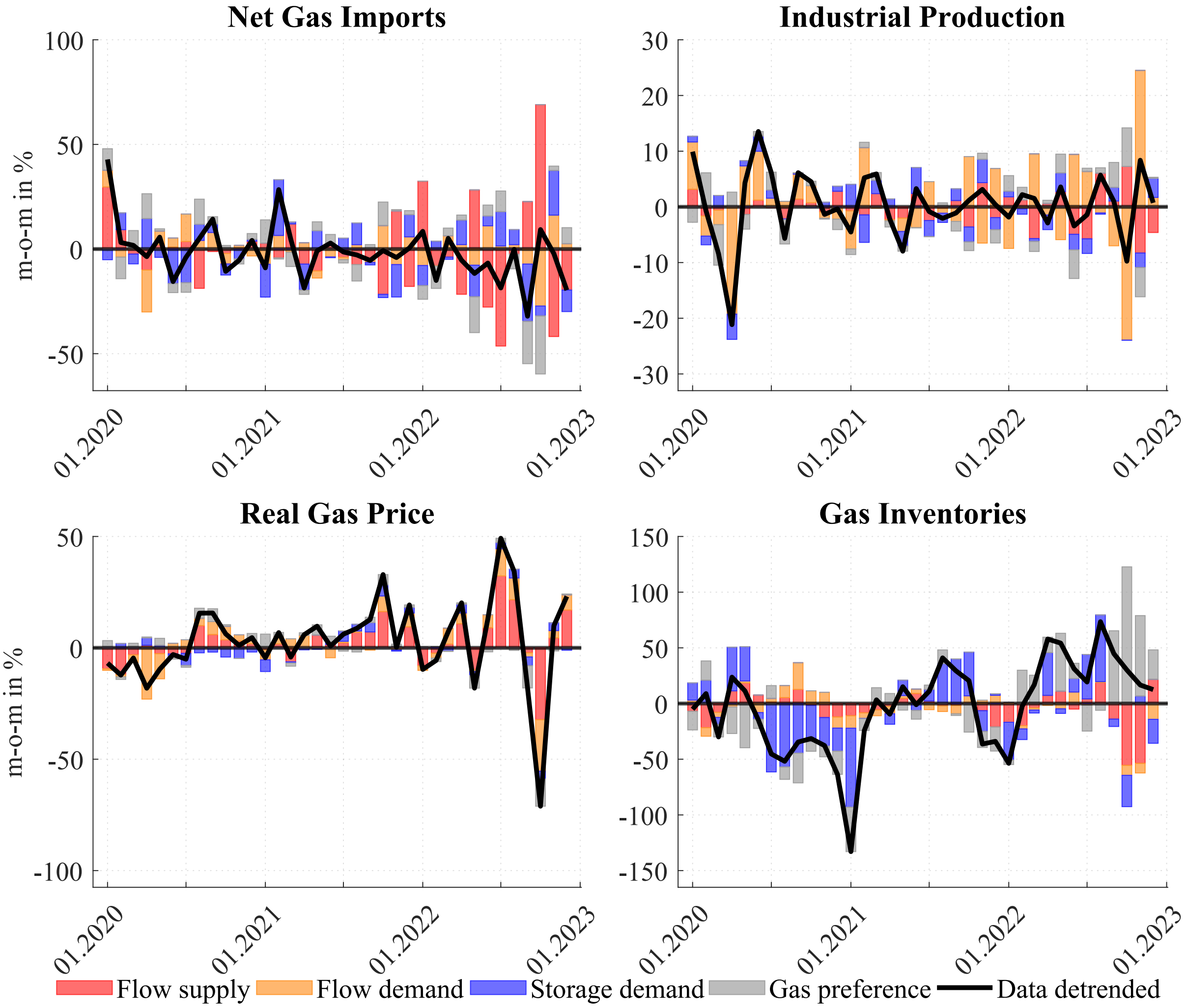

Figure 4: Historical decomposition for 2020–2022.

Notes: Historical decomposition based on the Bayes estimator of impulse response functions in Figure 2. Detrending refers to removing the deterministic components from the data.

growth in June and July 2022, whereas their signs and contributions are unrestricted for the rest of the time period in Figure 4. Nevertheless, flow supply shocks clearly dominate fluctuations in real natural gas prices throughout the entire episode. In July 2022, real gas price growth would have been 30% lower without the cumulative effect of adverse flow supply shocks.[19] In October 2022, when an unexpected increase in imports from other countries partially offset the loss of imports from Russia, real gas price growth would have been 25% higher without the cumulative effect of favorable flow supply shocks. Adolfsen

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[19] In September 2022, Nord Stream 1 and 2 were destroyed. Although both pipelines were inactive at the time, this signaled a permanent decoupling from Russian gas that could have raised gas prices. Since net gas imports weakly recovered in September 2022 mainly due to higher flows through Europipe I (see Figure figure:flows in the Appendix), and gas prices fell, we instead identify a (moderate) favorable flow supply shock during this episode, suggesting that the dynamics in gas import prices were not dominated by the adverse effects of the pipeline destruction.

et al. (2024) find for the euro area that both supply and demand shocks are important to explain natural gas prices during the energy crisis.[20] The dominance of supply shocks in our analysis might reflect the stronger dependency of the German economy on imports of Russian natural gas compared to the euro area. In June–August 2022, storage demand shocks also exerted non-trivial upward pressure on natural gas prices, while a substantial part of the relaxation in September and October of 2022 is attributed to adverse flow demand and gas-specific demand shocks. The latter effects are consistent with the political decision to ramp up natural gas inventories prior to the beginning of the winter and successful measures to conserve on natural gas use by German industry and households in fall 2022, respectively.

The successful natural gas-conserving efforts by German industry are reflected by the robust development of IP growth in the top-right panel. Following the substantial drop during the COVID-19 pandemic, which is largely attributed to adverse flow demand shocks, IP growth swiftly recovered again due to expansionary flow demand shocks.[21] From mid-2021 onwards, occasional adverse contributions of flow supply and storage demand shocks offset the expansionary effects of flow demand shocks and slowed down the recovery of German industry. During 2022, adverse flow supply, storage demand, and gas preference shocks initially exerted downward pressure on IP growth, consistent with the German parliament's decision to ramp up natural gas inventories before the upcoming winter. Until the end of our sample period, the combined effects of flow supply and storage demand shocks were roughly offset by the cumulative effects of opposite flow demand shocks, and IP growth remained close to its deterministic trend. The robustness of economic activity during this energy crisis reflects the successful attempts of German industry to reduce its dependence on natural gas in the face of geo-political disruptions following the Russian invasion of Ukraine, in particular in September and October of 2022, when favorable gas preference shocks contributed about 5% to stabilizing IP growth.[22]

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[20] It is important to note that Adolfsen et al. (2024) measure euro area natural gas prices using the TTF price in nominal terms, whereas we consider the CPI-deflated German import price of natural gas.

[21] Strong flow demand in the aftermath of the pandemic arguably reflects catch-up effects following the relaxation of lockdown measures and supply-chain frictions as well as fiscal support measures (see, e.g., Bachmann et al., 2021; Balleer et al., 2022).

[22] Relative to the 2018–2021 average, German industrial natural gas consumption was about 15% and

While the reduction of natural gas inventories in 2020 is mostly attributed to adverse storage demand shocks, the reduction after mid-2021 reflects a mix of adverse flow supply and gas-specific demand shocks. From March 2022 onwards, natural gas inventories strongly increased — initially due to favorable storage demand shocks and then due to gas preference shocks, reflecting the successful attempts of German industry and households to reduce their natural gas use for industrial and heating purposes.

The historical decomposition in Figure 4 corresponds to both a plausibility check for our SVAR model during an important episode, where we can draw on narrative evidence, and a quantitative analysis of the recent turmoil in the German natural gas market. Our results suggest that, while the economy was hit by severe gas supply and demand shocks leading to a dramatic price hike, the consequences for real economic activity were rather modest, in line with the theoretically founded predictions in Bachmann et al. (2022).

5 Structural Scenario Analysis

The benefit of our structural VAR framework is that we can conduct scenario analyses in the spirit of Antolín-Díaz, Petrella, and Rubio-Ramírez (2021) by assuming hypothetical realizations for one or more of the structural shocks and investigating the resulting time paths of the endogenous variables. Subsequently, we consider the counterfactual scenario of an embargo on natural gas imports from Russia starting in April 2022 and the importance of a milder winter 2022/2023 for German natural gas inventories.[23]

5.1 Russian natural gas embargo

In response to the Russian invasion of Ukraine on February 24, 2022, the US government and the European Council, jointly with other governing bodies, adopted a number of restrictive measures to weaken Russia's economic base. As part of the "Fifth package of sanctions in response to Russia's invasion of Ukraine" the European Council banned

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18% lower in 2022 and 2023, respectively (see Figure A.4 in the online Appendix).

[23] Given that pointwise posterior medians generally imply similar impulse response functions as the Bayes estimator in Figure 2, the results in this section are based only on pointwise inference for visibility.

imports of coal and other fossil fuels from Russia on April 8, 2022. A ban on oil imports from Russia was discussed and implemented in the form of a price cap at $60 per barrel for crude oil and petroleum oils by the EU and the G7 member states on December 5, 2022. Although a ban on natural gas imports from Russia was discussed by German economists (e.g. Bachmann et al., 2022; Krebs, 2022), politicians, and the media, it was not implemented before Russia itself throttled natural gas exports to Germany in June and July and eventually suspended them altogether in September 2022.

Suppose instead that Germany had taken initiative and banned natural gas imports from Russia as early as April 2022. A complete halt without immediate substitution would have reduced German natural gas imports by 49%. Assuming that natural gas exports also decreased by 49% and domestic production developed as observed in the data, German net imports would have dropped by 46.2%. In the SVAR model, this corresponds to a *one-off six unit adverse flow supply shock*, which might have a permanent effect on the level of net natural gas imports, in April 2022.[24] Subsequently, we assume parameter estimates for the full sample and realized monthly average temperatures for 2022:4–2023:3. Thus, we can compare conditional forecasts of the endogenous variables both to their unconditional forecasts and to the realized data (up to December 2022).

Figure 5 plots the "Scenario" forecast (dotted lines) with and the "Baseline" forecast without the six unit adverse flow supply shock in April 2022 (solid lines) against the realized data (dashed lines) for the endogenous variables. For ease of comparison with the data, monthly growth rates of net gas imports are converted to levels in 1,000 terra joules (TJ) starting from the realized value in March 2022. Monthly growth rates of German industrial production and the real natural gas price are cumulated over time, while the effect on natural gas inventories is expressed as a fraction of German capacity.[25]

The adverse flow supply shock leads to a substantial drop in net natural gas imports in April and persistently lower levels afterwards (top left panel). The parallel movement

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[24] Month-on-month reductions in German natural gas supply of 20% or more occur on at least ten occasions during our sample period (see Figure A.2 in the online Appendix).

[25] Recall that gas inventories enter the model as monthly changes. To convert this into % of capacity, we compute the conditional forecast of inventory changes in TJ and cumulate over the forecast horizon. We then convert TJ to MWh (1 TJ = 277.778 MWh) and divide by the total capacity of 230 million MWh of the 47 gas storage facilities located in Germany (see ENBW, 2024).

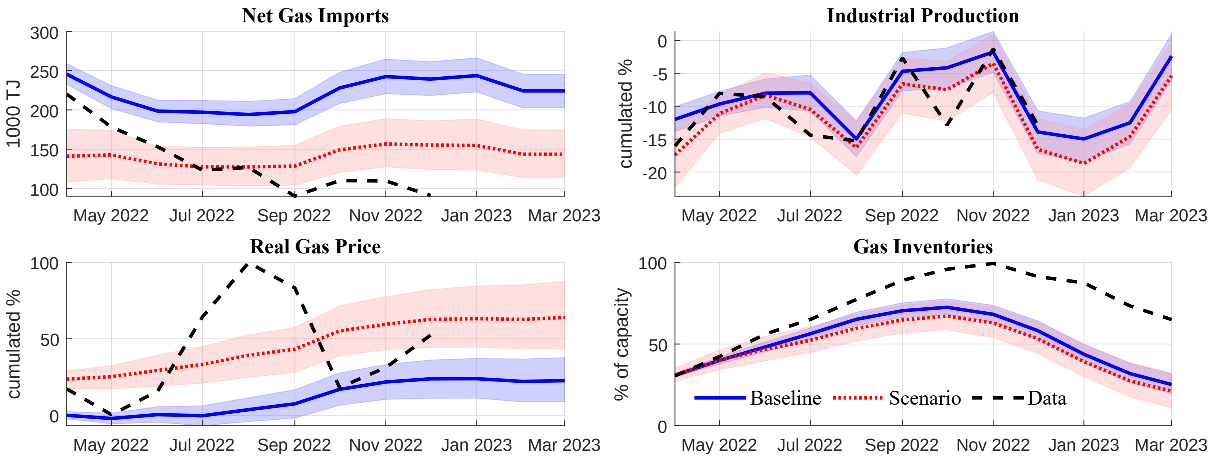

Figure 5: Conditional forecasts for a natural gas embargo against Russia starting in April 2022
Note: Pointwise median conditional forecasts with 68% posterior credibility sets based on the SVAR identified by conventional and narrative sign restrictions.

of net natural gas imports in the baseline and the scenario implies a level shift on impact, yet similar growth rates over the remaining forecast horizon. The actual data, in turn, reflect the gradual reduction of imports from Russia during April through July, the partial reactivation of Nord Stream 1 and Transgas in August, and the definite suspension of Russian exports to Germany in September 2022, leading to a substantial deviation from the baseline forecast, albeit comparable levels of net natural gas imports as in the embargo scenario from July onwards.

Consistently, the scenario forecast implies substantial upward pressure on the real natural gas price relative to the baseline forecast in April 2022 (bottom left panel). In the data, a similar price hike is visible after the Russian invasion of Ukraine, which first reverses and then accelerates about three months after the start of the embargo scenario. According to the historical decomposition in Figure 4, this reflects the unfortunate combination of adverse flow supply shocks due to the Russian cuts of gas exports to Germany and storage demand shocks due to the political decision to ramp up German natural gas inventories before the start of the heating season.

In the embargo scenario, German IP (top right panel) would have dropped by about 5% relative to the baseline in April 2022. Throughout the forecast horizon, the paths of IP in the embargo scenario and the baseline forecast are similar, and the actual data is inside the 68% posterior credibility set of the scenario forecast except for October. This reflects our earlier finding that supply effects on economic activity were short-lived and moderate in comparison, as illustrated by the impulse response functions in Figure 2.

Following a suspension of imports from Russia in April 2022, natural gas inventories would likely have fallen short of their level in the baseline forecast by up to 6% of capacity in October, although the 68% posterior credibility sets overlap for the entire forecast horizon (bottom right panel). Both the embargo scenario and the baseline forecast track actual changes in natural gas inventories in April through June 2022. Starting in July, however, inventories increase much faster in the data due to the concerted attempt to fill storage facilities before the start of the winter (see Figure A.1), leading to strong deviations from both the embargo scenario and the baseline forecast. Accordingly, our SVAR-based scenario analysis yields a plausible characterization of the consequences of a hypothetical embargo on natural gas imports from Russia that would have benefited policy makers at the start of the energy crisis in 2022 and complements the theoretical work by Bachmann et al. (2022), for example. Quantitatively, our results are in line with those of Bachmann et al. (2022). For German IP, our model predicts a reduction relative to the no-embargo baseline by 5% on impact in April 2022, which stays broadly constant throughout the forecast horizon. When replacing German IP with GDP (see Section 6.1), we find that the cumulated IRFs of real GDP growth display similar dynamics, which are three to four time smaller than those for IP. Accordingly, Figure A.9 in the online Appendix illustrates that an embargo against Russia might have caused a reduction of real GDP by 1.25 to 1.67% — in the middle of the ballpark from 0.3 to 3% reported by Bachmann et al. (2022).[26]

5.2 The role of temperature

In the media as well as the reports of German economic and policy institutions (see, e.g., Joint Economic Forecast, 2022; Deutsche Bundesbank, 2022), the risk of a natural gas shortage in Europe and Germany, in particular, was repeatedly linked to the severity of

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[26] In Section 6.4, we show that our baseline results are robust to ending the sample period in December 2021, before the war in Ukraine. As a result, a scenario analysis would have been possible in real time with very similar results. This holds for both IP and GDP growth as measures of real economic activity.

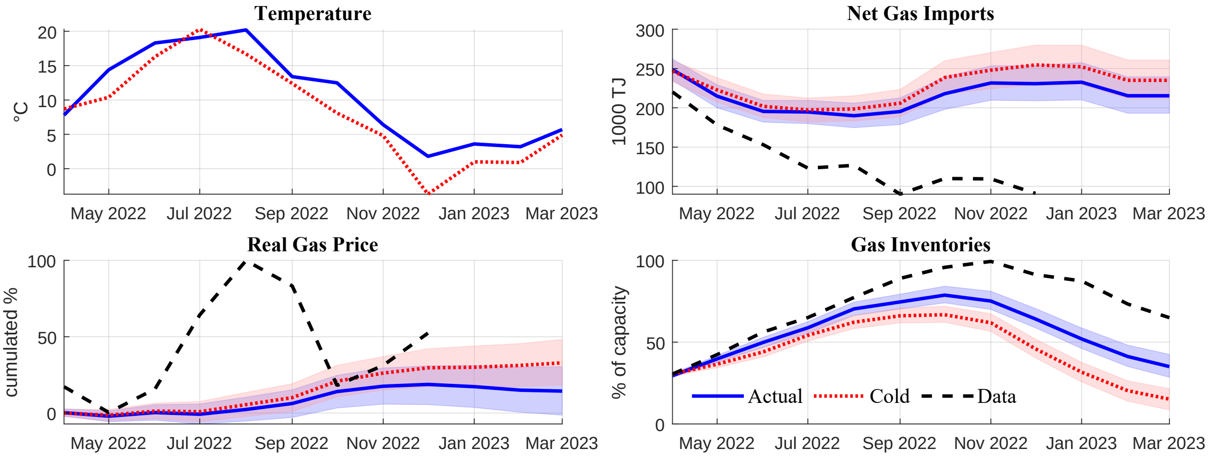

Figure 6: Conditional forecasts for actual monthly temperatures in April 2022–March 2023 and the coldest year in the sample period, April 2010–March 2011

Note: Pointwise median conditional forecasts with 68% posterior credibility sets based on the SVAR identified by conventional and narrative sign restrictions.

the winter of 2022/2023. The SVAR model in (1) accounts for seasonal variation in the form of monthly dummies as well as contemporaneous and lagged observations of average monthly temperatures. We can therefore investigate whether different temperature scenarios indeed imply substantially different time paths of the endogenous variables.

Figure 6 plots the actual monthly temperatures for April 2022 through March 2023 against the coldest consecutive twelve-month sequence during our sample period (i.e. April 2010 through March 2011) and pointwise median forecasts and 68% posterior credible sets of natural gas market variables based on the model with narrative sign restrictions conditional on these temperature paths. To facilitate the interpretation, the conditional forecasts for net natural gas imports and the real gas price are again cumulated to levels in 1,000 TJ and percent, respectively, while that for gas inventories is converted to a fraction of German capacity (see Footnote 25).

From the first panel of Figure 6, temperatures were consistently higher in April 2022 through March 2023 than in April 2010 through March 2011, except for July. The second panel shows that higher average monthly temperatures implied a cumulated reduction of net natural gas imports by about 20,000 TJ during the same period. Higher temperatures also yield up to 18.5 percentage points lower real natural gas prices towards the end of the forecast horizon. Most importantly, we find that natural gas inventories would have been about 20% (of full capacity) lower in a cold winter, such as the winter 2010/2011.

Given that German natural gas inventories were down to 25% of full capacity in March 2022 (see Figure A.1), differences in average monthly temperature indeed seem to account for a non-trivial part of the variation in inventories. This finding lends strong ex-post empirical support to the political decision in April 2022 to ramp up German natural gas inventories before the start of the winter.

While the temperature-dependent conditional forecasts of net natural gas imports and real natural gas price are quantitatively, albeit not statistically different, the last panel of Figure 6 indicates that natural gas inventories were also statistically higher between April 2022 and March 2023 relative to a cold year during our sample period.

For the sake of readability, we do not compound the temperature scenario with the Russian natural gas embargo. Given that the SVAR model in (1) is linear in the structural shocks and in temperature, the compound effects of an embargo on Russia in a cold year correspond to the sum of the effects in Figures 5 and 6. Accordingly, the effects on net gas imports and the real gas price are dominated by the embargo scenario, while the effect on natural gas inventories depends on the temperature scenario. It is important to note that the pointwise median forecast of inventories falls to 10% of storage capacity in the compound scenario, while the posterior credible set approaches the zero line.

5.3 Disruption of Europipe I and II

As of 2023, Germany has been relying on natural gas imports from Belgium, the Netherlands, and Norway as well as its slowly increasing capacity of LNG import terminals. Europipe I and II, which transport gas from Norway to Germany, accounted for 19.8% and 21.7%, respectively, of natural gas imports on average between July and December 2022 (see Figure figure:flows). Along the German coast, however, Europipe I and II run in juxtaposition with each other in shallow water, making them highly susceptible to targeted disruptions.[27]

For the same export and production assumptions as in the Russian embargo scenario,

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[27] In May 2023, UK Defence Secretary Ben Wallace and Norwegian Defence Minister Bjørn Arild Gram signed a security partnership to increase cooperation on undersea capabilities and counter threats to undersea infrastructure (www.gov.uk), signaling increased political awareness of related risks.

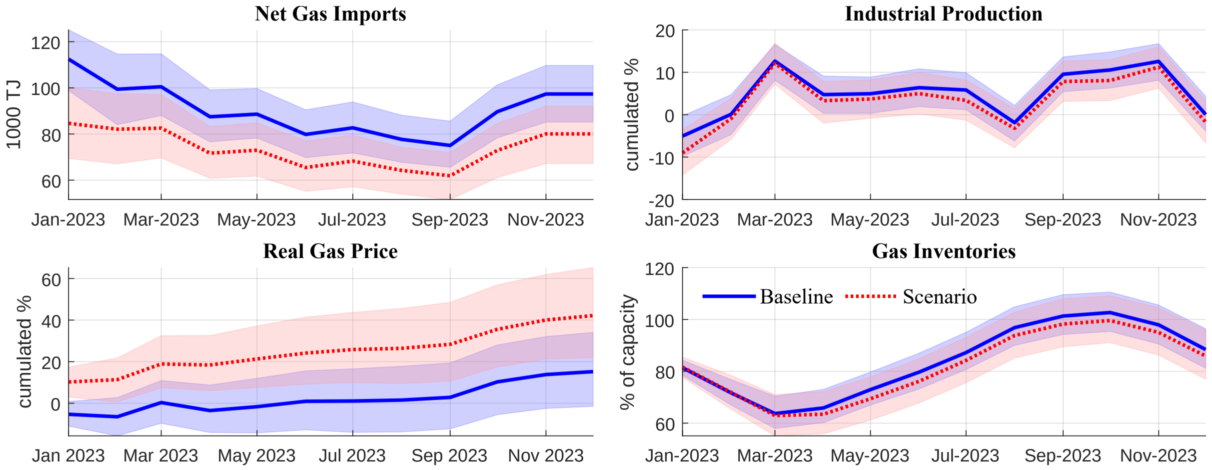

Figure 7: Conditional forecasts for a disruption of Europipe I and II in January 2023

Note: Pointwise median conditional forecasts with 68% posterior credibility sets based on the SVAR identified by conventional and narrative sign restrictions

a disruption of natural gas imports from Norway corresponds to a drop in German net gas imports by 17.6% (Europipe I), 19.3% (Europipe 2), or 36.9% (both). Accordingly, we analyze a third structural scenario, in which we subject the SVAR model to a *one-off four unit adverse flow supply shock*. While we assume that this shock occurs in January 2023 and trace out the effects over the subsequent calendar year, any other starting point would yield quantitatively similar effects.

Figure 7 plots pointwise median conditional forecasts with 68% posterior credible sets of German net gas imports, industrial production, gas import price, and gas inventories using the same transformations as in the previous scenarios without (solid lines) and with (dashed lines) the shock. The top left panel illustrates the immediate drop in the level of net gas imports due to the hypothetical disruption of natural gas flows from Norway, leading to an immediate hike in the real natural gas price by about 15 percentage points relative to the baseline, which persists over the remaining forecast horizon. Nevertheless, this adverse flow supply shock exerts only a moderate effect on IP on impact, which largely disappears before the end of the forecast horizon. After three months, natural gas inventories are 2.5% (of total capacity) lower than in the baseline, given that adverse flow supply shocks tend to induce a moderate drawdown of inventories during our sample period (see Figure 2), which largely persists for the duration of the forecast horizon.

In contrast to the temperature scenario in Figure 6, the conditional forecasts for

January 2023 are statistically different for net gas imports and the real gas price, whereas the posterior credibility sets for natural gas inventories overlap throughout the forecast horizon. In particular, the latter finding of a moderate effect on inventories must be taken with a grain of salt. Despite a number of non-trivial gas supply disruptions during our sample period, Germany was generally able to draw on alternative sources of gas imports or reduce its own exports. In this scenario, in which Belgium, the Netherlands, and direct LNG imports are the only remaining outside options, it is unlikely that savings and substitution of natural gas will be equally smooth as in the past.

6 Further Analysis and Robustness Checks

Below, we conduct a number of additional analyses and robustness checks that relate our findings more directly to the existing literature and the current policy debate. For the sake of brevity, we discuss the results in this section only verbally, while deferring the corresponding figures to the online Appendix.[28]

6.1 Monthly GDP growth

Our baseline specification uses German IP growth as the measure of economic activity, which is potentially sensitive to fluctuations in energy prices. The political debate and prior work investigating the effects of a natural gas embargo against Russia (see, e.g., Bachmann et al., 2022; German Council of Economic Experts, 2022; Krebs, 2022) were instead concerned with the associated losses in terms of real GDP (growth). To evaluate the repercussions of shocks on the natural gas market on German GDP, we substitute IP growth with an estimate of monthly real GDP growth for Germany, while keeping the other model specifications and identifying assumptions unchanged.[29]

We find that the IRFs of the natural gas market variables are broadly unaffected by

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[28] Here, we focus on the discussion of impulse response functions and historical decompositions, while the scenario analysis for each of the alternative specifications are available from the authors on request.

[29] The monthly GDP estimate is derived from the multivariate Chow-Lin interpolation of Mönch and Uhlig (2005). A similar model is used by the Deutsche Bundesbank to assess the current state of the German economy (Deutsche Bundesbank, 2023).

different measures of real economic activity. Moreover, the cumulated IRFs of monthly real GDP growth (see Figure A.6 in the Appendix) are qualitatively very similar, albeit quantitatively about three to four times smaller than those for German IP growth in Figure 2.

The HDs from this model also reveal qualitatively similar patterns compared with our baseline model (see Figure A.7). For example, the cumulative effect of flow supply shocks and storage demand shocks on monthly real GDP growth was positive during 2000–2019 and negative during 2021–2022. Moreover, flow supply shocks and storage demand shocks contributed negatively to real GDP growth in mid-2022, while gas preference shocks contributed positively in September and October 2022, reflecting the successful gas conservation efforts of German industry and households (see Figure A.8). Hence, the effects of a Russian natural gas embargo in April 2022 on German GDP growth would likely have been contained, at least relative to our baseline forecast.

6.2 Energy-intensive industrial production

While our baseline measure of economic activity excludes the German construction sector, it does not distinguish between energy-intensive and non-energy-intensive sectors. To assess how shocks in the German natural gas market affect these two components of industrial activity, we augment our baseline SVAR model and replace IP excl. construction with energy-intensive and non-energy-intensive IP in month-on-month growth rates.[30]

We find that the impact of adverse flow supply, storage demand, and gas preference shocks exert markedly negative effects on energy-intensive IP, whereas the reaction of non-energy-intensive IP is smaller in the short run. About two years after the shock, the differences in impulse responses become less pronounced, suggesting that reduced output from energy-intensive sectors, which primarily serve as intermediate goods producers, eventually spill over to non-energy-intensive sectors (see Figure A.10 in the Appendix).

The HDs from this specification reveal that flow supply shocks account for a much larger fraction of the cumulative change in energy-intensive than non-energy-intensive

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[30] Note that separate IP indices for these two categories are only available beginning in January 2005, which shortens thus our estimation period.

IP or IP excl. construction (see Figure A.11) — the cumulative effect of flow supply shocks on energy-intensive IP before and after the COVID-19 pandemic is about twice as large relative to non-energy-intensive IP. Conversely, demand-side disturbances account for similar fractions of the cumulative change of both IP series. Note also that, in this specification, the vast majority of the increase in German natural gas inventories during 2021–2022 is attributed to storage demand shocks, thus downplaying the role of gas preference shocks in Figure 3. During 2020–2022, energy-intensive IP growth was relatively more volatile, and a larger share of this volatility is attributed to flow supply, storage demand, and gas preference shocks, respectively (see Figure A.12). Overall, these results suggest that, in the case of Germany, IP excl. construction represents a sensible measure of economic activity. Using more granular data on industrial activity may, however, help to understand how energy price shocks propagate through the economy.

6.3 Effect on German consumer prices

While this article focuses on the effects of supply and demand shocks in the German natural gas market on real economic activity, policy makers and economists might be equally concerned about the consequences for consumer prices. For this reason, we replicate our baseline analysis, where we replace IP growth with German HICP inflation, while keeping the rest of our baseline specification unchanged.[31]

The IRFs of the natural gas market variables closely resemble those from our baseline model (see Figure A.15). Following a flow supply disruption, HICP steadily increases and peaks at about 0.6 percentage points after one year. The response to a favorable flow demand shock peaks at 1.9 percentage points after about 14 months, whereas the storage demand shock induces only a small positive response of consumer prices.

The cumulative change in the HICP is predominantly driven by expansionary flow demand shocks — both before and after the COVID-19 pandemic (see Figure A.13). This is also evident during the last three years of our sample period, where the role of

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[31] Without a measure of real economic activity, we cannot meaningfully distinguish flow demand shocks from gas preference shocks, both of which induce positive comovement of net gas imports, real gas prices, and HICP as well as negative comovement with natural gas inventories. For this reason, we abstain from identifying a gas preference shock and preserve a residual shock in Figures A.13–A.14 in the Appendix.

flow supply and storage demand shocks for the recent surge in consumer prices is limited, at least relative to that of flow demand shocks (see Figure A.14).

6.4 Before the Russian invasion of Ukraine

The recent turmoil in the German natural gas market was preceded by an extended period of comparatively low and stable gas prices. To prevent that a change in the volatility of supply and demand shocks confounds the coefficient estimates based on our full sample, the SVAR model in (1) allows for a temporary shift in the residual covariance matrix, as in Lenza and Primiceri (2022). Nevertheless, we re-estimate our baseline specification for a sub-sample ending in December 2021, dropping the war episode and potential anticipation effects in January and February of 2022.[32]

We find that the IRFs and HDs are both qualitatively and quantitatively very similar to our baseline results (see Figures A.16–A.18 in the Appendix), suggesting that the latter are not distorted by extreme observations at the end of the sample period. If anything, excluding the last year of our sample period implies somewhat more pronounced responses of real natural gas prices to flow supply and flow demand shocks. As a result, there is no evidence of a structural break that invalidates our analysis based on a constant-parameter VAR, while allowing for higher volatility in the natural gas market after the Russian invasion of Ukraine.

6.5 Heating and cooling degree days

To account for seasonal variation in the demand for natural gas, our baseline specification in (1) comprises monthly dummies as well as contemporaneous and lagged observations of average monthly temperatures. However, one might argue that heating degree days (HDDs) and cooling degree days (CDDs) are a more accurate measure of natural gas demand for domestic gas-heating units and marginal energy production for cooling units.

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[32] When the estimation period ends in December 2021, NSRs 2 and 3 as well as the scaling factor of the residual covariance matrix are ineffective, while we retain the conventional sign restrictions in Table 1. The share of retained draws after conventional sign restrictions satisfying the remaining NSRs 1 and 4 is very similar to that for all four NSRs in Table 2.

Replacing average monthly temperatures with contemporaneous and lagged observations of the sum of HDD and CDD yields virtually identical results. Both the IRFs in Figure A.19 and the HDs in Figures A.20 and A.21 closely resemble those from our baseline specification. This does not come as a surprise, given that the unconditional correlation between average monthly temperatures and HDDs is $-.99$, while CDDs play a negligible role for Germany during our sample period.

7 Conclusion

We propose a structural VAR model to disentangle the role of supply and demand shocks in the German natural gas market and conduct structural scenario analyses. The model plausibly explains the fluctuations of the endogenous variables based on economically interpretable shocks. Our model suggests that (i) supply and demand shocks have large and persistent price effects but rather moderate output effects, (ii) the natural gas price hike of 2022 was largely driven by the Russian suspension of exports to Germany and the simultaneous attempt to ramp up gas inventories before the start of the winter, (iii) an immediate embargo on natural gas imports from Russia in April 2022 would have merely precipitated a price increase of similar magnitude, and (iv) a milder-than-average winter was crucial for avoiding natural gas shortages during the winter of 2022/2023.

We thus provide empirical evidence that substantiates the political debate in similar situations. However, given the backward-looking nature of our econometric approach, it should be clear that structural changes in the German gas market *after* the end of the sample period, such as the current expansion of LNG capacities or shifts in behavioral regularities and seasonal patterns, are not incorporated. Monitoring the role of these changes is left for future research.

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Appendix

A.1 Additional Figures

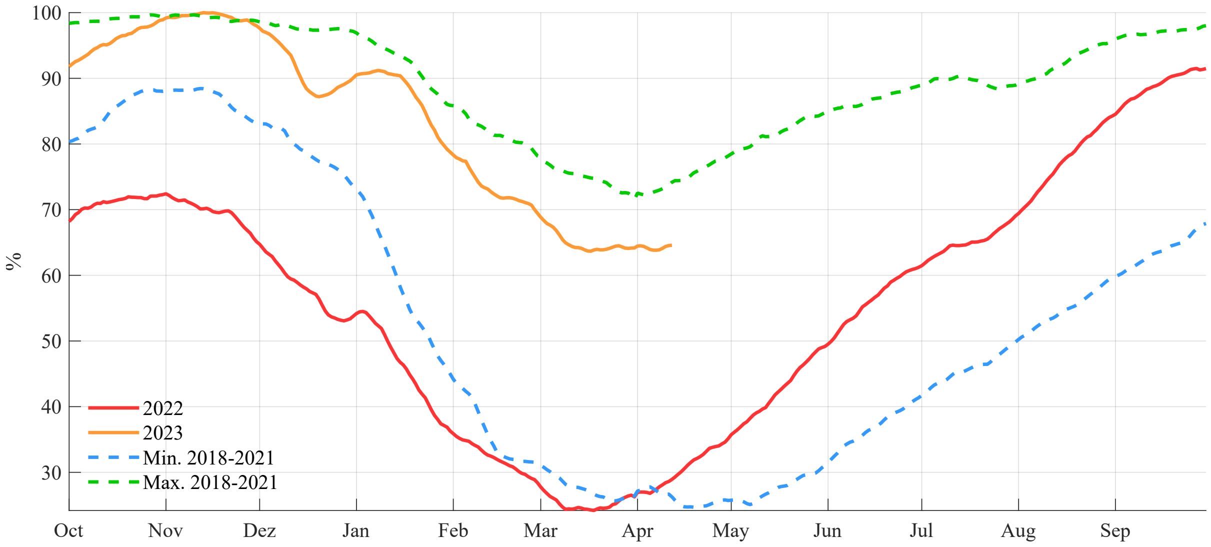

Figure A.1: Use of German natural gas storage capacity for October 2021 through April 2023

Source: Bundesnetzagentur

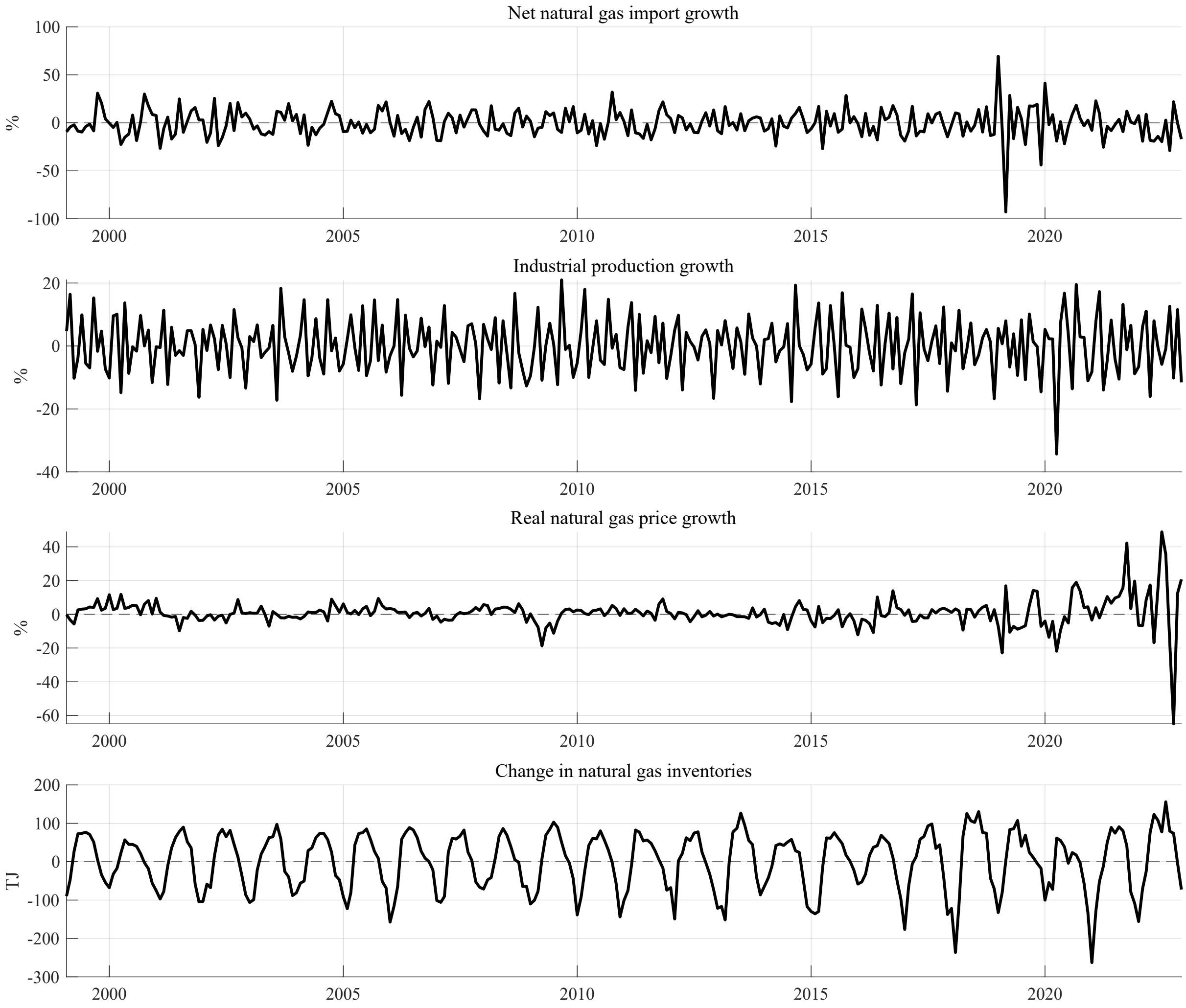

Figure A.2: Data on German natural gas supply growth, industrial production, real gas price growth, and gas inventories for 1999:2–2022:12

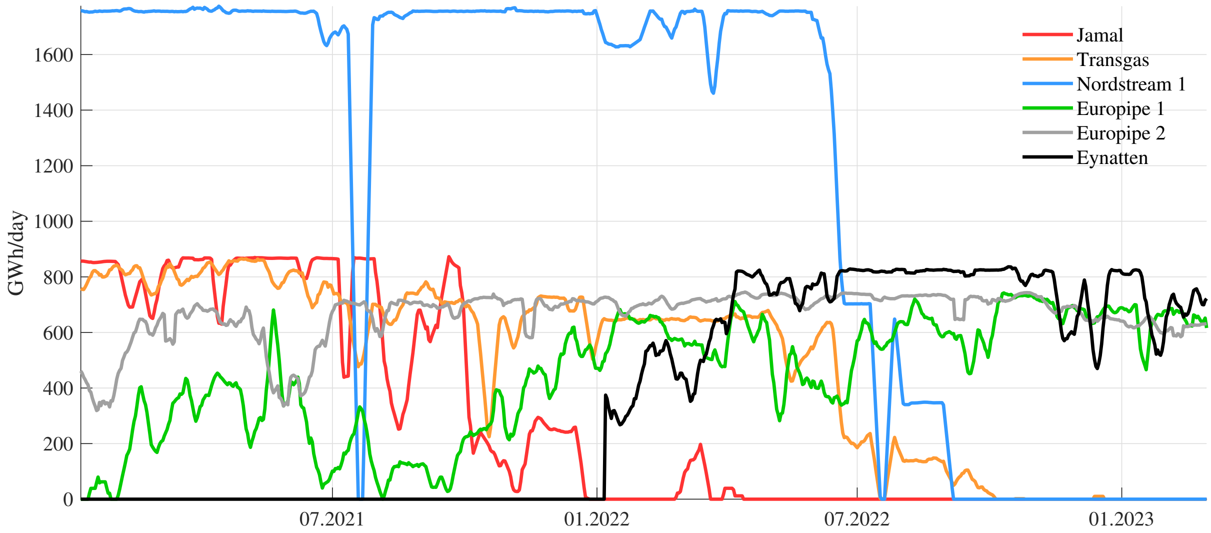

Figure A.3: Daily German natural gas import flows for selected pipelines

Sources: European Network of Transmission System Operators for Gas (ENTSO-G), German Statistical Office

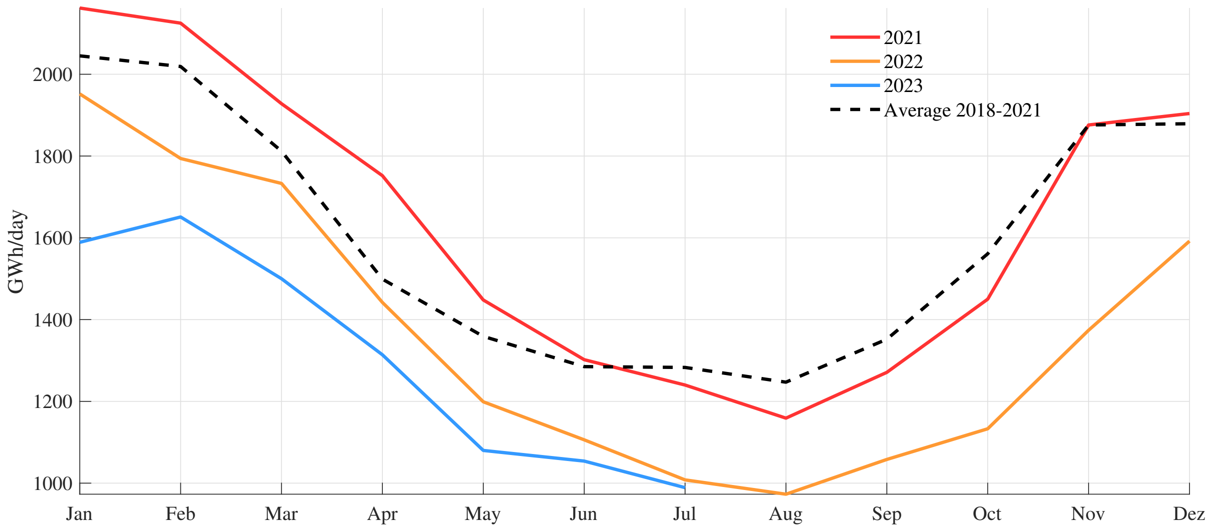

Figure A.4: Natural gas use by German industry in 2022 and 2023 relative to 2018–2021 average

Source: Bundesnetzagentur

A.2 Posterior Distribution of the Hyperparameters

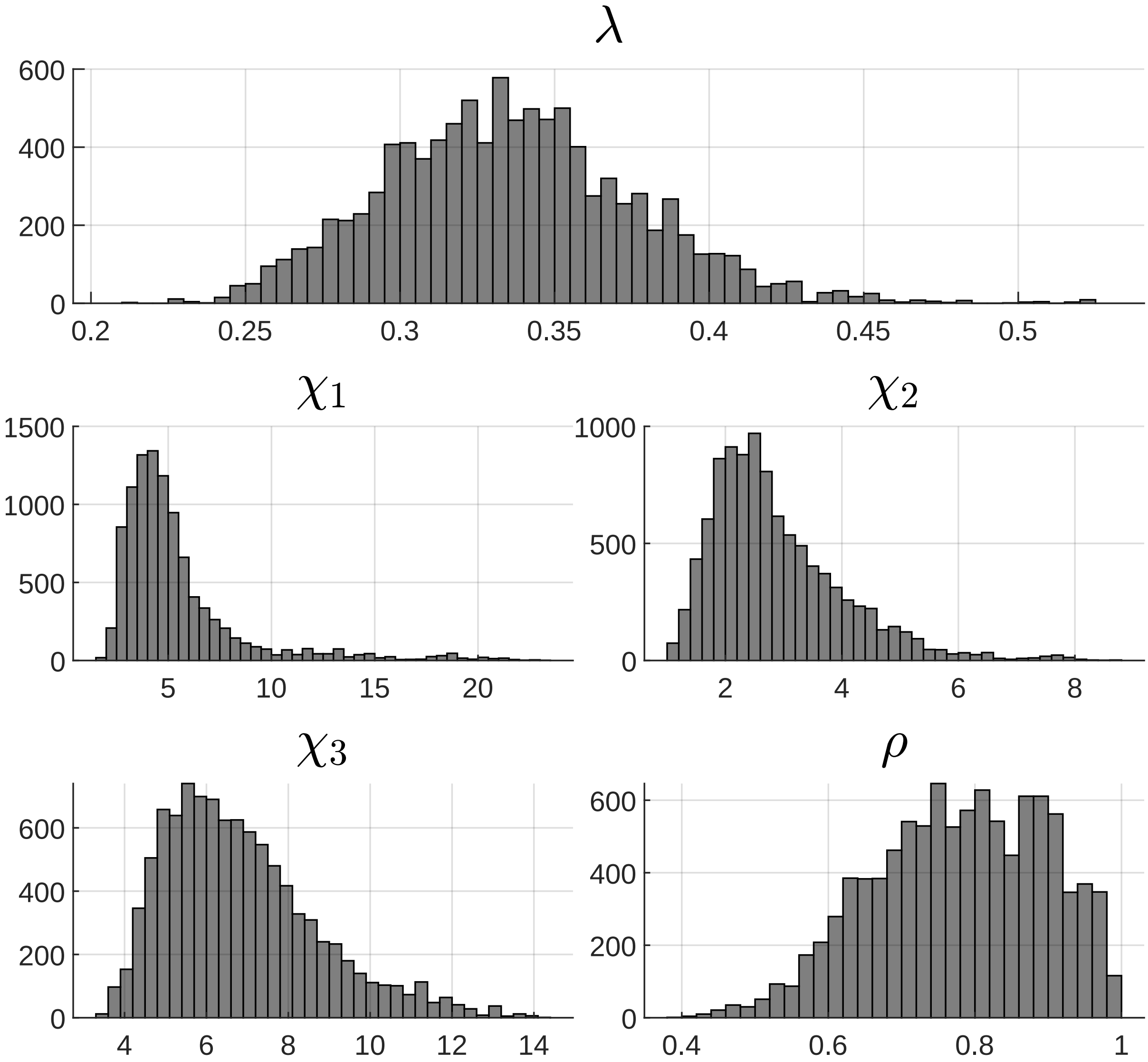

Figure A.5: Posterior distribution of the hyperparameters
[1ex] **Note:** Distributions are obtained using the algorithm of Giannone et al. (2015) with the modification of Lenza and Primiceri (2022).

A.3 Further Analysis and Robustness Checks

A.3.1 Monthly GDP growth

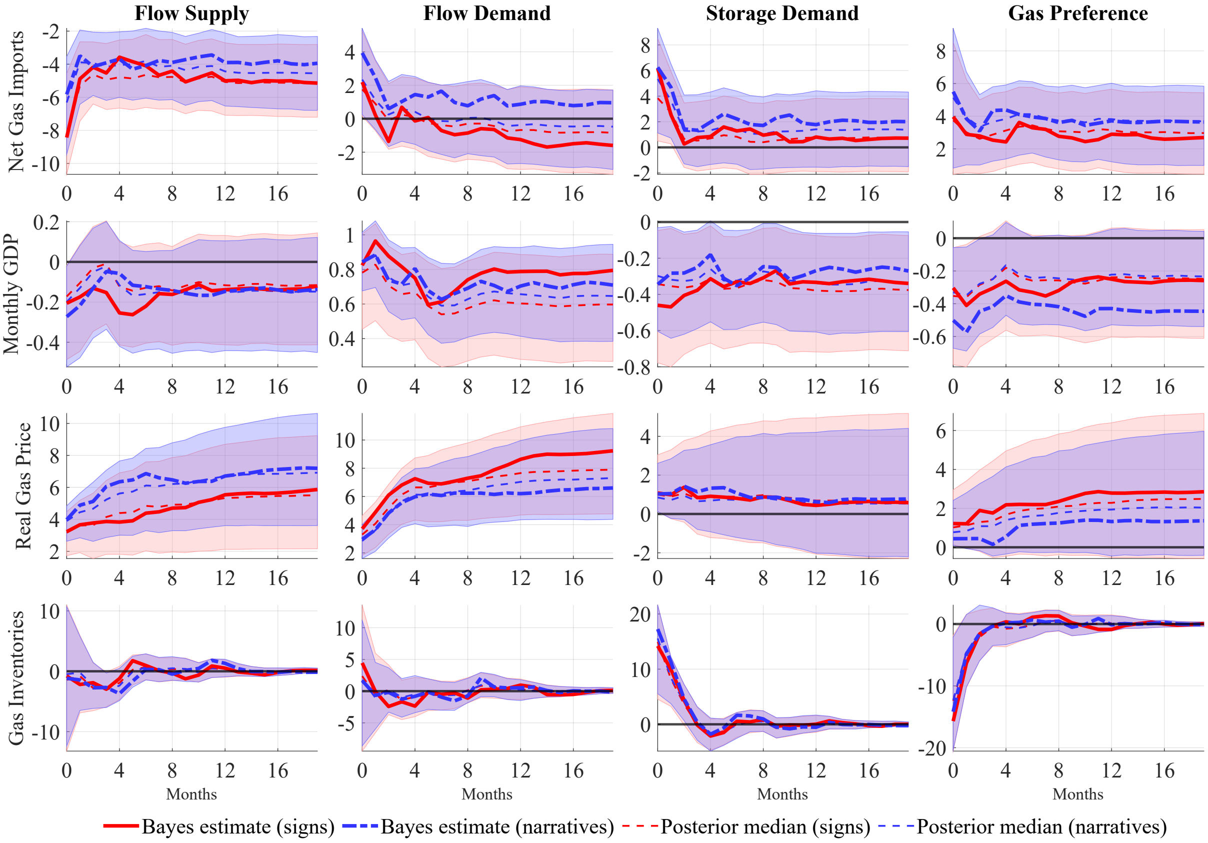

Figure A.6: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions.

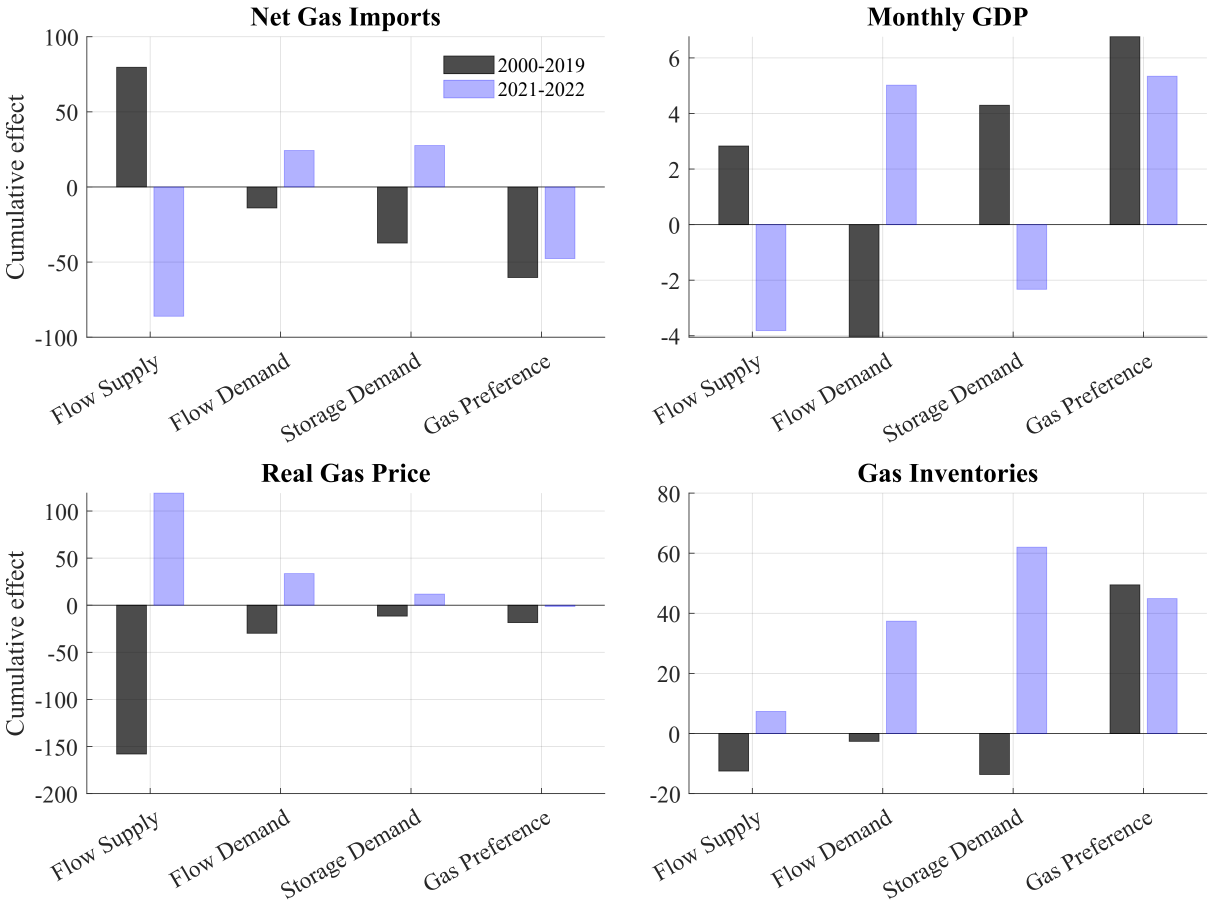

Figure A.7: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and 2021–2022, respectively. Decomposition is based on Bayes estimator of impulse response functions in Figure A.6.

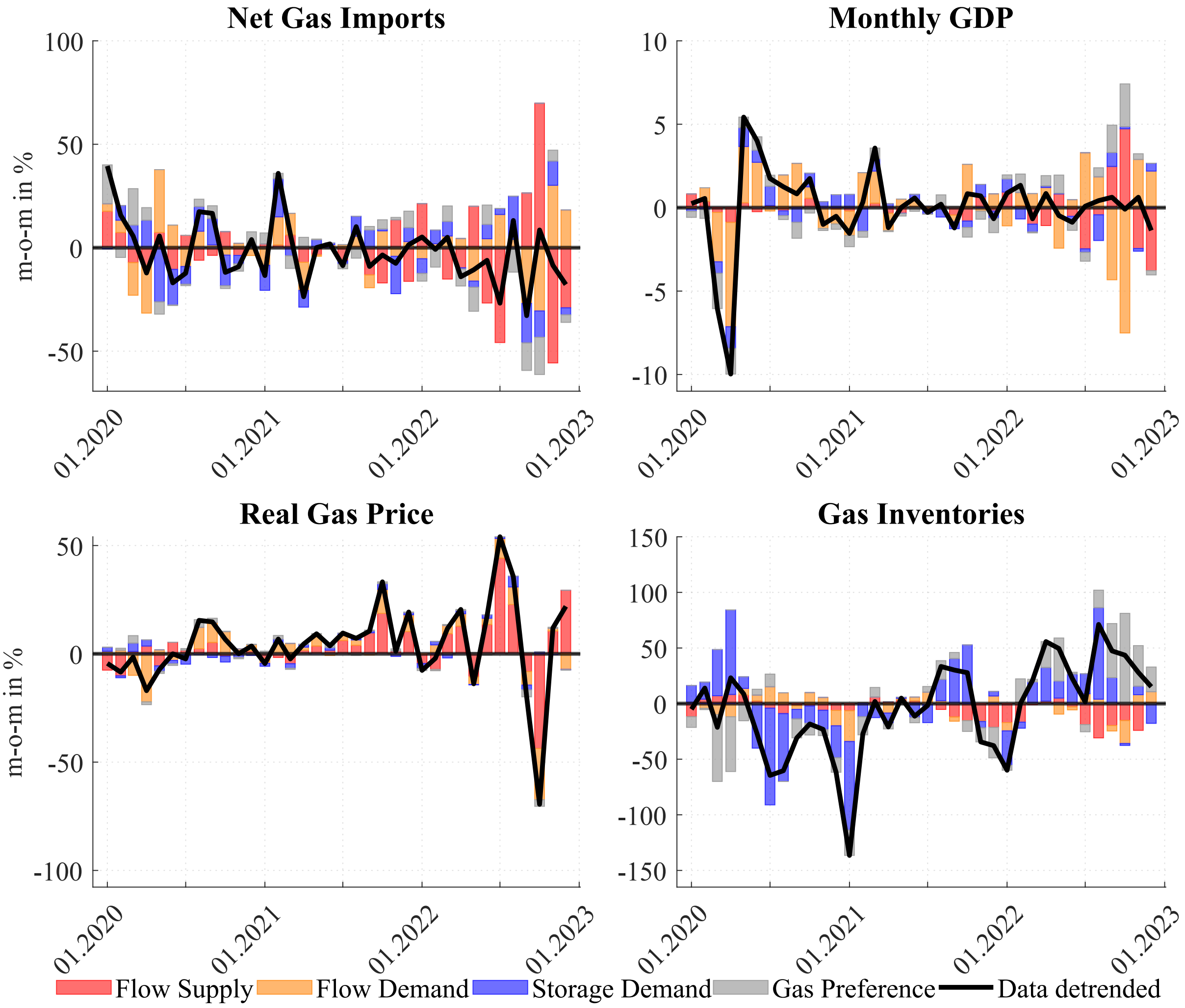

Figure A.8: Historical decomposition for 2020–2022.

Note: Historical decomposition based on the Bayes estimator of impulse response functions in Figure A.6.

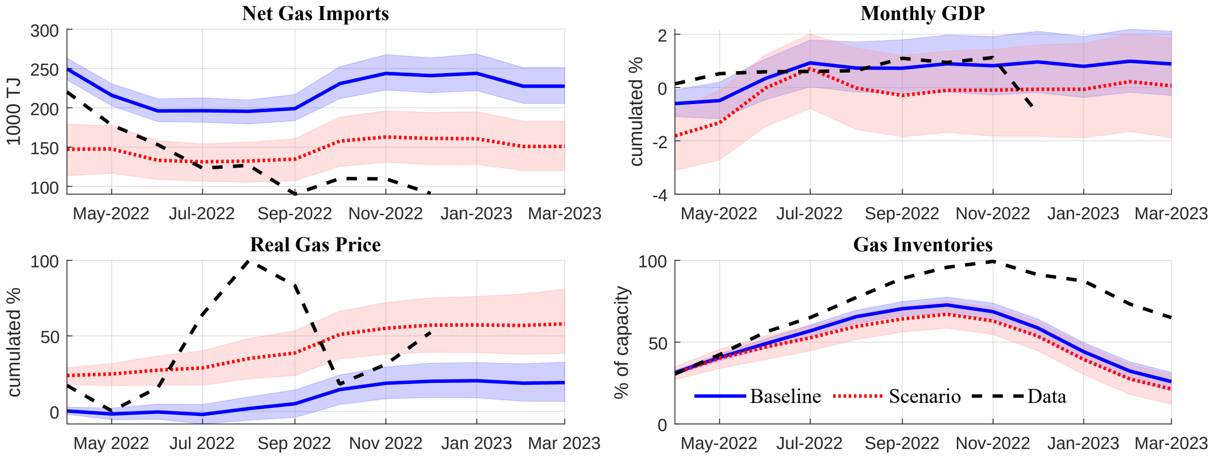

Figure A.9: Conditional forecasts for a natural gas embargo against Russia starting in April 2022

Note: Pointwise median conditional forecasts with 68% posterior credibility sets based on the SVAR identified by conventional and narrative sign restrictions.

A.3.2 Energy-intensive industrial production

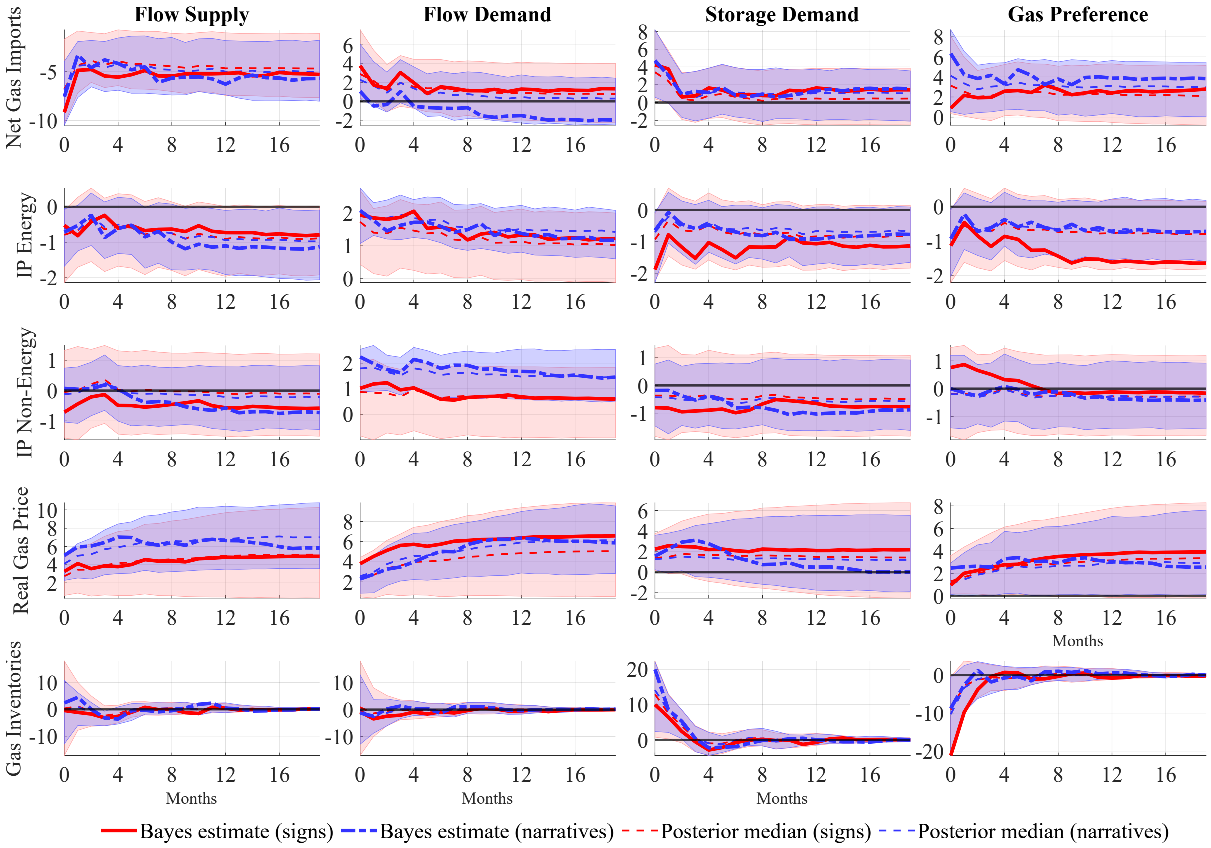

Figure A.10: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions.

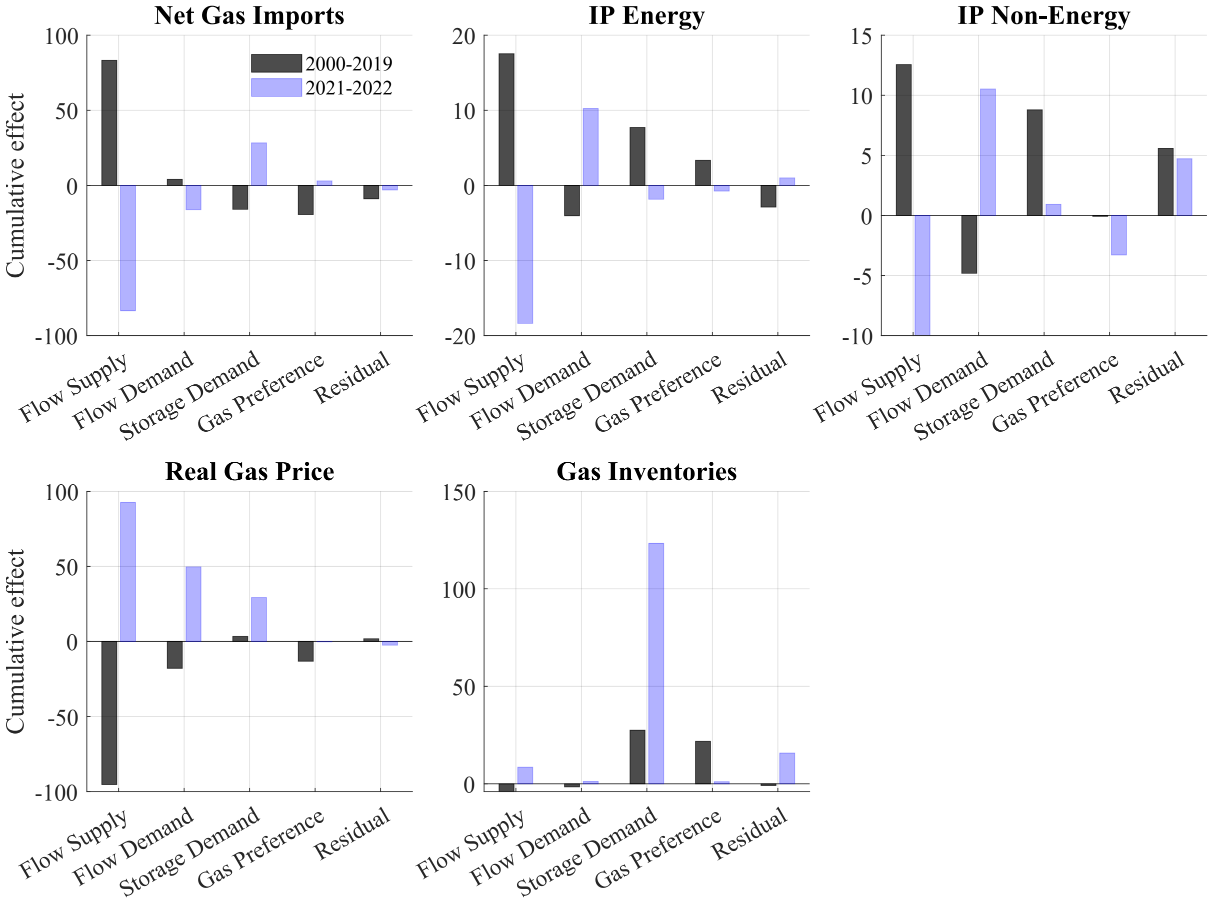

Figure A.11: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and 2021–2022, respectively. Decomposition is based on Bayes estimator of impulse response functions in Figure A.10.

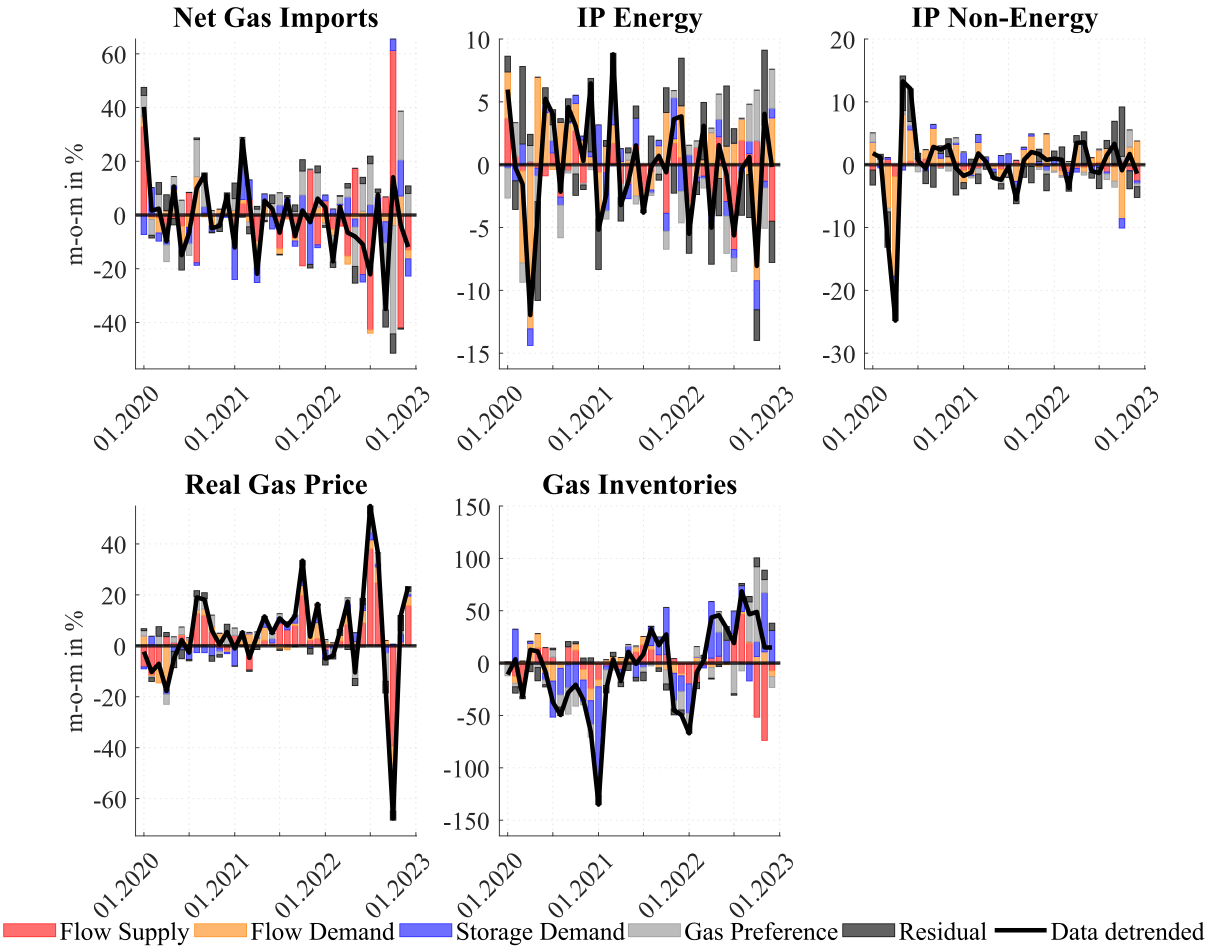

Figure A.12: Historical decomposition for 2020–2022.

Note: Historical decomposition based on the Bayes estimator of impulse response functions in Figure A.10.

A.3.3 Effects on German consumer prices

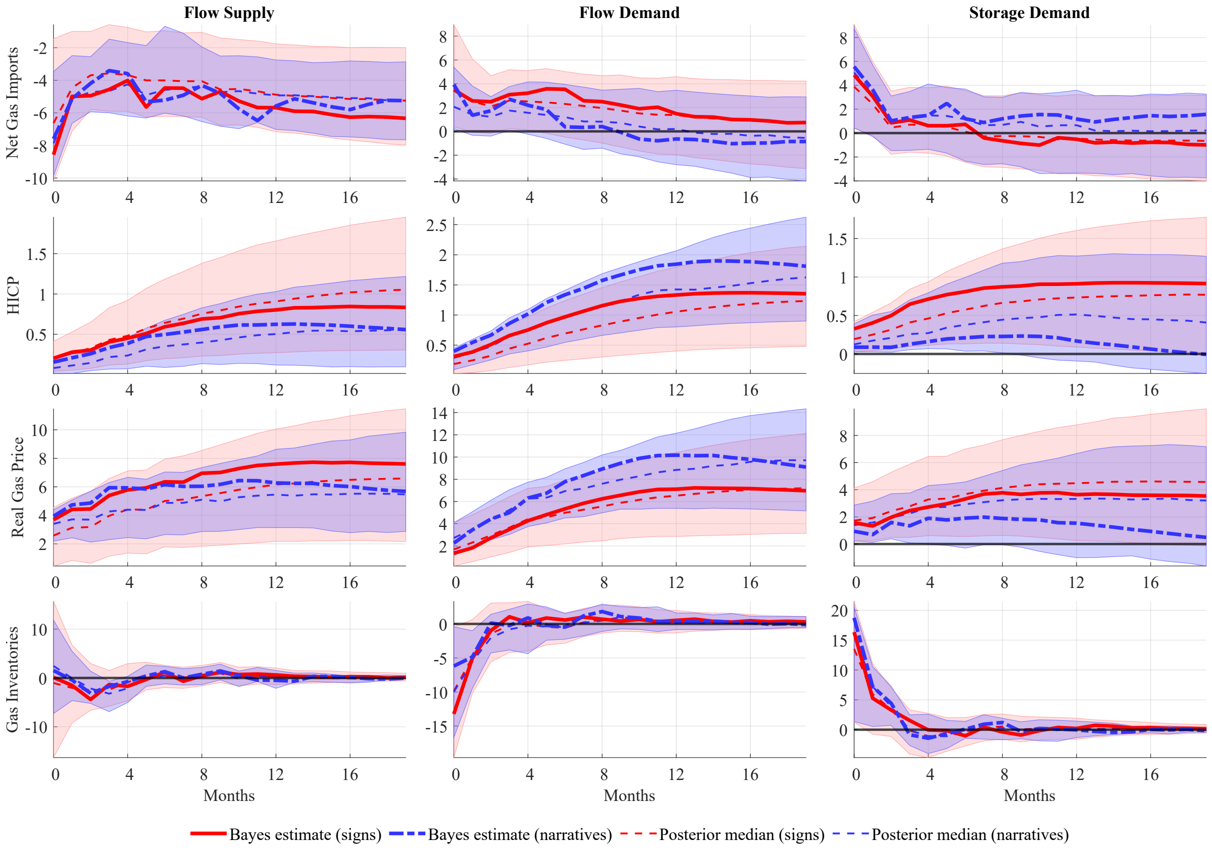

Figure A.13: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions.

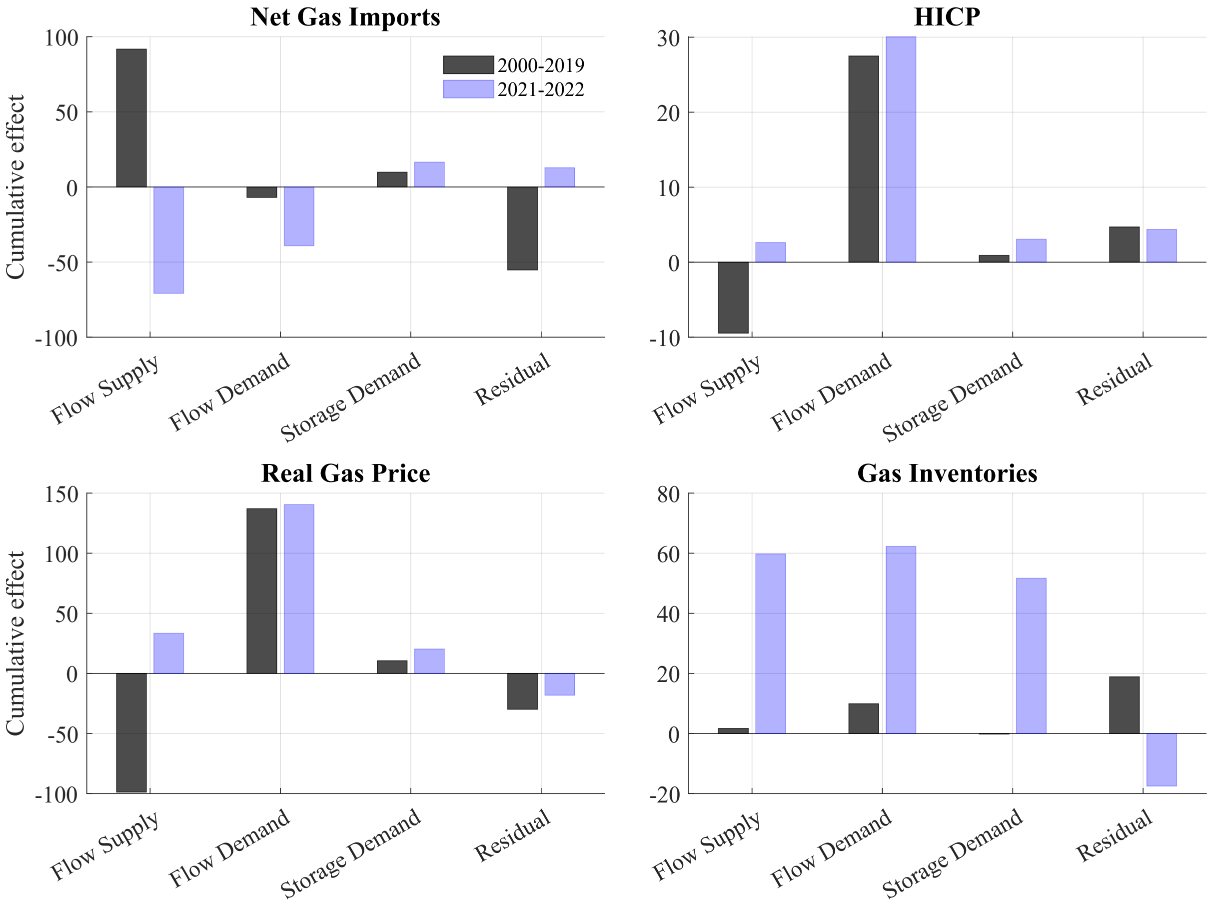

Figure A.14: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and 2021–2022, respectively. Decomposition is based on Bayes estimator of impulse response functions in Figure A.13.

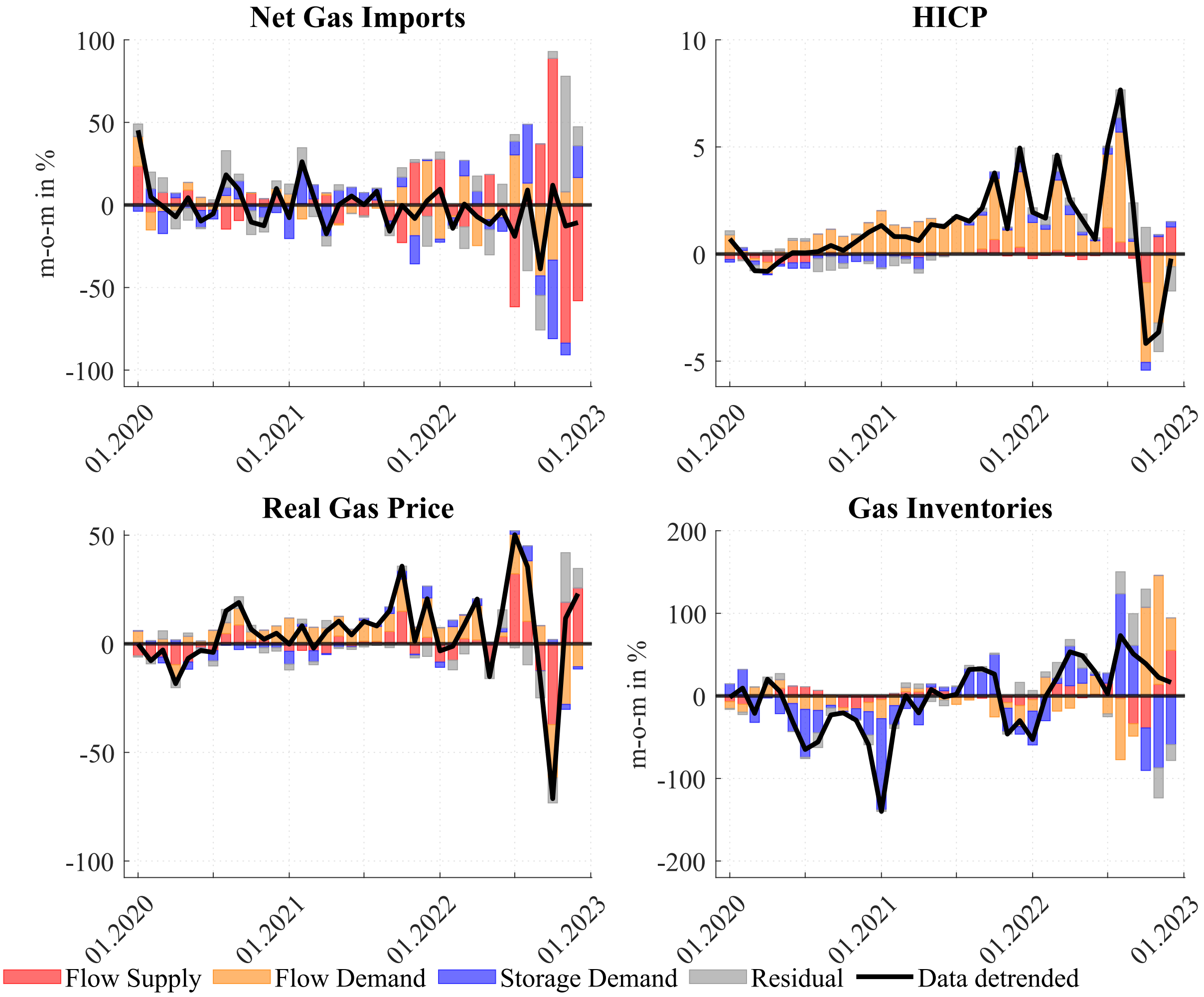

Figure A.15: Historical decomposition for 2020–2022.

Note: Historical decomposition based on the Bayes estimator of impulse response functions in Figure A.13.

A.3.4 Before the Russian invasion of Ukraine

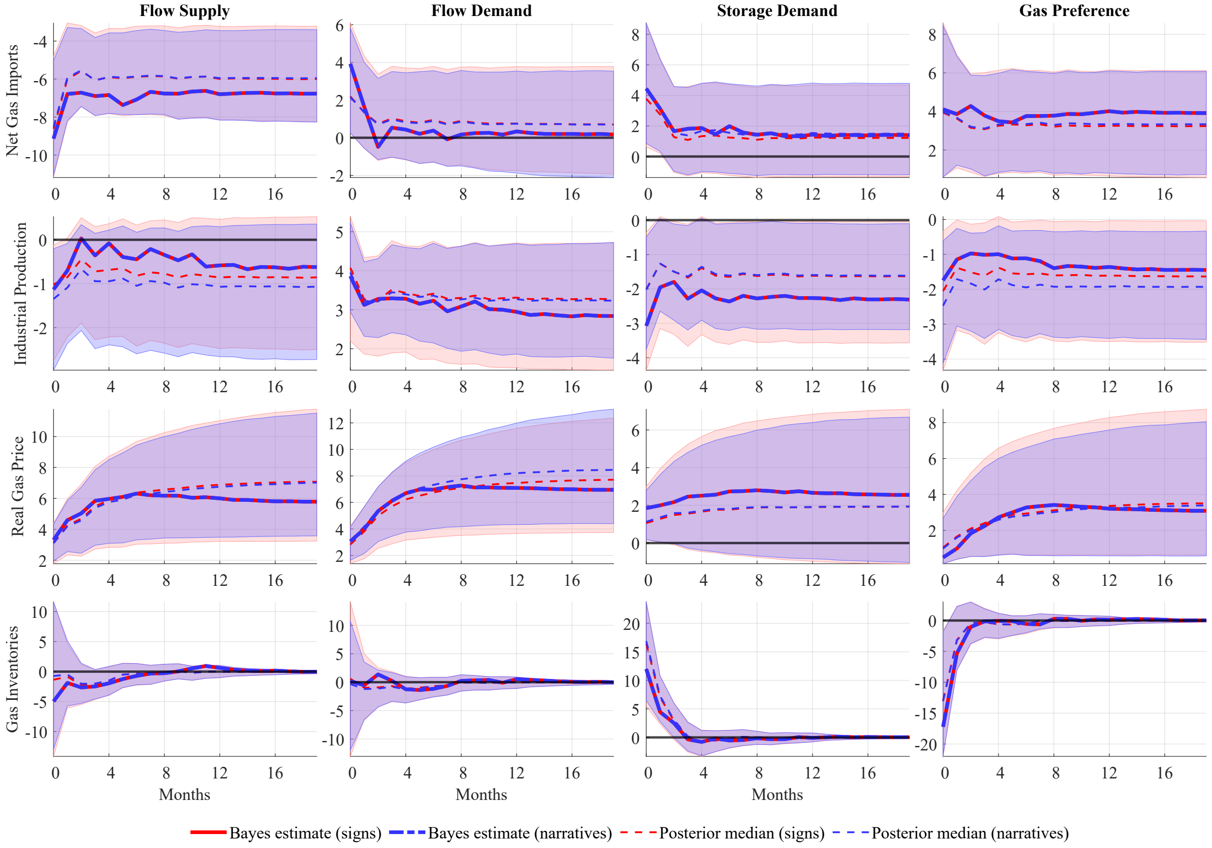

Figure A.16: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions.

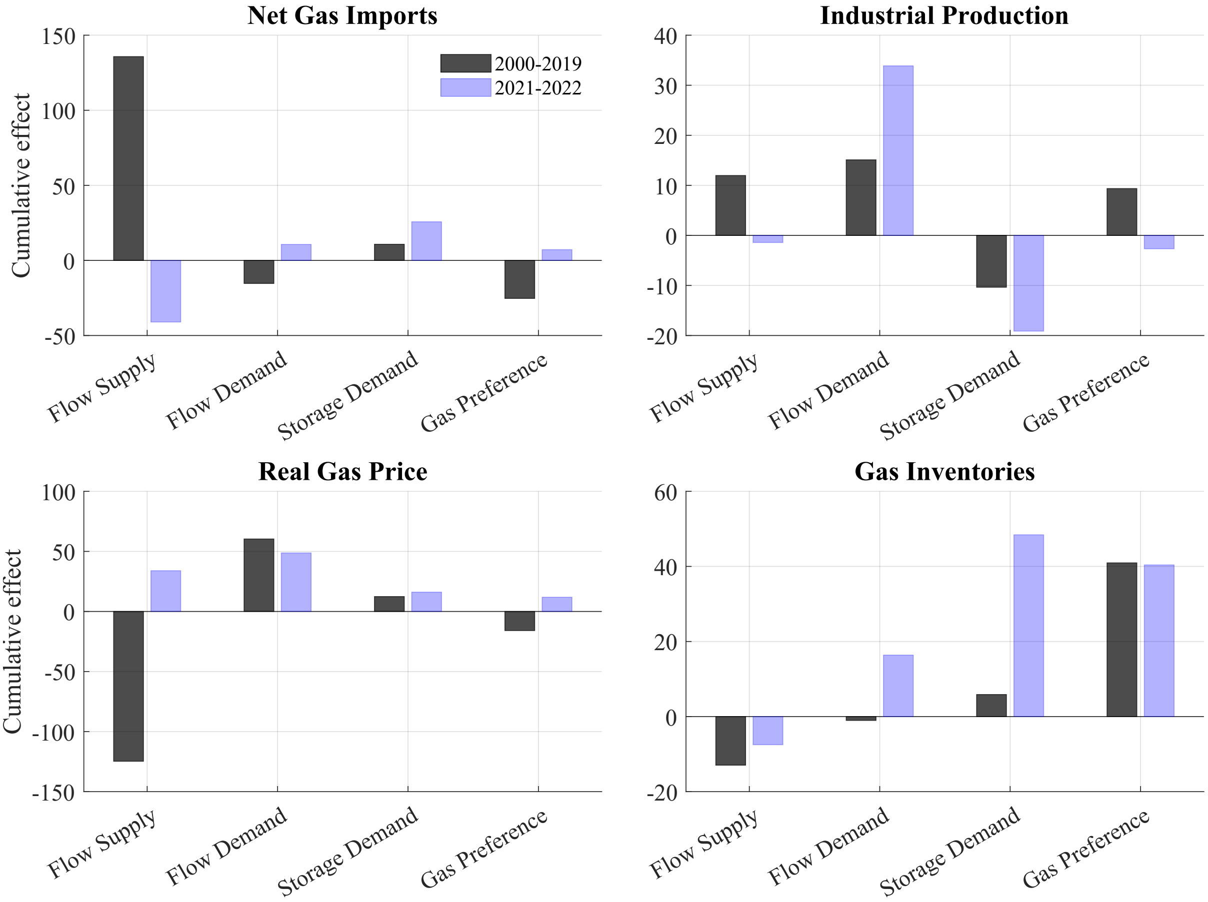

Figure A.17: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and in 2021,s respectively. Decomposition is based on Bayes estimator of impulse response functions in Figure A.16.

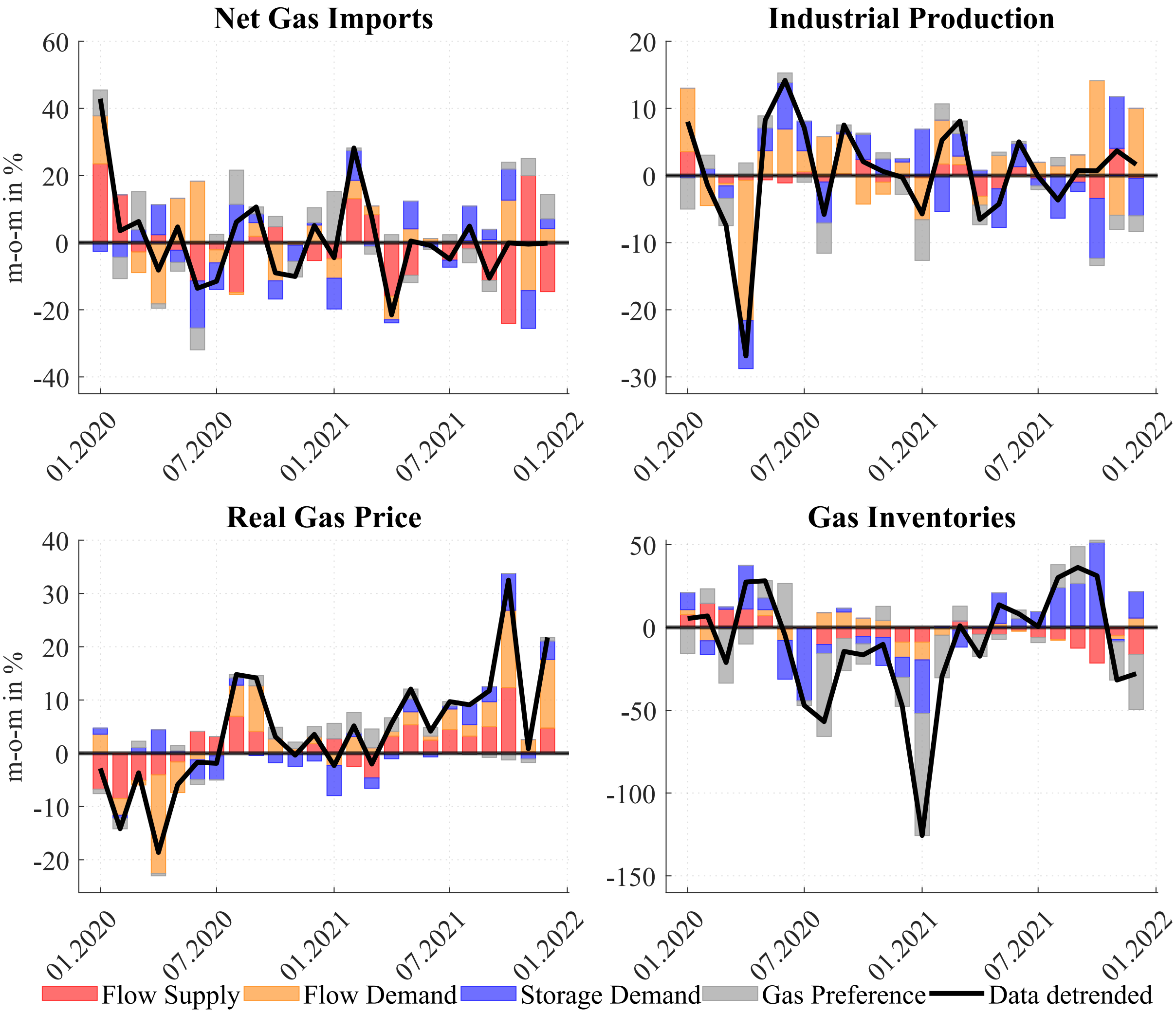

Figure A.18: Historical decomposition for 2019–2021.

Note: Historical decomposition based on the Bayes estimator of impulse response functions in Figure A.16.

A.3.5 Heating and cooling degree days

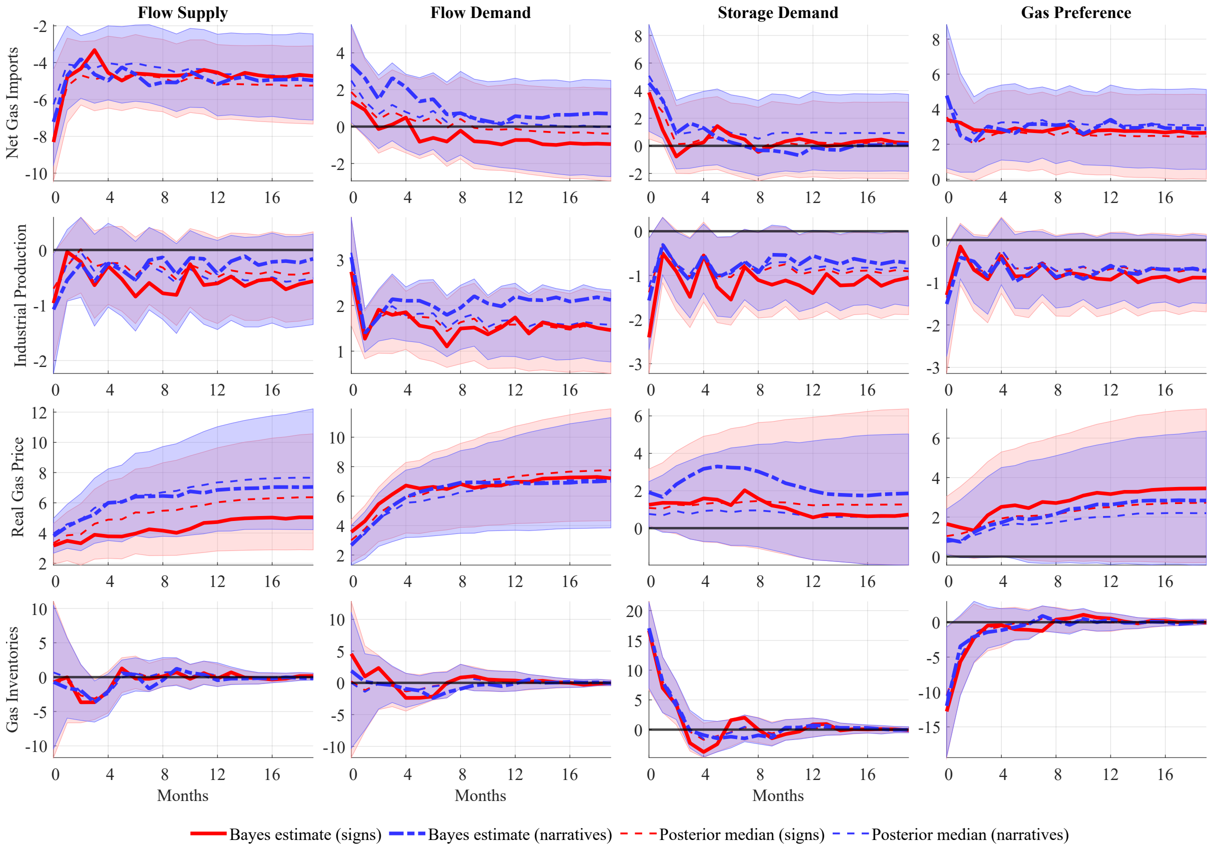

Figure A.19: Impulse response functions to structural gas supply and demand shocks

Note: Red shaded areas are 68% simultaneous posterior density intervals based on the SVAR identified by conventional sign restrictions. Blue shaded areas are the corresponding objects based on the SVAR identified by conventional and narrative sign restrictions. .

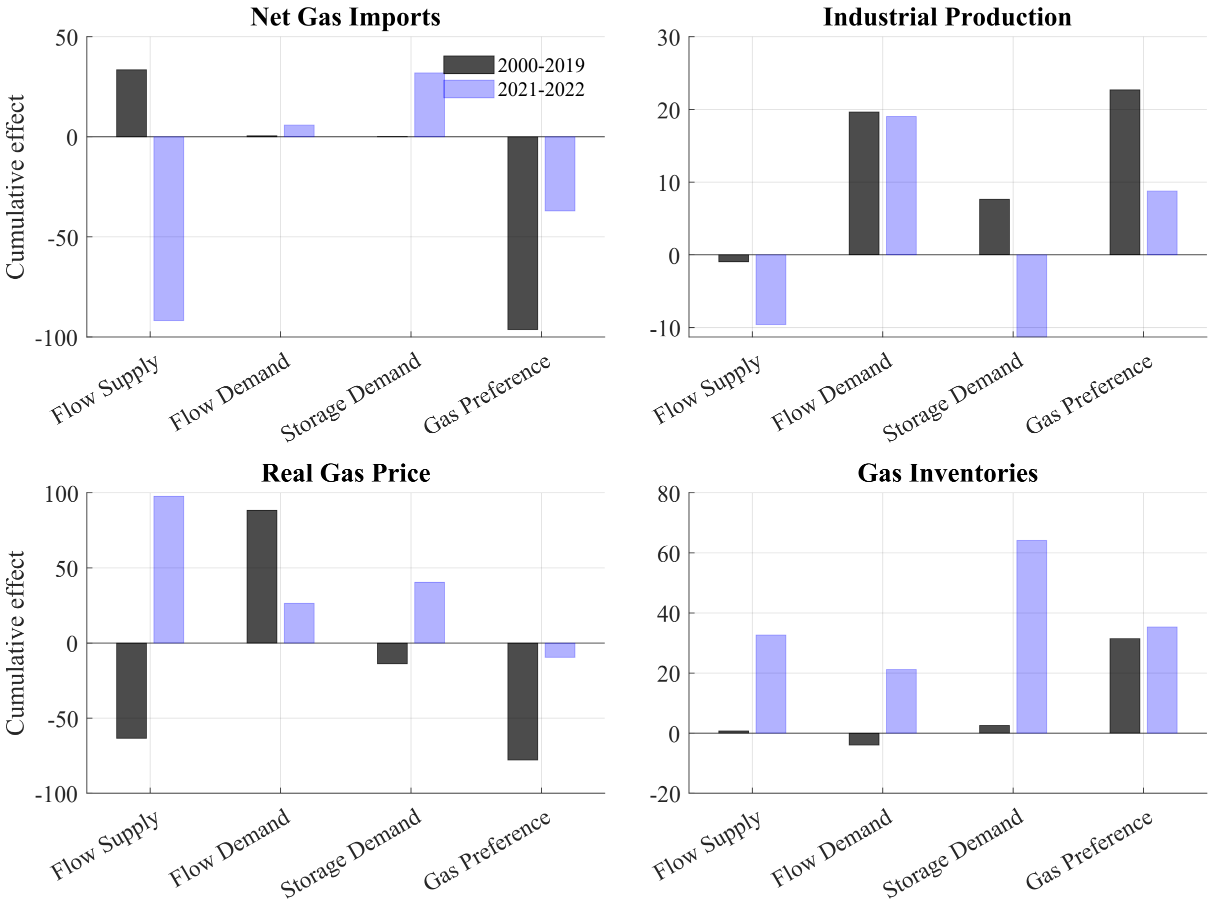

Figure A.20: Contributions of structural shocks to the historical decomposition of the endogenous variables before and after the COVID-19 pandemic

Note: Each bar gives the cumulative contribution of the shock on the horizontal axis to the deviations of the endogenous variable from its deterministic component during 2000–2019 and 2021–2022, respectively.Decomposition is based on Bayes estimator of impulse response functions in Figure A.19.

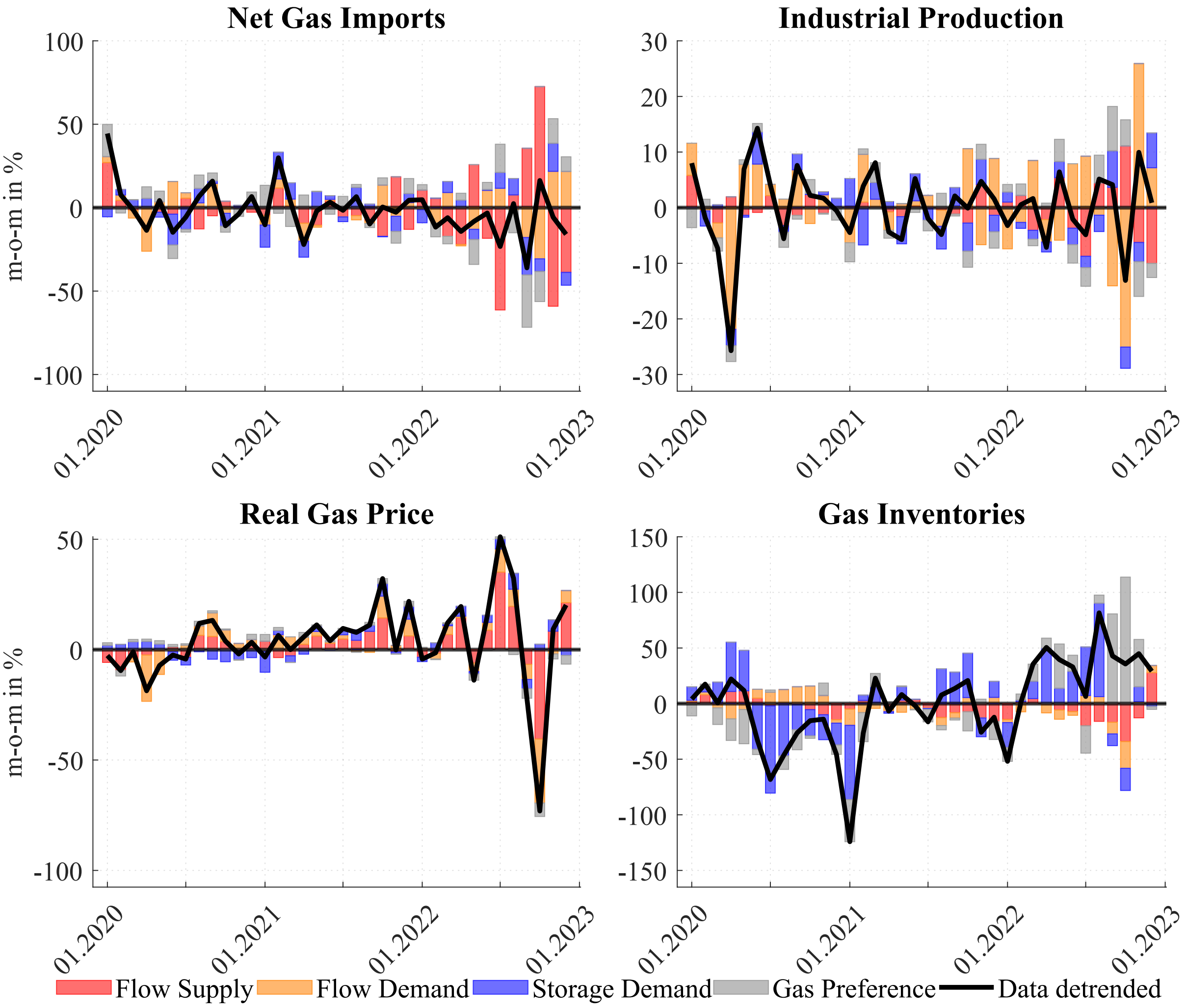

Figure A.21: Historical decomposition for 2020–2022.

Note: Historical decomposition based on the Bayes estimator of impulse response functions in Figure A.19.