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The pass-through to inflation of gas
price shocks

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Abstract

This paper uses a Bayesian Structural Vector Autoregressive (BSVAR) framework to estimate the pass-through of unexpected gas price supply shocks on HICP inflation in the euro area and its four largest economies. In comparison to oil price shocks, gas price shocks have approximately one-third smaller pass-through to headline inflation. Country-specific results indicate gas price increases matter more for German, Spanish and Italian inflation than for French inflation, hinging on the reliance on energy commodities in consumption, production, and different electricity prices regulation. Consistent with gas becoming a prominent energy commodity in the euro area, including time-variation through a time-varying parameter BVAR demonstrates a substantially larger impact of gas price shocks on HICP inflation in recent years. The empirical estimates are then rationalized using a New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) model augmented with energy. In the model, the elasticity of substitution between gas and non-energy inputs plays a critical role in explaining the inflationary effects of gas shocks. A decomposition of the recent inflation dynamics into the model structural shocks reveals a larger contribution of gas shocks compared to oil shocks.

JEL: C11, C32, E31, Q41,

Key words: Natural gas and oil shocks; Inflation; Bayesian VARs; New Keynesian DSGE

Non-technical summary

The recent inflation surge in the euro area was significantly influenced by energy prices, particularly gas following Russia's invasion of Ukraine in February 2022. While past studies have largely focused on the impact of oil prices on inflation, this research shines a light on the role of gas prices.

Through various empirical methods based on Bayesian techniques, this paper estimates the pass-through of international gas prices to consumer prices in the euro area, including the largest economies in the region: Germany, France, Italy, and Spain. The sample period goes from January 1997 to December 2022. We also develop a theoretical model to gain deeper insights into how disturbances to gas prices influence consumer prices differentiating between their direct and indirect effects. Direct effects include basically increased spending on home heating, while indirect effects involve gas usage in the production processes.

Overall, the paper enhances our understanding of the complex relationship between gas prices and inflation, offering useful insights for policymakers and researchers alike. Findings indicate that while unexpected increases in gas prices do contribute significantly to inflation, their impact is somewhat less pronounced compared to oil price shocks. The theoretical analysis reveals that gas plays a critical role as a complementary input in production. That is, gas is more important in the production side than in the consumption basket so that indirect effects dominate. We also provide a narrative for the contribution of several structural shocks to the recent inflation dynamics in the euro area. We find that these were explained by a combination of gas price shocks, with a much larger contribution relative to oil shocks, followed by wage mark-up shocks, demand and productivity shocks.

1 Introduction

The energy component has been a key driver of the recent inflation surge in the euro area. Precisely, gas took the center stage of energy commodity markets after Russia's invasion of Ukraine in February 2022 triggered unprecedented increases in gas prices. Yet, the inflationary effects of gas price shocks remain relatively unknown because the literature has focused on oil price shocks (see, for example, Blanchard and Galí, 2007b; Clark and Terry, 2010; Kilian and Lewis, 2011; Baumeister and Peersman, 2013; Gao et al., 2014; Choi et al., 2018; Känzig, 2021; Cai et al., 2022) or the relation between oil and gas prices (see, for example, Brigida, 2014; Zhang and Ji, 2018; Szafranek and Rubaszek, 2023). This paper instead provides a comprehensive study of the pass-through to consumer prices inflation of gas price shocks. Our contribution to the literature is twofold in that we marshal several pieces of empirical evidence together with a theoretical analysis that rationalises our estimates embedding gas in a standard New Keynesian Dynamic Stochastic General Equilibrium model (NK-DSGE).

First, we build a Structural Bayesian Vector Autoregressive (SBVAR) framework to estimate the pass-through of international wholesale gas prices into the Harmonised Index of Consumer Prices (HICP) inflation in the euro area and the four largest economies in the region: Germany, France, Italy and Spain. The dataset of monthly observations spans from January 1997 to December 2022. Because not all commodity shocks are equal (Kilian, 2008), we focus on unexpected supply-side gas price shocks and exploit the non-linearities due to historically high gas prices in the latest part of the sample to complement the identification of the structural BVAR with the narrative sign restrictions methodology introduced by Antolín-Díaz and Rubio-Ramírez (2018). Motivated by the changes in the institutional setting over time because of the development of the European gas markets, we also estimate a time-varying parameter Bayesian VAR with stochastic volatility to formally asses the potential time variation of the inflationary effects of gas supply shocks.

We also contribute to understanding better the dynamics of gas price shocks breaking down the estimated total pass-through into direct and indirect effects. In terms of consumer prices, *Direct* effects stem from higher consumer spending on home heating. *Indirect* effects capture the downstream impact of using gas as an input in the production processes. The importance of the latter depends on whether gas is used intensively during the production processes or whether gas

prices influence the pricing of other inputs such as electricity or heat production (Pacce et al., 2021). Moreover, the intensity of the total pass-through varies depending on the regulations in place, the types of contracts used in each country's retail energy markets or the profit margin developments in the face of rising energy input costs.

We find that unexpected gas price shocks have significant inflationary effects. A gas price increase of 10 percent increases leads to a gradual pass-through on headline inflation that peaks at close to 0.1 after two years. Compared to oil price shocks, gas price shocks have about one third smaller pass-through to headline inflation. The results suggest that the transmission of unexpected gas price supply shocks gained significance only when the pricing of gas meaningfully decoupled from oil prices (a practice known as oil indexation). Country-level estimates indicate that economies with the highest inflationary effects tend to be more intensive users of energy commodities in their production structures or electricity generation. Our results suggest unexpected gas price changes matter more for German, Spanish and Italian than for French inflation.

Second, we develop a New Keynesian dynamic stochastic general equilibrium (NK-DSGE) model augmented with energy, which is a complementary input for intermediate goods firms and a complementary good for households. In the baseline framework, the energy component is only gas, however, in the extended model the energy bundle is composed by gas and oil, which are assumed to be (imperfect) substitutes. In this way, and similar to the empirical section, we also account for oil fluctuations when identifying the gas shock.

Our baseline NK-DSGE model performs well matching the IRFs of the SBVAR analysis. We obtain the same qualitative results with some quantitative differences, although the model-based IRFs lie well within the empirical credibility intervals. We also find a key role of the elasticity of substitution between gas and non-energy inputs in transmitting the effects of gas shocks. That is, gas is more important in the production side than in the consumption basket so that indirect effects dominate. The latter result holds only with sufficient nominal (wage) rigidities. Intuitively, when wages are flexible, these can adjust to fully absorb disturbances in gas prices. By contrast, rigid wages cannot decline sufficiently in the aftermath of a shock to compensate the large increase in marginal costs, leading to a more pronounced pass-through to inflation.

We also provide a narrative for the recent contribution of several structural shocks to inflation in the euro area. For this exercise, we employ the extended NK-DSGE model to better account for oil shocks. We find that the recent inflation dynamics are explained by a combination of gas shocks, with a much larger contribution relative to oil shocks, followed by wage mark-up shocks, demand shocks and productivity shocks.

A recent but still scant literature is building up evidence about the pass-through of gas price shocks in Europe. Lan et al. (2022) estimate the direct pass-through of international gas prices on German HICP gas inflation. Günter et al. (2024) apply the oil market model pioneered by Kilian (2008) to the German gas market. Both papers thus focus on a single European economy. Casoli et al. (2022) extend the oil market model with additional blocks for the gas market and inflation in Europe, but the contemporaneous relationship between gas and oil prices in their model might cast doubt on the estimates of the pass-through of gas prices. Adolfsen et al. (2024) use estimated structural gas shocks from a gas market model to analyse the pass-through to euro area inflation of demand-driven, supply-driven and expectations-driven structural gas shocks using local projections. In a step forward, they also control for crude oil prices in the estimation of the pass-through. Like Alessandri and Gazzani (2023), we rely on narrative methods to achieve identification of the effects of unexpected gas supply shocks on European inflation in a complex sample including observations post-Covid. However, we extend the analysis along several dimensions. First, we look into different HICP items and extend the sample to the four largest European economies. Second, we conduct an evaluation of the potential time-varying pass-through of unexpected gas price increases. Third, and most importantly, we rationalise our empirical findings with a theoretical model. Among the most closely related theoretical work, Gagliardone and Gertler (2023) develop a New Keynesian model aimed at accounting for the recent sudden and persistent rise in inflation in the US economy. Their model places particular emphasis on the role of oil shocks. Instead, we account for both oil and natural gas fluctuations in the euro area.

The remaining of the paper is organised as follows. Section 2 summarises the development of the European gas market and the narrative episodes used to complement the identification of the structural BVAR model outlined in Section 3. Section 4 presents the estimates of the pass-through to HICP inflation of gas price shocks, while Section 5 studies the time variation in
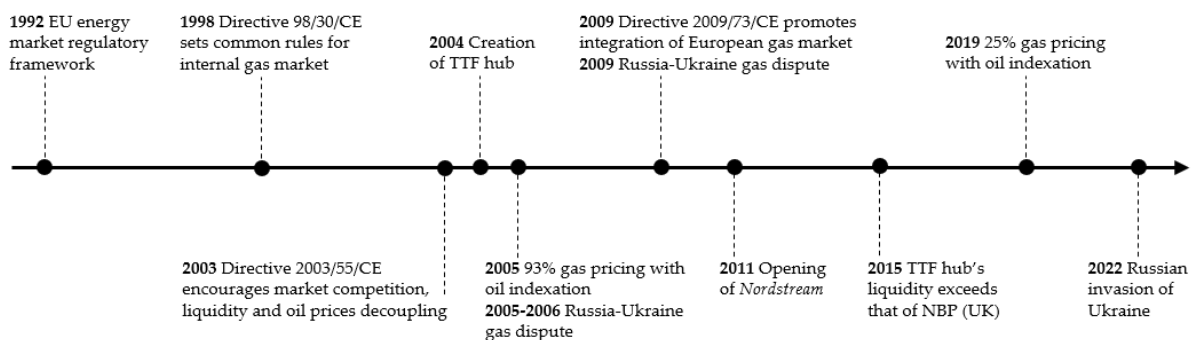
Figure 1: Timeline of the European Gas Market

the pass-through and compares it with that of oil. Section 6 contains a NK-DSGE model with energy inputs to rationalize the empirical results. Section 7 offers concluding remarks.

2 Institutional Framework

2.1 A Brief History of the European Gas Market

The creation of the European gas market took off in the late 1990s. Figure 1 presents a timeline with key dates in its development. European Directives in 1998 and 2003 set the benchmark to expand the internal EU gas market. The Directives aimed at breaking vertical integration in the gas industry and introducing competition. A third Gas European Directive in 2009 promoted the integration of the European gas market and introduced incentives for launching trading hubs (Bastianin et al., 2019).

In the early stages of the European gas market, openness and competitiveness were difficult because long-term contracts linked to oil prices predominated (a system also known as *oil indexation*). Oil indexation provided the necessary stability to develop gas infrastructures, but prices did not necessarily reflect supply and demand fundamentals of the gas market. Over the last two decades, gas prices have moved away from oil indexation to spot pricing. International Energy Agency data shows that oil-indexed contracts went from accounting for 93% of the European gas imports pricing mechanism in 2005 to 25% in 2019.[1] This transition to spot pricing accelerated after the 2008 financial crisis amid loose market conditions, the ending of contracts

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[1]See IEA, Evolution of Europe's gas import pricing mechanisms: from oil- to hub-indexation, https://www.iea.org/data-and-statistics/charts/evolution-of-europe-s-gas-import-pricing-mechanisms-from-oil-to-hub-indexation.
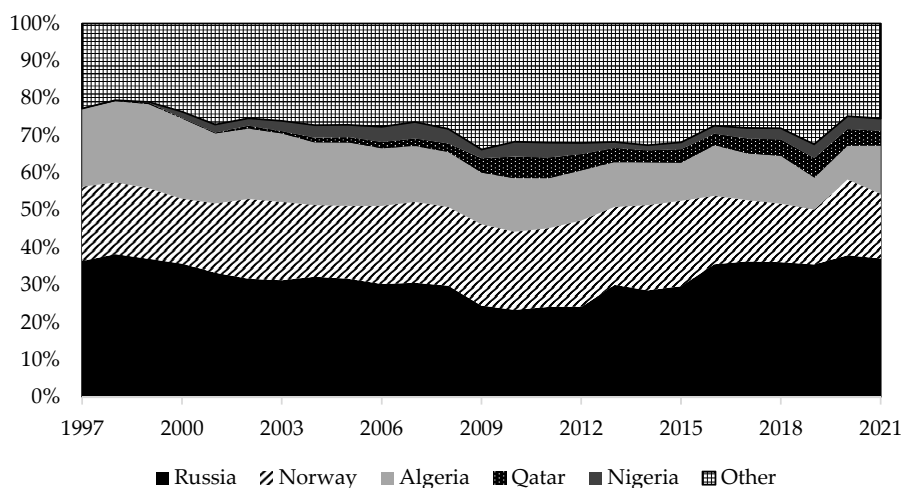
Figure 2: Euro Area Gas Imports by Origin. 1997-2021

or the renegotiation of their terms to include spot pricing terms, as well as a new round of EU energy market legislation to improve the operation of the internal energy market.[2]

Over time, liberalisation promoted deep and liquid wholesale gas trading hubs such as the Title Transfer Facility (TTF) gas market, operative since 2004. The TTF has become the most liquid gas market in Europe, overcoming traded volumes in the UK National Balance Point (NBP) market around the mid-2010s (see, for example, European Comission, 2018). Currently, the TTF constitutes a benchmark for gas prices in Europe and worldwide, together with the US Henry Hub.

2.2 Narrative Episodes of Supply-Driven Gas Price Disruptions

Another unique characteristic of the European gas market is its dependency on imports from Russia. Figure 2 shows that Russia has been the sole largest provider of gas to the euro area. Moreover, Ukraine has been a major corridor for the transit of Russian gas to Europe. To bypass Ukraine's quasi-monopoly in the gas transit to Europe, Russia made several attempts of constructing new pipelines traversing either to the south or to the north of Ukraine. These efforts were marked by numerous gas disputes, the most remarkable for European gas flows being the 2005–2006 and 2009 gas crises, while in 2011 they led to the opening of the gas pipeline *NordStream*. Conversely, following the Russian invasion of Ukraine in 2022 gas flows from Russia plummeted.

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[2]See International Gas Union Wholesale Price Reports for different years at www.igu.org.
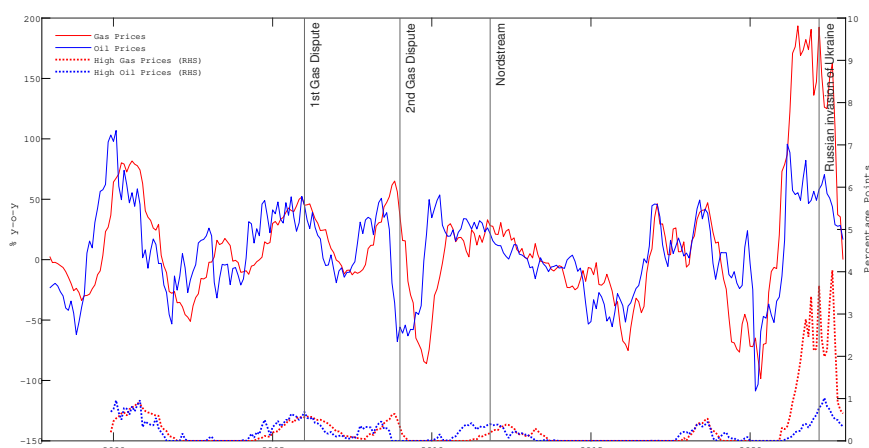
Figure 3: Episodes of Exogenous Gas Supply Shocks

Figure 3 highlights the episodes of gas price shocks in 2005-2006 ("1st Gas Dispute"), in 2009 ("2nd Gas Dispute"), in 2011 ("Nordstream") and in 2022 ("Russian Invasion of Ukraine"). The figure shows high commodity prices calculated following Hamilton (2003):

$$\pi_t = \max \left\{ 0, \frac{p_t}{\bar{p}_t^{3yr}} - 1 \right\} \tag{1}$$

, with p_t the commodity price in month t and $\bar{p}_t^{3yr}$ the average price during the most recent 3 years. Figure 3 also shows that oil price increases used to lead gas price increases until the 2010s. Next, we go over each episode in turn.

Stern (2006) and Pirani et al. (2009) document that the deterioration in Russian-Ukrainian relations during 2005 led to a short-lived but significant dispute during 1-3 January 2006 (1st gas dispute).[3] The Russian demands to update the long-term contracts with Ukraine to charge higher prices were continuously rejected by Ukraine, preferring instead an extended transition period before paying higher prices. As a result, Russia cut off gas supplies to Ukraine and, in turn, Ukraine diverted volumes destined to the rest of Europe. By January 2, Hungary reported to have lost up to 40% of its Russian supplies; Austrian, Slovakian and Romania supplies were said to be down by one third, France 25-30% and Poland by 14%. Italy reported having lost around 25% of deliveries during January 1-3. German deliveries were also affected but no further details are known. On 4 January 2006, a preliminary agreement was achieved, and gas flows were restored. At the same time, relatively mild weather and the halt in production of gas-intensive

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[3]See also "Russia vows to end gas shortage", January 2, 2006, *BBC News Website*.

industrial producers during the New Year holiday period side with the evidence that this episode of high gas prices was supply-side driven. Therefore, we assume that the 1st Russia-Ukraine gas dispute constitutes a negative supply gas shock.

In 2009 took place another significant gas dispute between Russia and Ukraine (2nd gas dispute). The accumulation and failure to clear debts by Ukraine owed to Russia led to a new crisis during 1-22 January 2009. By January 6 Russian gas deliveries to Europe were drastically reduced, and cut off on January 7. Gas was cut off completely to countries in south-eastern Europe which were fully dependent on Russian imports, and partially to other countries, for 13 days. Supplies to Europe had never been halted before, as during the 2006 episodes the shortfalls in supplies to Europe resulted not from European supplies being halted, but from Ukraine being cut off and diverting a proportion of European volumes for its own use. On 19 January two new long term contracts for supply and transit between Russia and Ukraine were signed and gas flows to Europe were restored the following day. Again, we assume that the 2nd Russia-Ukraine gas dispute constitutes a negative supply gas shock.

In 2011, several new gas facilities were developed, including pipelines from Algeria and Russia (IEA, 2012). In November 2011, the Nord Stream pipeline was officially inaugurated. Its construction was part of Russia's politically motivated strategy to limit the influence of transit countries such as Ukraine, while increasing Europe's energy dependence on Russia (Solum Whist, 2008). The opening of Nord Stream increased gas supply to Europe, and the route ranks among the most significant gas corridors from Russia (McWilliams, 2021). By 2014 Russia was delivering 33 bcm of gas via Nord Stream, slightly more than the 31 bcm of gas routed via Ukraine/Slovakia (Erbach, 2016). Therefore, we assume a positive gas supply shock in the month of the opening of Nord Stream.

More recently, Russia's invasion of Ukraine in February 2022 resulted in restrictions to the volume of energy imports from Russia, which generated tensions in the European wholesale natural gas markets. The conflict put further pressures on already tight European energy markets, as evidenced by diminished gas storage levels compared to historical averages and a substantial decline in Russian pipeline gas imports (see, for example, IEA, 2022). Ultimately, Russia unilaterally decided to cut deliveries through its main pipeline to Europe (Nord Stream), with an astonishing 80% reduction in European imports via the major Russian route including
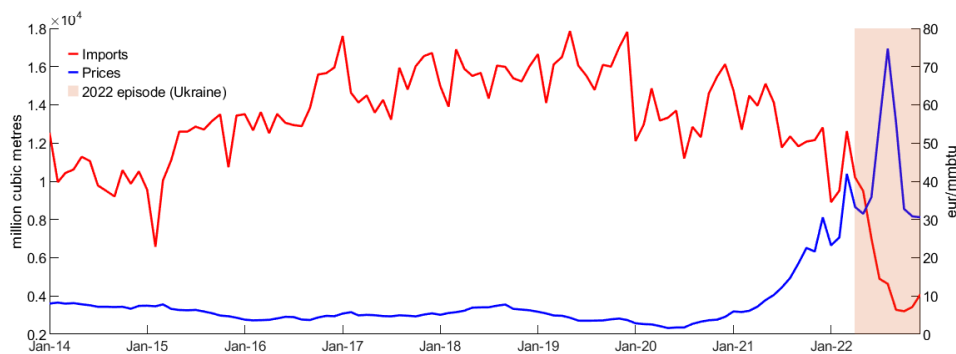
Figure 4: Europe: Russian gas imports and prices

also transit through Ukraine and Belarus. The gas shortages drove gas prices to record highs, as illustrated in Figure 4. Again, we assume this episode constitutes a negative gas supply shock.

Finally, we have discarded disruptions in the European gas price that coincided or seemed to be led with developments in other commodity markets, such as coal or oil. For instance, rising oil and coal prices provided support to European hub prices in September 2018. We also discarded episodes with a sizeable contribution of demand factors or when it was not possible to isolate whether demand or supply factors dominated. For example, early in 2018 a cold wave in UK and Ireland triggered an outstanding increase in seasonal demand. We discarded this episode even if the severe weather conditions had consequences on certain key elements of supply infrastructure in March 2018. We also discarded the gas price disputes around the Russian invasion of Crimea in 2014, as they did affect the gas supply to Ukraine but did not affect the transit flow of gas to the rest of Europe.

3   The Baseline Empirical Framework

Consider the standard Vector Autoregressive (VAR) model:

$$\mathbf{y}_t = c + \sum_{j=1}^{12} A_j \mathbf{y}_{t-j} + \beta \mathbf{X}_t + \mathbf{u}_t \tag{2}$$

where $\mathbf{y}_t$ represents the $n \times 1$ vector of endogenous variables, c is the intercept, A_j denotes the $n \times n$ matrices of lagged coefficients and $\mathbf{X}_t$ contains exogenous control variables. The innovations $\mathbf{u}_t = \mathbf{B}\epsilon_t$ correspond to a linear combination of the structural shocks ϵ_t under the assumption

of invertibility $A_0^{-1} \equiv \mathbf{B}$. We use 12 lags according to the Akaike information criteria and the conservative upper bound set by Kilian and Lütkepohl (2017). The VAR model is estimated using Bayesian methods adopting a non-informative conjugate uniform-normal-inverse Wishart prior (Antolín-Díaz and Rubio-Ramírez, 2018).

We use a combination of sign and narrative restrictions to identify economically meaningful impulse responses. We impose restrictions on the sign that the different shocks have *on impact* on the variables. Table 1 illustrates that an unexpected gas supply shock increases the gas price, decreases activity and increases inflation. We separately identify a demand shock, for which gas prices, activity and general inflation increase. Moreover, understanding the implications of high gas prices for inflation during periods like the recent energy crisis is highly relevant but challenges identification. Thus, we *complement* the traditional sign restrictions with narrative episodes of exogenous gas supply disruptions. We follow the method of "narrative sign restrictions" developed in Antolín-Díaz and Rubio-Ramírez (2018).[4] Based on our institutional knowledge (see again Section 2), Table 1 summarises again our selection of episodes when unexpected and significant gas supply changes occurred. The method does not require a complete narrative, but the key identifying assumption that gas supply shocks are a significant contributor to gas price dynamics during the narrative episodes. We consider four episodes: i) Gas Disputes of January 2006; ii) Gas Disputes of January 2009; iii) opening of Nord Stream in November 2001; and iv) Russian invasion of Ukraine in March 2022. We assume that the 2006 and 2009 episodes constitute a negative gas supply shock and the 2011 episode a positive gas supply shock; in the 2022 episode, the gas supply shock constitutes the main contributor to explaining the gas price dynamics at the time. Given the lack of public data during the earliest episodes to characterise well the gas market dynamics at the time, our baseline is to use narrative sign restrictions based on the 2022 episode, while leaving to the robustness checks exploring alternative restrictions based on the other episodes.

The dataset includes monthly observations from 1997m1 to 2022m12 for the euro area, and, respectively, the four largest economies in the region: France (FR), Germany (DE), Italy (IT) and Spain (ES). $\mathbf{y}_t$ contains gas prices and consumer prices inflation, as well as controls for the general level of economic activity and the stance of monetary policy. Long series of

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[4]Following the recommendations of Antolín-Díaz and Rubio-Ramírez (2018) and An et al. (2021) we set the the number of draws and resampling weights to have approximately 1000 posterior draws that uniquely satisfy both the sign and narrative restrictions.

Table 1: BVAR Identifying Restrictions

Variable	Gas supply shock	Demand shock
Sign Restrictions:		
Gas price$_{h=0}$	+	+
Activity$_{h=0}$	-	+
HICP$_{h=0}$	+	+
ECB rate$_{h=0}$	...	...
Narrative Sign Restrictions:		
01/2006	$\uparrow \epsilon_t^{\text{gas price}}$	
01/2009	$\uparrow \epsilon_t^{\text{gas price}}$	
01/2011	$\downarrow \epsilon_t^{\text{gas price}}$	
03/2022	$\uparrow \epsilon_t^{\text{gas price}}$, major contributor	

country-level gas prices are not available because European gas hubs developed late (see Section 2). We overcome this shortcoming using the m-o-m growth rates of gas prices for Europe from the World Bank's pink sheet data. Reassuringly, the correlation between the European gas prices and the available individual countries' series is very high. Gas prices are converted into euros, seasonally adjusted and deflated by the headline inflation. Consumer prices inflation refers to the m-o-m growth rates of headline harmonised consumer prices index (HICP), retrieved from Eurostat and seasonally adjusted. We use the Economic Sentiment Indicator (ESI) produced by the European Commission as the monthly indicator for economic activity. The ESI is a survey based indicator that tracks GDP growth. The coverage is wider than other monthly activity indicators like industrial production as it includes the sectors of industry, services, consumers, retail and construction. Regarding the control variables for monetary policy, we use the short-term interbank interest rate for the euro area (Eonia for 1997-2004 and ESTER in the final months of 2022). However, standard interest rates can not capture the non-conventional measures that the ECB has implemented since the 2008 financial crisis. We use instead the Wu and Xia (2016, 2020) euro area shadow rate from September 2004 to August 2022. Notice that the Bayesian VAR (BVAR) is estimated on the m-o-m growth rates of all the variables except for the interest rate.

Additional details about the empirical model are worth pointing out. First, unlike other recent work (Alessandri and Gazzani, 2023; Casoli et al., 2022), we use a long sample with data since the 1990s. Having a long sample allows us to evaluate the stability of the coefficients over time, as well as other robustness exercises. This is important because the European gas market

developed over the entire sample period. Our analysis, therefore, solves for the best initial sample period rather than imposing it. Second, regardless of the sample period, the historical relationship between oil and gas prices makes it essential to clean all series in $\mathbf{y}_t$ of oil shocks. Otherwise, one might question whether the inflationary effects of wholesale gas price shocks actually capture variation in oil prices. To address such concerns, $\mathbf{X}_t$ contains the exogenous oil supply news shocks of Känzig (2021). Third, we include exogenous monthly dummy variables to control for the Covid lock-downs and re-opening disruptions between March 2020 and September 2020.

Finally, to gain insights into the components of the total pass-through, we also present results that distinguish between direct and indirect effects. Direct effects can be approximated substituting headline inflation for the gas products HICP item in the BVAR. For the indirect effects, we estimate explicitly the indirect effects on the electricity HICP item and calculate the rest by difference with the point estimates for headline inflation.

4 The Pass-through to HICP Inflation of Gas Supply Shocks

Figure 5 shows the gas price pass-through to headline inflation in the Euro Area for the baseline BVAR. The black lines show the median impulse response functions (IRFs) identified with traditional sign restrictions. The red lines show the results using complementary narrative restrictions based on the episode of the Russian invasion of Ukraine in early 2022. Specifically, we assume a negative gas supply shock that is the largest contributor to explaining the gas price dynamics in March 2022. To facilitate the interpretation of the results we present annualised IRFs (the non-transformed IRFs are presented in Appendix B). We find that narrative sign restrictions achieve more accurate estimates, but not significantly different point estimates than traditional sign restrictions. On impact, an unexpected gas price increase of 10 percent increases headline year-on-year inflation by 0.4 pp. The inflation response is statistically significant around 15 months. The pass through, measured in the right plot as the cumulative inflation response standardized by the cumulative change in the gas price, builds up over time and reaches a maximum of 0.06 pp about two years after the shock. Although not shown for brevity, economic activity falls following a gas price increase, while the interest rate increases. Our estimates are in line with Alessandri and Gazzani (2023), although they find inflationary effects slightly weaker on impact (see figure A9 in their appendix).

Table 2 compares the relevance of alternative narrative episodes that could be used as a complement to achieve identification. Narrative sign restrictions are more relevant the more they challenge the draws satisfying the traditional sign restrictions. That is, given the number of draws that identify the BVAR with the traditional sign restrictions, the higher the probability of rejecting the narrative sign restrictions. Our baseline has one of the highest relevance. Although other episodes yield higher probabilities, Figure C.9 in the Appendix shows that the alternative narrative episodes do not significantly contribute to produce more accurate estimates. Actually, the alternative narrative sign restrictions produce again similar point estimates but wider credibility intervals. It is also worth pointing out that the most relevant identifying assumption of the baseline is that gas supply shocks are the major contributor to the evolution of gas prices, rather than the sign of the shock. However, we found difficult to argue a shock to be the major contributor without accounting for the sign of the same.

Finally, Appendix A presents further robustness exercises. We have verified the estimates are not driven by confounding developments in other commodities prices. Specifically, that it is good practice to control for exogenous oil prices in the BVAR and that the estimated gas prices pass-through does not capture inflationary effects driven by food commodities prices.[5] We have also verified that the baseline results are robust to the control for economic activity included in the BVAR. Actually, we find somewhat stronger inflationary effects of gas price shocks when including industrial production or a monthly estimate of GDP growth, albeit the results are not statistically different from the baseline. Moreover, we have also verified that the estimated gas price pass-through does not capture other supply shocks, represented by proxies for production bottlenecks.[6] Finally, the changing institutional setting of gas markets in Europe challenges the temporal stability of the coefficients. Estimates for different sub-samples imply that observations in the last part of the sample have higher explanatory power. The impact effects prevail for different sub-samples, but the persistence of the inflationary effects is affected by the sample choice. Restricting the estimation sample post 2010s produces very similar estimates to the baseline, implying that the early observations contribute little explanatory power. Restricting the estimation sample to end in December 2019 also yields less persistent inflationary effects.

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[5]For food commodities prices we use the euro area total farm-gate and wholesale market prices in euros.

[6]We use three proxies for production bottlenecks: the euro area's supply bottlenecks index based on newspaper data of Burriel et al. (2023), the world's Purchasing Managers' Indices (PMIs) for suppliers' delivery times (Attinasi et al., 2022) and the Global Supply Chain Pressures Index (GSCPI) of Benigno et al. (2022).
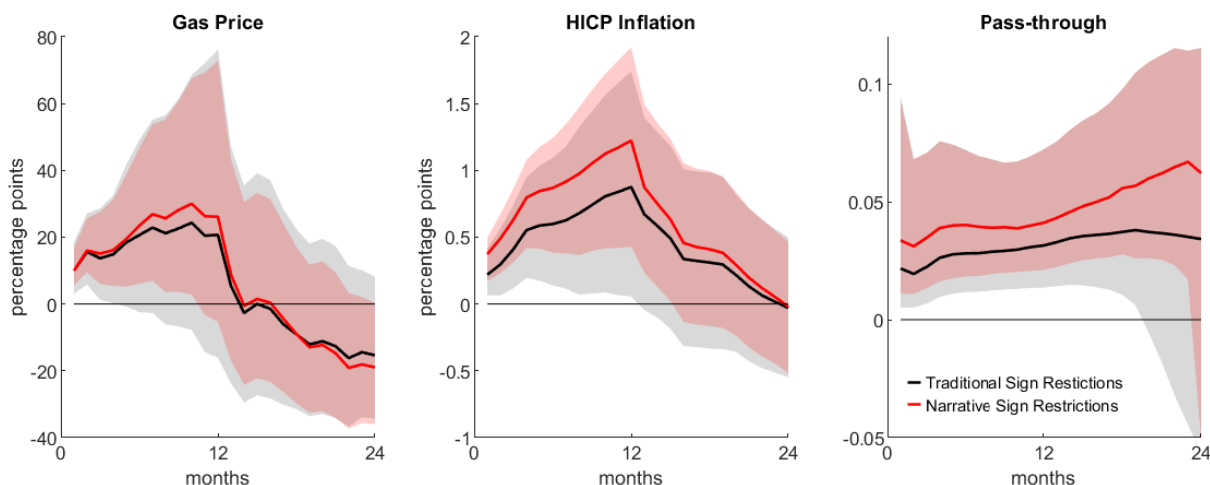
Figure 5: Gas Prices Pass-through to Headline Inflation in the Euro Area

Notes: The figure shows median impulse response functions (cumulative impact in the left-hand-side panel) to a 10% increase in the price of gas in the euro area identified with traditional sign restrictions (black lines) and narrative sign restrictions (red lines). 68% credibility intervals. Sample 1997 m1 to 2022 m12.

Table 2: Probability Rejecting Narrative Sign Restrictions

	Negative shock	Positive shock	Major contributor	Any restriction
03/2022	60.0	-	85.8	85.5
01/2006	93.4	-	-	-
01/2009	93.9	-	-	-
11/2011	-	81.2	-	-

Nonetheless, the results for the alternative samples are not statistically different from the baseline BVAR. We discuss further the stability of the coefficients in Section 5.

4.1 Estimates for the Largest Euro Area Economies

This section presents estimates of the inflationary effects of gas price supply shocks for the four largest economies in the euro area: Germany (DE), France (FR), Italy (IT) and Spain (ES). The analysis contributes relevant details due to disparities in productive structures, consumption baskets or domestic regulations in each country, which the baseline median estimates for the euro area conceal.

Figure 6 compares the IRFs by country with the baseline estimates. Again, all country estimates complement the standard sign restrictions with the narrative episode of the Russian war of aggression against Ukraine. The IRFs have been annualized and report the response to a 10% increase in the gas price. Important country-specific differences emerge. The inflationary effects in
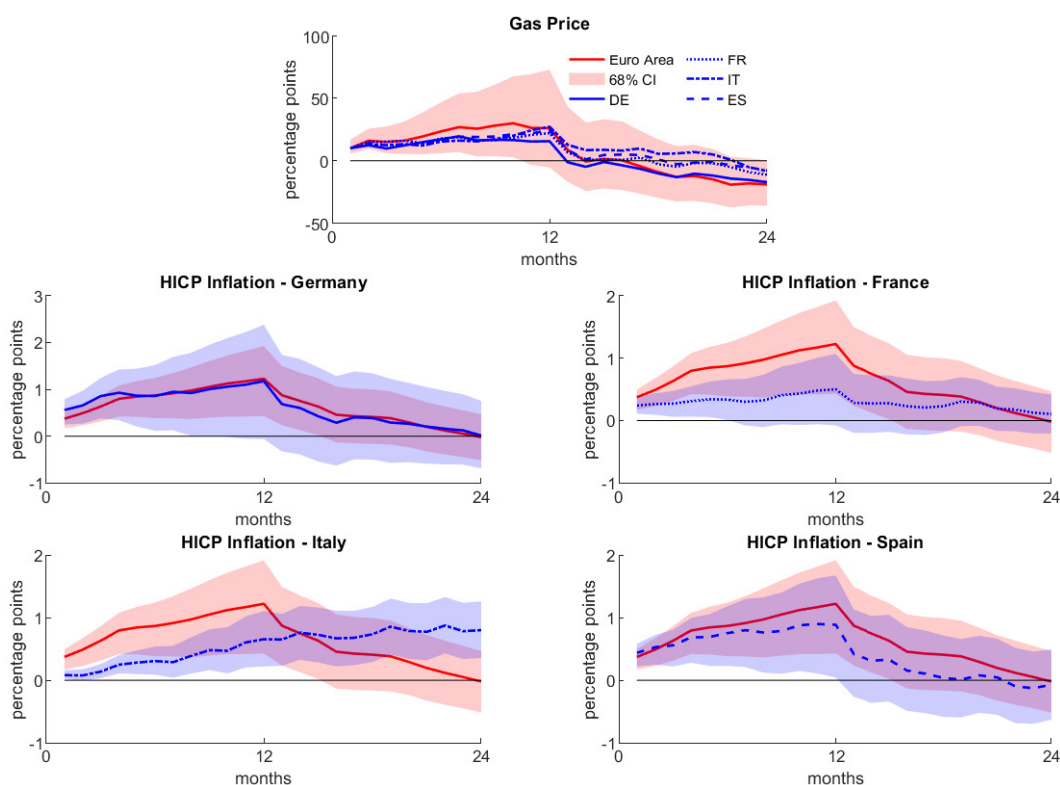
Figure 6: Gas Price Pass-Through to Headline Inflation by Country

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas in the euro area, Germany, Spain, France and Italy identified with narrative sign restrictions. 68% credibility intervals. Sample 1997 m1 to 2022 m12.

the euro area are the closest to those in Germany. This is not surprising considering that Germany contributes around 30% to the euro area inflation aggregate. Germany also experiences the largest increase in inflation, especially when taking into account the subdued gas price dynamics compared to the other countries. Spain shows the second largest inflationary response. These dynamics can be explained by the regulatory system of the retail electricity market in Spain, which we discuss later. In Italy, the persistence of the pass-through is noteworthy, with the inflationary peak being reached the latest. The pass-through in France is the weakest, with the estimates turning quickly statistically not significant.

To shed light on the differences by country we break down the total pass-through into three components following the European Classification of Individual Consumption According to Purpose (ECOICOP). First, the heating item of the HICP serves as a measure of the *direct* impact that gas prices have on consumer prices. Second, the relationship between energy commodities and
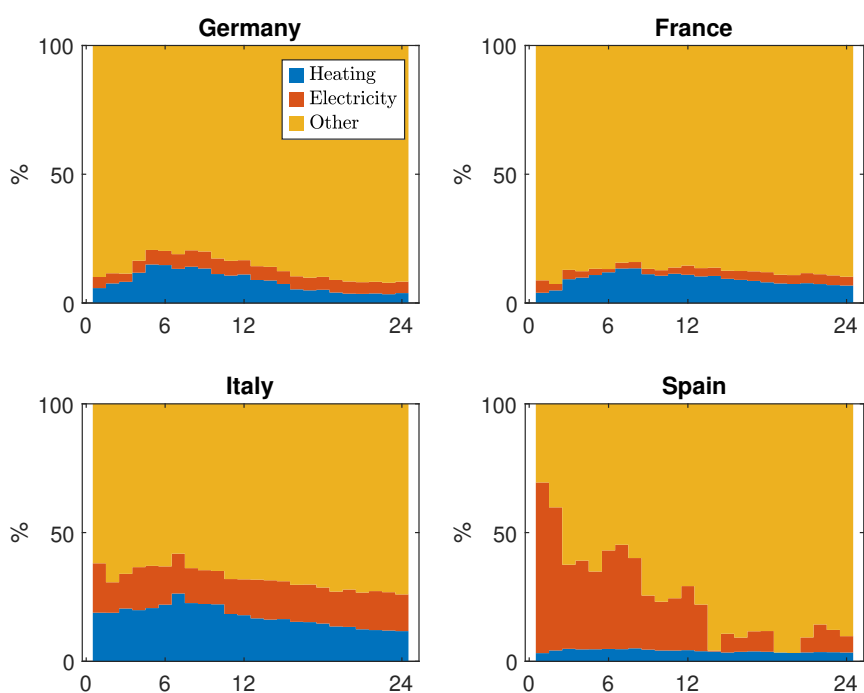
Figure 7: Composition of Gas Price Pass-Through to Headline Inflation by Country

electricity is sufficiently relevant to isolate the *indirect* effects through the electricity component of the HICP, which captures the impact on retail electricity prices. Third, other indirect effects can be inferred by the difference of the previous too and the estimates for headline inflation.

Figure 7 shows the contribution of heating, electricity and other indirect effects to the pass-through of gas supply shocks to headline inflation by country. Given the different dynamics of the gas prices by country, and to ensure comparability, we calculate again the contributions using the cumulative inflation response standardised by the cumulative change in the gas price. We find disparities across economies: higher inflationary effects tend to be associated with a more intensive use of energy commodities in industrial production structures (other, yellow area) or electricity generation (electricity, orange area), while the speed of the pass-through also hinges on the regulation of the electricity and gas markets.

The break down of the pass-through rationalises the inflationary effects of gas supply shocks in Spain. Unlike the majority of the euro area countries, Spain has a regulated retail electricity tariff since 2014, the regulated rate for small consumers or PVPC by its Spanish acronym, which links hourly retail electricity prices to hourly wholesale prices. Pacce et al. (2021) argue that as a result of the tariff, the final electricity price borne by domestic consumers is substantially more

volatile in Spain than in the main euro area economies. Figure D.1c in the Appendix also shows that electricity accounts for a larger share of the consumption basket in Spain. By contrast, the direct effect of gas shocks in Spain is limited because since 2008, Spain has a regulated natural gas tariff, with retail gas prices being set by the Government quarterly. Moreover, Figure D.1a in the Appendix shows that gas accounts for the smallest proportion of household expenditure across the four largest euro area economies.

Regarding the rest of countries, the sizeable direct effects in Italy reflects the high weight of heating in the Italian consumption basket compared to other countries (Figure D.1a). Moreover, The results for France and Germany illustrate well the delayed pass-through to regulated retail gas and electricity prices of increases in gas prices in the wholesale market (Kuik et al., 2022). Finally, also highlight the large other indirect effects in Germany most likely because the size of the German industrial sector stands out from the other euro area economies. According to Eurostat, Germany is the substantial producer of manufacturing of basic metals and fabricated metal products.[7] Germany is also the top EU exporter of chemicals.[8] These industries use intensively gas in production, face limited possibilities of input substitution, and have strong linkages with other downstream industries. We discuss further the role of gas in the production structure in Section 6.

5   Has the Pass-through Changed Over Time?

Our sample includes important changes in the institutional framework, like an increase of the share of gas in the energy consumption and the shift from oil indexation to spot gas pricing. As a result, the responsiveness of inflation to unexpected gas prices increases might have changed over time. Moreover, our focus on gas shocks begs the question of comparing the potentially time-varying inflationary effects of unexpected supply shocks of gas prices with those of oil. To assess potentially time variation in the IRFs we estimate a time-varying parameter Bayesian VAR with stochastic volatility:

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[7]See, for example, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_production_statistics.

[8]See, for example, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Production_and_international_trade_in_chemicals#Growing_trade_in_chemicals.

$$\mathbf{y}_t = c_t + \sum_{j=1}^{6} \mathbf{A}_{(t,j)} \mathbf{y}_{t-j} + B^{-1} \Sigma_t^{\frac{1}{2}} \mathbf{u}_t \,, \tag{3}$$

$$c_{t,n} \equiv c_{t-1,n} + v_{c,t,n} \quad \text{for} \quad n = 1, \dots, 4 \,, \tag{4}$$

$$a_{t,j,(i,k)} \equiv a_{t-1,j,(i,k)} + v_{a,t,(i,k),j} \quad \text{for} \quad i,k = 1, \dots, 4 \,, \tag{5}$$

$$\Sigma_t \equiv \left(\sigma_{1,t}^2, \dots, \sigma_{4,t}^2 \right) \,, \tag{6}$$

$$\log(\sigma_{n,t}^2) = \log(\sigma_{n,t-1}^2) + \eta_{n,t} \quad \text{for} \quad n = 1, \dots, 4 \,, \tag{7}$$

such that c_t is the time-varying intercept, $\mathbf{A}_{t,j}$ the time-varying coefficient matrices, with elements $a_{t,(i,k),j}$, B^{-1} is a lower triangular matrix with ones on the diagonal, $u_t \sim_{\text{iid}} \mathcal{N}(0, I_3)$, $(\eta_{1,t}, \dots, \eta_{3,t})' \sim_{\text{iid}} \mathcal{N}(0, \Xi)$, and $[v_{c,t}'; v_{a,t}'] \sim_{\text{iid}} \mathcal{N}(0, Q)$, with $v_{c,t}$ and $v_{a,t}$ containing the $v_{c,t,n}$ and $v_{a,t,(i,k),j}$, where Ξ and Q are not constrained to be diagonal. As in the case of the constant parameter BVAR, the vector of variables is defined as $\mathbf{y}_t = [\Delta oil_t, \Delta ng_t, \pi_t, \mathrm{SR}_t]'$, where Δoil_t and Δng_t denote the month-on-month growth rates of the real price of oil and the real price of gas, respectively, π_t denotes the month-on-month inflation and SR_t denotes the euro area shadow rate based on Wu and Xia (2020).[9] As before, real oil prices are seasonally adjusted and in euros. The BVAR model is estimated using the Gibbs sampler of Del Negro and Primiceri (2015), with the main difference being that B^{-1} is time-invariant which simplifies the Gibbs step. Priors for the time-varying parameters are set by OLS estimates on an initial in-sample of 72 observations from 1997m1 to 2002m12 (see, for instance, Del Negro and Primiceri (2015)). Priors on the stochastic volatility parameters are set as in Ganics and Odendahl (2021). We use six lags, instead of 12 as in the constant parameter BVAR, to avoid excessive parameter proliferation. The estimation sample is then 2003m7 until 2022m12.

Figure 8 plots the cumulative response of euro area HICP to an oil (black line) and a gas (blue line) price shock, again normalized by the cumulative response of the commodities prices, respectively, for the TVP-BVAR over time. Dashed lines show 68% credibility intervals. Overall, the impact on HICP of a gas price shock is smaller than that of an oil price shock. Importantly, the responsiveness of HICP inflation to a gas price shock markedly increased since 2010 whereas the cumulative impact of an oil price shock remained stable. The size of the HICP cumulative

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[9]Results are robust to including the ESI instead of the shadow rate into the model.
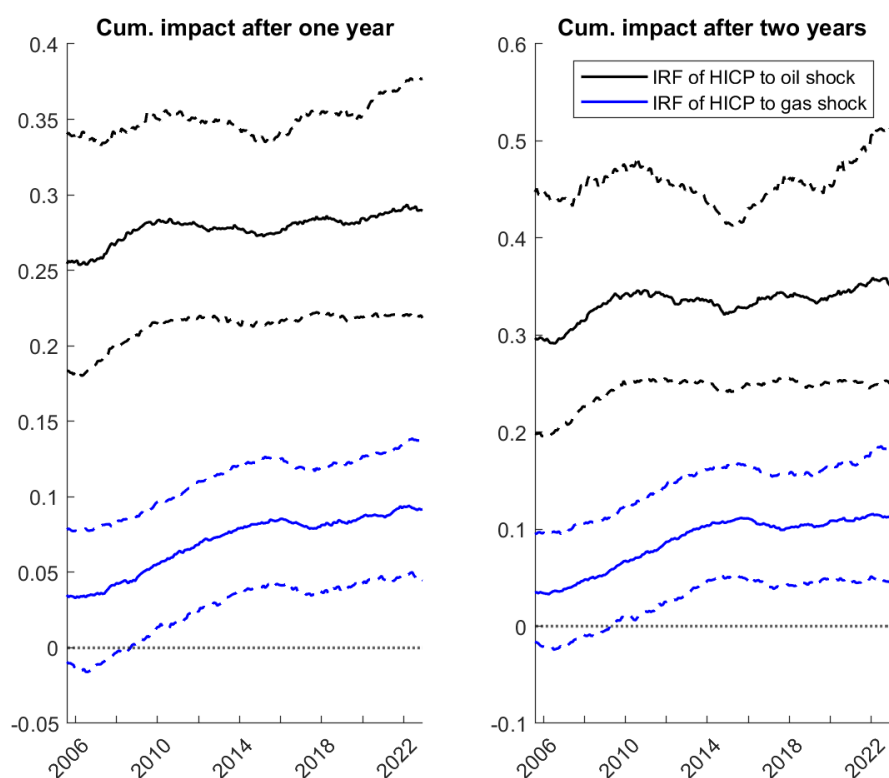
Figure 8: Cumulative impact of oil and gas price shocks on HICP inflation over time

Notes: The figure shows the estimated cumulative impact on headline euro area HICP inflation due to a 10% increase in oil (black line) and gas (blue line) prices, after one and two years. The dashed black and blue lines show 68% credibility intervals for the cumulative response of HICP to an oil and gas shock respectively.

responses are comparable to the time-invariant model results in the previous section and in other recent empirical studies of the pass-through to consumer prices of oil price shocks (Choi et al., 2018; Känzig, 2021; Cai et al., 2022). The results suggest that the transmission of unexpected gas price shocks gained significance only when spot pricing replaced sizeably oil indexation. The increasing importance and contribution of gas price shocks in the posterior median of the oil and gas price shocks (Figure 9) and the forecast error variance decomposition (FEVD) of HICP inflation (Figure 10) over time reinforce this intuition.
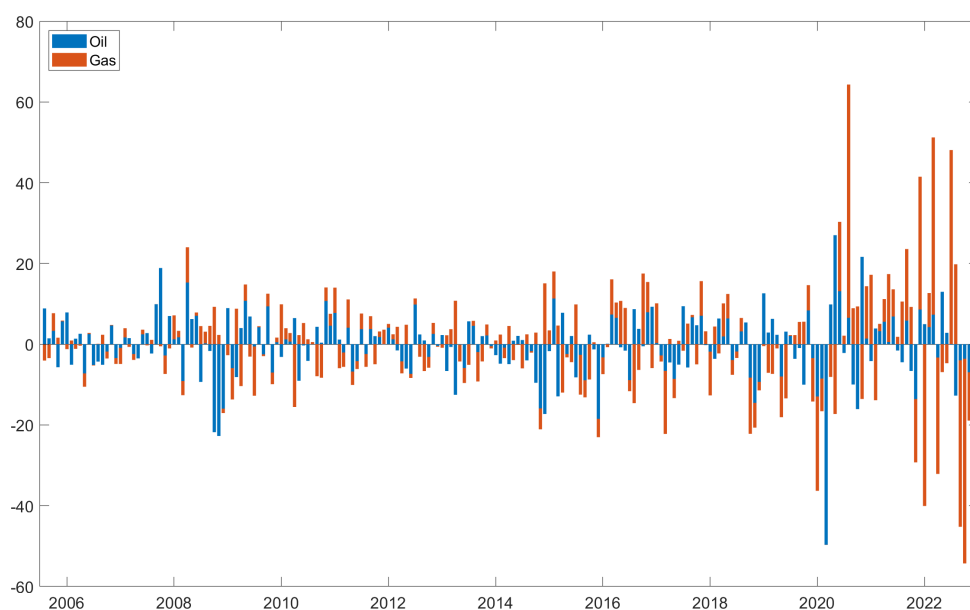
Figure 9: Oil and gas price shocks

Notes: The figure shows the posterior median of the oil and gas price shocks over time.
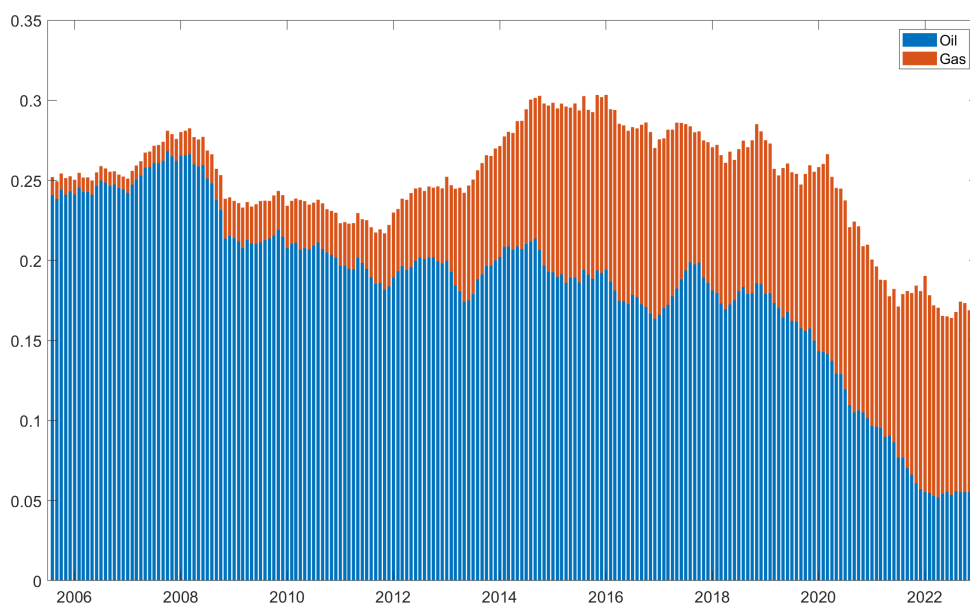
Figure 10: Forecast error variance decomposition of HICP inflation over time

Notes: The figure shows the posterior median of the contribution of oil and gas price shocks to the forecast error variance of HICP inflation over time.

6   The Theoretical Framework

Now we turn our attention to the theoretical model. The starting point is a canonical New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) model augmented with gas,

which is a complementary input for intermediate firms and a complementary good for households. The whole economy is populated by households, intermediate producers, a final good sector and a monetary authority. Next we detail the agents' decision problems.

6.1 Households

There is a continuum of households indexed by j. The households maximize their utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ ln(c_{jt} - \kappa c_{jt-1}) - \xi \frac{l_{jt}^{1+\psi}}{1+\psi} \right\}, \tag{8}$$

subject to the resource constraint

$$c_{jt} + i_{jt} + \frac{b_{jt+1}}{p_t} = R_{t-1} \frac{b_{jt}}{p_t} + w_{jt} l_{jt} + \Xi_t + T_t, \tag{9}$$

where β is the subjective discount factor, ψ is the inverse of the Frisch elasticity of labor supply and κ denotes the degree of habit persistence. Households invest in government bonds, b_{jt}, and receive a nominal gross interest rate, R_t. They also supply labor, l_{jt}, in exchange for the real wage rate w_{jt}. Through their ownership of firms, households receive the profit Ξ_t. Moreover, they are subject to lump-sum taxes T_t.

Household total consumption is denoted by c_{jt}. Specifically, households consume a composite final good, which is made of gas, $c_{g,jt}$, and a consumption good excluding gas, $c_{x,jt}$

$$c_{jt} = \left(\nu_c^{\frac{1}{\mu_c}} (c_{g,jt})^{\frac{\mu_c-1}{\mu_c}} + (1-\nu_c)^{\frac{1}{\mu_c}} (c_{x,jt})^{\frac{\mu_c-1}{\mu_c}} \right)^{\frac{\mu_c}{\mu_c-1}}, \tag{10}$$

where ν_c represents the weight of gas in the consumption bundle and μ_c is the elasticity of substitution between both goods. A small value for the latter would imply that gas and consumption goods excluding gas are not easy to substitute in the total consumption basket. In other words, the total consumption basket for the household would clearly reflect the dependence on gas consumption when a negative shock to gas prices hits the economy.

Expenditure minimization yields the demand equations for gas and the consumption good excluding gas

$$c_{g,jt} = \nu_c \left(\frac{p_{g,t}}{p_t} \right)^{-\mu_c} c_{jt}, \tag{11}$$

$$c_{x,jt} = (1 - \nu_c) \left(\frac{p_{x,t}}{p_t} \right)^{-\mu_c} c_{jt}, \tag{12}$$

where $p_{g,t}$ is the price of gas and $p_{x,t}$ the price of the consumption good excluding gas.[10] The aggregate (headline) price index is then defined as

$$p_t = \left(\nu_c p_{g,t}^{1-\mu_c} + (1 - \nu_c) p_{x,t}^{1-\mu_c} \right)^{\frac{1}{1-\mu_c}} . \tag{13}$$

Denoting by λ_{jt} the Lagrange multiplier, the optimality conditions for the household's maximization problem with respect to bond holdings and consumption are

$$\lambda_{jt} = \beta \mathbb{E}_t \lambda_{jt+1} \frac{R_t}{\Pi_{t+1}}, \quad \text{with} \quad \Pi_{t+1} = \frac{p_{t+1}}{p_t} \tag{14}$$

$$(c_{jt} - \kappa c_{jt-1})^{-1} - \kappa \beta \mathbb{E}_t (c_{jt+1} - \kappa c_{jt})^{-1} = \lambda_{jt} \tag{15}$$

Wages are determined following a Calvo's staggered nominal setting, i.e., in each period, households are only allowed to reset their wage with probability $1 - \theta_w$, regardless of the time elapsed since they last adjusted their wage contracts. Thus, in each period a measure $1 - \theta_w$ of households optimally reset their wages at the same rate, $\widetilde{w}_t = \widetilde{w}_{jt}$. Those households that do not re-optimize are allowed to update their wages according to the following indexation rule

$$w_{jt} = (\Pi_{t-1})^{\chi_w} \Pi^{1-\chi_w} w_{jt-1} \tag{16}$$

where Π is the steady-state (headline) inflation and wage indexation is controlled by the parameter χ_w.

The first-order condition of the households that optimize their wage reads as follows

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[10]We normalise to one the price of the composite consumption good when solving the model.

$$\mathbb{E}_t\left[\sum_{k=0}^{\infty}(\beta\theta_w)^k\left(\lambda_{jt+k}\frac{\widetilde{w}_t}{p_{t+k}}\left(\frac{p_{t+k-1}}{p_{t-1}}\right)^{\chi_w}\Pi^{(1-\chi_w)k}-\xi\frac{\eta_w}{\eta_w-1}l_{jt+k}^{\psi}\right)l_{jt+k}\right]=0 \qquad (17)$$

The previous equation comes from maximizing the household's utility function subject to the indexation rule, the budget constraint, and the demand for its differentiated labor services, $l_{jt}=\left(\frac{w_{jt}}{w_t}\right)^{-\eta_w}l_t^d$, where l_t^d is the aggregate labor demand and η_w is the elasticity of substitution among different types of labor.[11]

6.2 Final Good Sector

The final good is produced by a perfectly competitive sector which assembles a continuum of intermediate goods using the aggregate CES function

$$y_t=\left(\int_0^1 y_{it}^{\frac{\eta_p-1}{\eta_p}}di\right)^{\frac{\eta_p}{\eta_p-1}}, \qquad (18)$$

where η_p is the elasticity of substitution. Given the previous aggregator, the demand function faced by each firm i is

$$y_{it}=\left(\frac{p_{x,it}}{p_{x,t}}\right)^{-\eta_p}y_t. \qquad (19)$$

6.3 Intermediate Firms

The indirect effects of supply shocks from energy commodities are incorporated into the model introducing an additional energy input in the production function of the intermediate producers. In particular, each firm i combines gas with labor services

$$y_{it}=z_t\left(\nu_y^{\frac{1}{\mu_y}}(e_{g,it})^{\frac{\mu_y-1}{\mu_y}}+(1-\nu_y)^{\frac{1}{\mu_y}}(l_{it}^d)^{\frac{\mu_y-1}{\mu_y}}\right)^{\frac{\mu_y}{\mu_y-1}}, \qquad (20)$$

where $e_{g,t}$ is the quantity of gas used and l_{it}^d is the amount of the "packed" labor input rented by the intermediate firm i. The elasticity of substitution between the utilization of gas and labor is represented by μ_y, and ν_y determines the share of gas in the production technology. The aggregate variable z_t represents the productivity level.

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[11]See Gomes et al. (2012) for detailed derivations.

The objective of each intermediate firm is to maximize profits. By solving the intermediate firms' program, we get the following optimality conditions

$$e_{g,it} = \nu_y \left(\frac{p_{g,t}}{z_t mc_t} \right)^{-\mu_y} \frac{y_{jt}}{z_t}, \tag{21}$$

$$l_{it}^d = (1 - \nu_y) \left(\frac{w_t}{z_t mc_t} \right)^{-\mu_y} \frac{y_{jt}}{z_t}, \tag{22}$$

with

$$mc_t = z_t^{-1} \left(\nu_y p_{g,t}^{1-\mu_y} + (1 - \nu_y) w_t^{1-\mu_y} \right)^{\frac{1}{1-\mu_y}}, \tag{23}$$

Notice that marginal costs are the same across intermediate good firms since all producers face the same input prices. The variable mc_t is the marginal cost of producing a unit of the intermediate good.

The intermediate good producers set their prices in a staggered fashion following Calvo (1983). With probability $1 - \theta_p$ they maximise the discounted sum of their expected nominal profits. Thus, in each period t a measure $1 - \theta_p$ of intermediate firms update their prices at the same rate, $\widetilde{p}_{x,t} = \widetilde{p}_{x,it}$. Those firms that do not re-optimize reset their prices according to the following indexation scheme

$$p_{x,it} = (\Pi_{x,t-1})^{\chi_p} \Pi_x^{1-\chi_p} p_{x,it-1}, \tag{24}$$

where $\Pi_{x,t-1}$ is the intermediate firms inflation rate and price indexation is controlled by the parameter χ_p.

The implied (symmetric) first-order condition is[12]

$$\mathbb{E}_t \left[\sum_{k=0}^{\infty} (\theta_p)^k \left(\lambda_{t,t+k} \prod_{s=1}^{k} \Pi_{x,t+s-1}^{\chi_p} \Pi_x^{(1-\chi_p)} \widetilde{p}_{x,t} - \frac{\eta_p}{\eta_p - 1} mc_{t+k} \right) y_{it+k} \right] = 0 \tag{25}$$

And the intermediate price index, $p_{x,t}$ evolves as

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[12]See Gomes et al. (2012) for a detailed derivation.

$$p_{x,t} = \left(\theta_p \left(\Pi_{x,t-1}^{\chi_p} \Pi_x^{(1-\chi_p)} p_{x,t-1} \right)^{1-\eta_p} + (1-\theta_p)(\widetilde{p}_{x,t})^{1-\eta_p} \right)^{\frac{1}{1-\eta_p}} \tag{26}$$

6.4 Monetary Policy and Resource Constraints

The monetary authority adjusts the nominal interest rate according to the following Taylor rule

$$(R_t)^{12} = R^{12} + \phi_\pi \left[(\Pi_{x,t}^{12}) - (\Pi_x^{12}) \right] + \phi_y \left[y_{gr,t} - 1 \right] + \epsilon_{R,t}, \tag{27}$$

where $\epsilon_{R,t}$ is a (persistent) monetary policy shock and $y_{gr,t}$ is the growth rate of real GDP, which is defined as

$$GDP_t = \frac{1}{p_t} \left(p_{x,t} y_t - p_{g,t} e_{g,t} \right). \tag{28}$$

In order to close the model, we assume that the supply of nominal bonds is set to zero and that the price of gas is exogenous. We calibrate the later to imply an increase of 10% in the real price of gas, consistent with the previous empirical sections.

6.5 Calibration

The model is solved by means of a first-order perturbation method. We calibrate the model to the euro area economy. Table 3 summarizes the (monthly) calibration of the model. We set the household discount factor and the Inverse of Frisch labor supply elasticity to $0.992^{\frac{1}{3}}$ (matching the annualized real interest rate of 3 percent in steady-state) and 2, respectively. The habit persistence parameter is set to $0.45^{\frac{1}{3}}$, which is consistent with the microeconomic literature (see Havranek et al., 2017). We set the Calvo wage parameter to $0.80^{\frac{1}{3}}$, similar to the estimates in Smets and Wouters (2003). Regarding prices, we calibrate the price stickiness parameter to $0.75^{\frac{1}{3}}$, implying a quarterly value similar to Alvarez et al. (2006). The indexation parameters on wages and prices are set, respectively, to 0.75 and 0.50, as in Gomes et al. (2012). For monetary policy, we set the reaction to annual inflation and the monthly output growth 1.50 and 0.033, respectively, as in Coenen et al. (2023) and Gomes et al. (2012).

Finally, we turn to gas. We set both the elasticity of substitution between gas and labor, and the elasticity of substitution between the consumption of gas and the consumption good excluding gas to 0.6. These small values imply low substitution among the consumption goods and between inputs in the production function. Regarding the share of gas in the household's

Table 3: Model Parameters

	Firms			
μ_y	Elast. of subst. between gas and labor		0.6	Low substitution
ν_y	Quasi-share of gas in the production of interm. goods		0.0203	To match $e_g/y = 0.0134$
η_p	Elast. of subst. between differentiated goods		6	Markup of 1.2
θ_p	Price stickiness		$0.75^{\frac{1}{3}}$	Alvarez et al. (2006)
χ_p	Price indexation		0.5	Gomes et al. (2012)
	Households			
β	Discount rate		$0.992^{\frac{1}{3}}$	Real interest rate of 3%
ψ	Inverse of Frisch labor supply elasticity		2	Gomes et al. (2012)
κ	Habit persistence		$0.45^{\frac{1}{3}}$	Havranek et al. (2017)
μ_c	Elast. of subst. between consumption goods		0.6	Low substitution
ν_c	Quasi-share of gas in the consumption basket		0.0095	To match $c_g/c = 0.0121$
η_w	Elast. of subst. among different types of labor		6	Markup of 1.2
θ_w	Wage stickiness		$0.80^{\frac{1}{3}}$	Smets and Wouters (2003)
χ_w	Wage indexation		0.75	Gomes et al. (2012)
	Monetary Policy			
Π_x^{12}	Inflation target		1.02	Gomes et al. (2012)
ϕ_π	Inflation coefficient TR		1.50	Coenen et al. (2023)
ϕ_y	Output growth coefficient TR		0.033	Gomes et al. (2012)

consumption basket, we set the quasi-share parameter to 0.0095, implying a steady-state share of gas in the household's consumption basket of $c_g/c = 0.0121$. This share is obtained combining the information conveyed by Coenen et al. (2023) and Eurostat's energy statistics. The former sets the total energy share in the consumption bundle to 0.055 out of the three energy producing sectors in the input-output tables from the 2018 of the OECD TiVA database, i.e., mining, petroleum products, and the conglomerate of gas, electricity, steam and air conditioning supply. We adjust this value to account only for the gas component using its contribution in Eurostat's gross energy balances 2019, around 22%. Similarly, we set ν_y to 0.0203 in order to match the share of gas in the production of the intermediate goods $e_g/y = 0.0134$. Again, this value applies Eurostat's gas contribution in the gross energy balances to the total dirty energy share of Coenen et al. (2023) calculated as $0.071 \times 0.717 = 0.0509$. It is worth nothing that our approach captures well all the uses of gas as an energy source. Eurostat's gross energy balances inform of different primary energy sources in the production and imports of total energy, and do not distinguish whether gas is used for electricity production, heat production, in manufacturing processes or directly in household consumption. Implying the calibration of the share of gas in conjunction with its downstream uses such as electricity and heat production.

6.6 Results

Figure 11 exhibits the response of headline inflation to a gas price shock.[13] We calibrate the shock to imply an increase of 10% in the real price of gas, as in the previous empirical sections. One can observe that the DSGE model performs well in matching the IRFs in Figure 5. We obtain the same qualitative results with some quantitative differences, although the responses always lie well inside the credibility intervals of the BVAR framework.
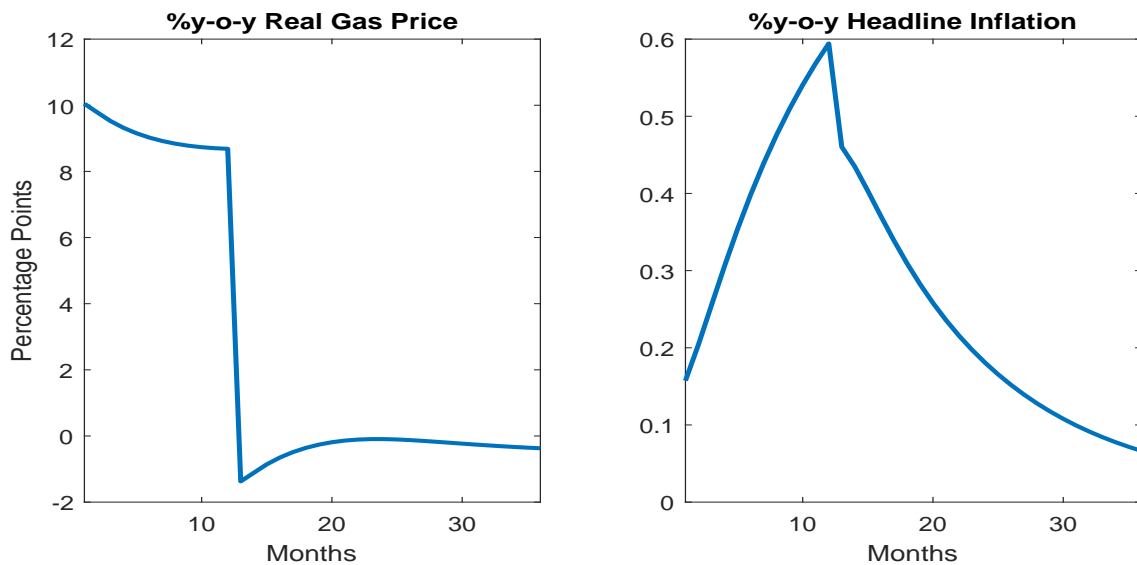

Figure 11: IRFs to a 10% increase in the real gas price

We now turn to the mechanisms through which increases in gas prices might transmits to the real economy. We show that the elasticities of substitution, nominal rigidities, and monetary policy play important roles in transmitting the effects of these shocks.

Regarding the parameters governing the elasticity of substitution between gas and the consumption good excluding gas, and among gas and labor, we observe that by increasing these parameters we get less pronounced responses (see Figure 12). The intuition is the following: if the elasticity of substitution increases, both in the consumption bundle and in production, then, in the aftermath of a gas shock, economic agents can substitute production inputs (as well as

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[13]We calibrate the persistence parameter of gas shocks to 0.95. This is in line with the persistence that we observe in the data.
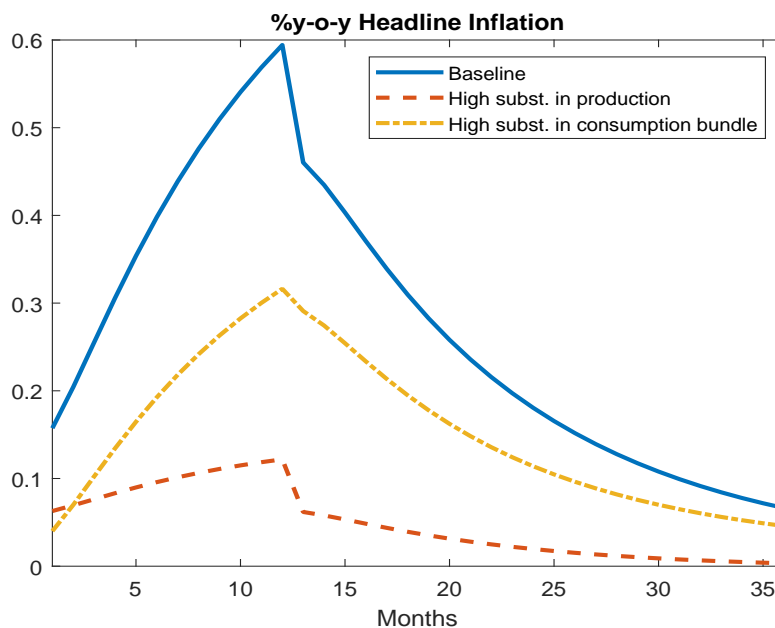
Figure 12: IRFs to a 10% increase in the real gas price: Direct vs. Indirect Effects

gas consumption in the total household's consumption bundle) more easily and therefore hedge against the rising costs associated with the price of gas.

However, one can see in Figure 12 that there is a notable difference depending on which elasticity is increased. The dashed-orange line exhibits the inflation response when we increase only the elasticity of substitution between the inputs in the production of the intermediate goods. In this case, the peak response of inflation is around six times smaller than in the baseline. Instead, if the elasticity of substitution in the consumption basket is increased, the reaction of inflation only halves (dash-dotted-yellow line). This result is consistent with the previous empirical evidence where the impact of gas price shocks were mainly transmitted to headline inflation through indirect effects. As we have previously argued, gas has become a key input for many production processes. On the other hand, gas main direct impact is through home heating, which tends to have a lower HICP weight.

Notice that the different lower inflation responses in both sensitivity analysis mainly arises from nominal rigidities. As seen in Figure 13, the gap between the dashed-orange and dash-dotted-yellow lines disappears under the counterfactual of flexible wages. Consequently, the presence of nominal rigidities is crucial to rationalise the empirical results. The intuition comes

%y-o-y Headline Inflation

Legend:
- Baseline w/o nominal rigidities
- High subst. in production
- High subst. in consumption bundle

x-axis: Months
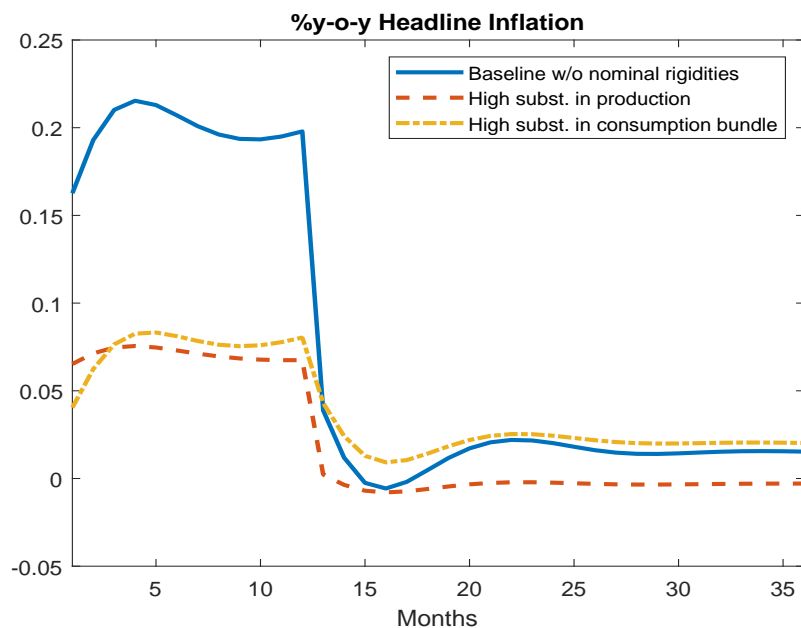
Figure 13: IRFs to a 10% increase in the real gas price: The role of Nominal Rigidities

from the fact that, when wages are rigid, they cannot declining sufficiently in the aftermath of the shock to compensate the large increase in marginal costs, then the pass-through to inflation is more pronounced. Put it differently, if wages were flexible, these could freely adjust to dampen the adverse effects of gas shocks on the economy, as it has been well established in the previous literature (see, e.g., Blanchard and Galí, 2007a).

Finally, Figure 14 shows how monetary policy can influence the pass-through of gas price shocks to inflation. It provides insights into the trade-off between output and inflation that monetary policy faces when the economy is hit by supply shocks. We explore two counterfactual scenarios: i) prioritising stabilizing inflation, when the Taylor rule inflation coefficient is set to 50; and ii) focusing on stabilizing output, implying that the Taylor rule inflation coefficient is set to 1.05. As observed, if the central bank strongly reacts to inflation, prioritising price stability over output, the peak response of headline inflation is one-fourth of what is observed in the benchmark scenario (dash-dotted-yellow line). However, achieving this outcome entails a substantial drop in real GDP, approximately −1.4%, in contrast to the baseline simulation, which exhibits a −0.4% decline. On the other hand, with an accommodating monetary policy the peak in inflation is
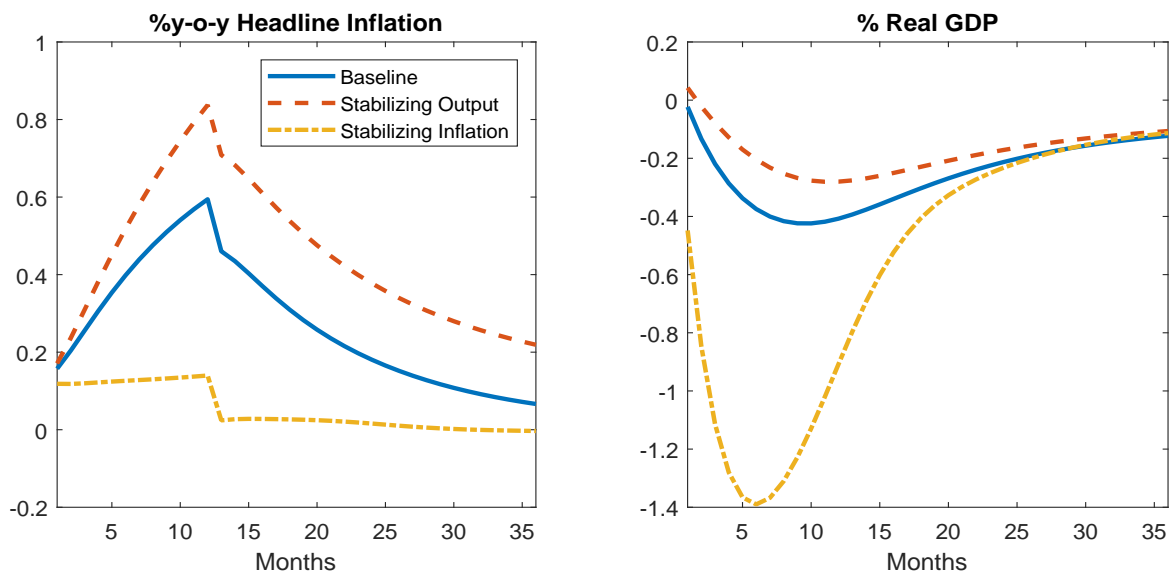
Figure 14: IRFs to a 10% increase in the real gas price: The Role of Monetary Policy

higher, around 0.8% (dashed-orange line), whereas real GDP now experiences a smaller drop compared to the benchmark case.

6.6.1 Contribution of Shocks to Headline Inflation in the euro area

In this section, we explore the structural driving forces that have contributed to the recent inflation dynamics. We use the calibrated parameters discussed in Section 6.5 and estimate our structural shocks using data from January 1997 to December 2022. We consider five key driving forces that are of relevance for inflation: gas and oil shocks, wage mark-up shocks, demand-side shocks and productivity shocks.

The empirical analysis showed that it is essential to control for oil price dynamics when examining historical relationships in the data concerning gas. Thus, with the aim to control for oil shocks in a historical decomposition, we now extend the energy input in the baseline model two include both gas and oil inputs. Specifically, we modify the following equations

$$c_{jt} = \left(\nu_c^{\frac{1}{\mu_c}} \left(c_{e,jt} \right)^{\frac{\mu_c-1}{\mu_c}} + \left(1 - \nu_c \right)^{\frac{1}{\mu_c}} \left(c_{x,jt} \right)^{\frac{\mu_c-1}{\mu_c}} \right)^{\frac{\mu_c}{\mu_c-1}}, \tag{29}$$

where $c_{e,jt}$ now reads as

$$c_{e,jt} = \left(\nu_e^{\frac{1}{\mu_e}} (c_{g,jt})^{\frac{\mu_e-1}{\mu_e}} + (1-\nu_e)^{\frac{1}{\mu_e}} (c_{o,jt})^{\frac{\mu_e-1}{\mu_e}} \right)^{\frac{\mu_e}{\mu_e-1}}, \tag{30}$$

Expenditure minimization yields the demand equations for gas, oil, total energy, and the consumption good excluding total energy

$$c_{x,jt} = (1-\nu_c) \left(\frac{p_{x,t}}{p_t} \right)^{-\mu_c} c_{jt}, \qquad\qquad c_{e,jt} = \nu_c \left(\frac{p_{e,t}}{p_t} \right)^{-\mu_c} c_{jt}, \tag{31}$$

$$c_{g,jt} = \nu_e \left(\frac{p_{g,t}}{p_{e,t}} \right)^{-\mu_e} c_{e,jt}, \qquad\qquad c_{o,jt} = (1-\nu_e) \left(\frac{p_{o,t}}{p_{e,t}} \right)^{-\mu_e} c_{e,jt}, \tag{32}$$

The aggregate (headline) price index is now defined as

$$p_t = \left(\nu_c p_{e,t}^{1-\mu_c} + (1-\nu_c) p_{x,t}^{1-\mu_c} \right)^{\frac{1}{1-\mu_c}}. \tag{33}$$

with

$$p_{e,t} = \left(\nu_e p_{g,t}^{1-\mu_e} + (1-\nu_e) p_{o,t}^{1-\mu_e} \right)^{\frac{1}{1-\mu_e}}. \tag{34}$$

Adding energy inputs requires redefining the values of the elasticities of substitution and the quasi-shares:

- $\nu_c = 0.031$. In order to match a share of 0.0313 (0.57×0.055). Where 57% reflects the sum of the natural gas and oil shares in the gross energy balances, 22% and 35%, respectively, according to Eurostat's 2019 energy statistics.

- $\nu_e = 0.39$ for gas and $(1-\nu_e) = 0.61$ for oil, reflecting the respective shares in the gross energy balances of both inputs.

- $\mu_e = 1.1$ (imperfect substitution).

- $\mu_c = 0.4$ (low substitution).

Intermediate good firms now use the following technology

$$y_{it} = z_t \left(\nu_y^{\frac{1}{\mu_y}} (e_{it})^{\frac{\mu_y-1}{\mu_y}} + (1-\nu_y)^{\frac{1}{\mu_y}} (l_{it}^d)^{\frac{\mu_y-1}{\mu_y}} \right)^{\frac{\mu_y}{\mu_y-1}}, \tag{35}$$

with

$$e_{it} = \left(\nu_{ey}^{\frac{1}{\mu_{ey}}} (e_{g,it})^{\frac{\mu_{ey}-1}{\mu_{ey}}} + (1-\nu_{ey})^{\frac{1}{\mu_{ey}}} (e_{o,it})^{\frac{\mu_{ey}-1}{\mu_{ey}}} \right)^{\frac{\mu_{ey}}{\mu_{ey}-1}}. \tag{36}$$

Again, we have to redefine the following values for the structural parameters:

- In order to match a share of 0.044, now ν_y is equal to 0.049. The total dirty energy share is then calculated as 0.071×0.717, from Coenen et al. (2023), resulting in 0.0509. However, when only accounting for oil and natural gas the share reduces to 0.044.

- $\nu_{ey} = 0.305$ for gas and $(1-\nu_{ey}) = 0.695$ for oil.

- $\mu_{ey} = 1.1$ (imperfect substitution).

- $\mu_y = 0.4$ (low substitution).

Figure 15 illustrates the historical shock decomposition of the year-on-year (y-o-y) headline inflation rate spanning from January 2010 to December 2022.[14] One can notice several noteworthy features. First, the period before the Covid crisis is characterized by a low inflation regime. As can be observed, this is a combination of negative demand shocks and low energy prices. In the absence of these shocks, productivity shocks would have implied significantly larger headline inflation rates. Second, after the Covid lockdown, the high spike in inflation is driven by a combination of energy shocks, where gas shocks have been contributing in a much larger proportion compared to oil shocks, followed by wage mark-up shocks, demand shocks and productivity shocks.

Bearing in mind that a one-to-one comparison is not possible, our historical decomposition is in line with that of Bańbura et al. (2023). They employ a structural VAR model, identified with zero and sign restrictions, in order to account for the drivers of core inflation. They use a rich set of variables in their empirical framework and consider different supply and demand shocks that affected core inflation following the Russia's invasion of Ukraine. Instead, we focused

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[14]We present the historical decomposition from 2010 to 2022 for better illustrative purposes. In Appendix E, we also show the historical shock decomposition of real GDP.
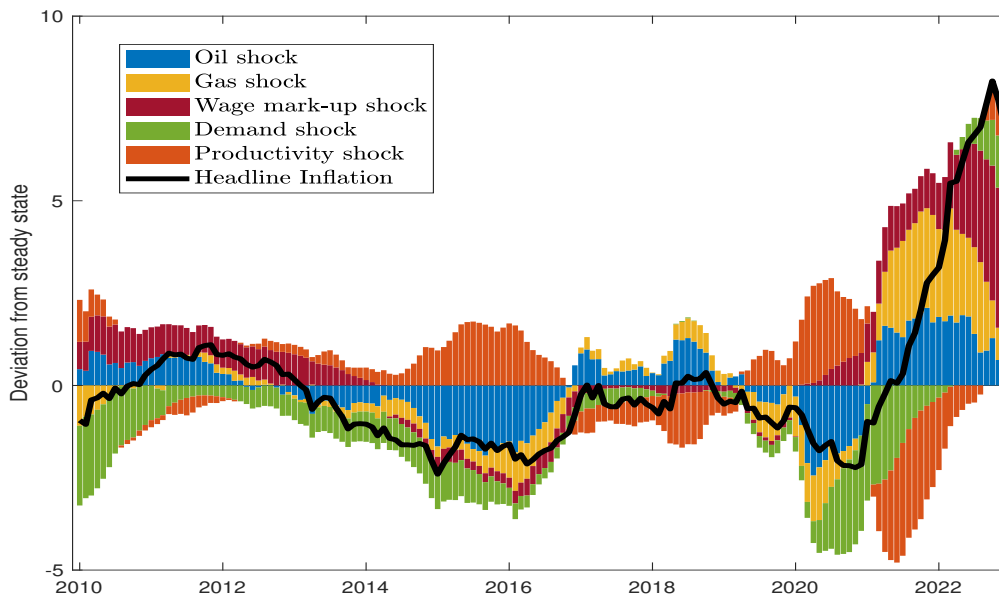
Figure 15: Historical shock decomposition of headline inflation in the euro area

Note: Horizontal axis: months. Vertical axis: percentage-point deviations from the steady state.

empirically on supply driven gas shocks and rely on a micro-founded theoretical model to study the potential transmission channels. Nevertheless, we obtain similar results regarding the relative contribution of energy price shocks.

7 Conclusions

Gas has become an important energy commodity in the euro area and recent developments in the European gas markets increased the interest in studying the connection between unexpected gas price increases and HICP inflation. For instance, for first time in 2023, the European Central Bank included the gas price explicitly as part of the technical assumptions in the macroeconomic projection exercise.

To assess the pass-through of gas prices we estimate a structural BVAR identified with narrative sign restrictions and find that a 10% increase in the gas price leads to a pass-through of roughly 0.1, with persistent inflationary effect beyond one year. Considering that the surge in gas prices between the beginning of 2022 and the peak reached in August 2022 was close to 200%, this would translate into an increase of inflation of roughly 2 percentage points.

To take into account that the institutional environment of the European gas market has changed over the past 20 years, we study the time-variation of the impact of gas price shocks on inflation. Our results suggest that over the last 10 years, and in line with the reduction of oil price indexation in the gas market, the pass-through of unexpected changes in the gas price to HICP inflation has increased in the euro area over time. We show that gas price shocks have gained importance over time relative to oil price shocks but the pass-through of gas price shocks still remains about one third smaller than of oil prices shocks.

Country-level estimates indicate that economies with the highest inflationary effects tend to be more intensive users of energy commodities in their production structures or consumption basket, while the speed of the pass-through also hinges on the regulation of the electricity and gas markets. Our results suggest unexpected gas price changes matter more for German, Spanish and Italian than for French inflation.

Finally, we develop a New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) model augmented with energy, which is a complementary input for intermediate goods firms and a complementary good for households. Our model matches well the Impulse Response Functions (IRFs) of the empirical analysis. We find a key role of the elasticity of substitution between gas and non-energy inputs in transmitting the effects of gas shocks.

We also provide a narrative for the recent contribution of several structural shocks to inflation fluctuations. We find that the recent inflation dynamics are explained by a combination of gas shocks, with a significantly larger contribution compared to oil shocks, followed by wage mark-up shocks, demand shocks and productivity shocks.

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Appendix

A Robustness Checks

This Appendix includes several robustness checks. First, we checked the results are robust to developments in other commodities prices. Excluding exogenous oil shocks from the BVAR introduces a positive bias, although the results are statistically the same (Figure A.1). Controlling for developments in food commodity prices produces also very similar results to the baseline. Second, the results are robust to alternative controls for economic activity and demand side shocks (Figure A.2). Third, the estimated inflationary effects do not capture other suppy-side shocks as proxied by indices of production bottlenecks (A.3). Fourth, we check the stability of the results for different sub-samples (Figures A.4 - A.7).
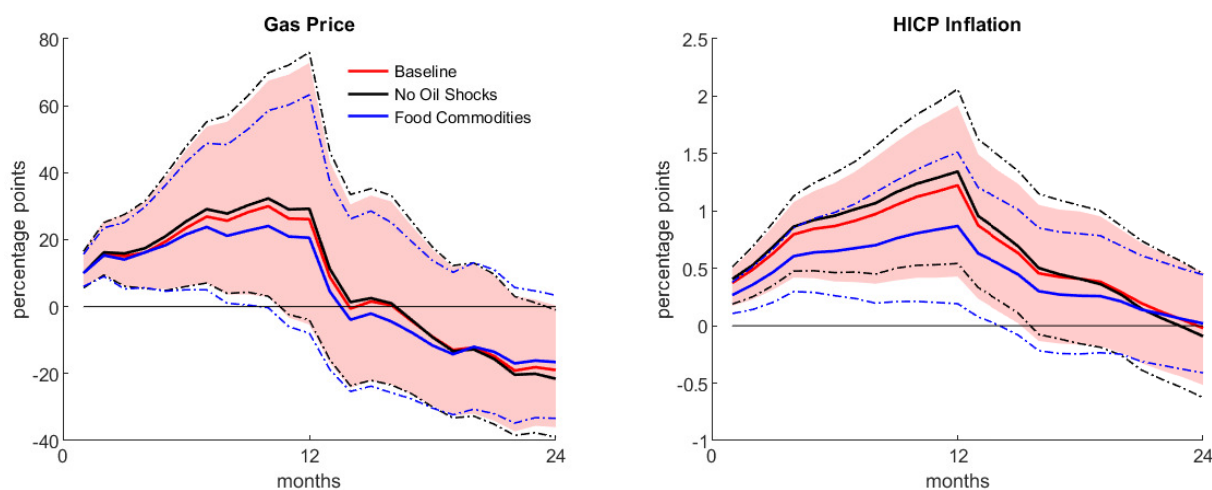
Figure A.1: Other commodities prices

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 1997 m1 (Food commodities 2000 m1) to 2022 m12.
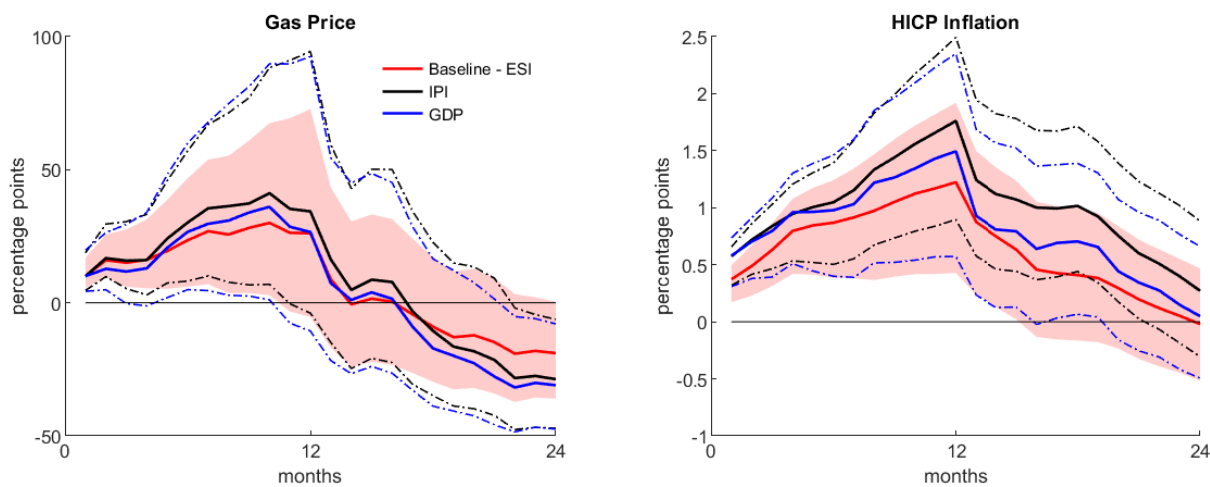
Figure A.2: Other controls for economic activity

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 1997 m1 to 2022 m12.
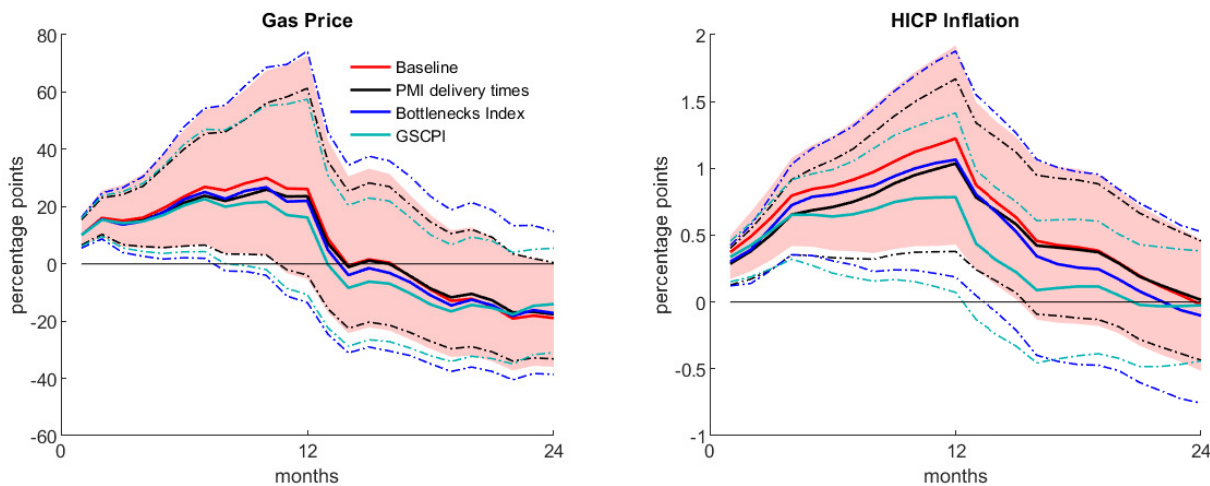

Figure A.3: Additional controls for supply shocks

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 1997 m1 (PMI and GSCPI 1998 m1, Bottlenecks index 2007 m1) to 2022 m12.
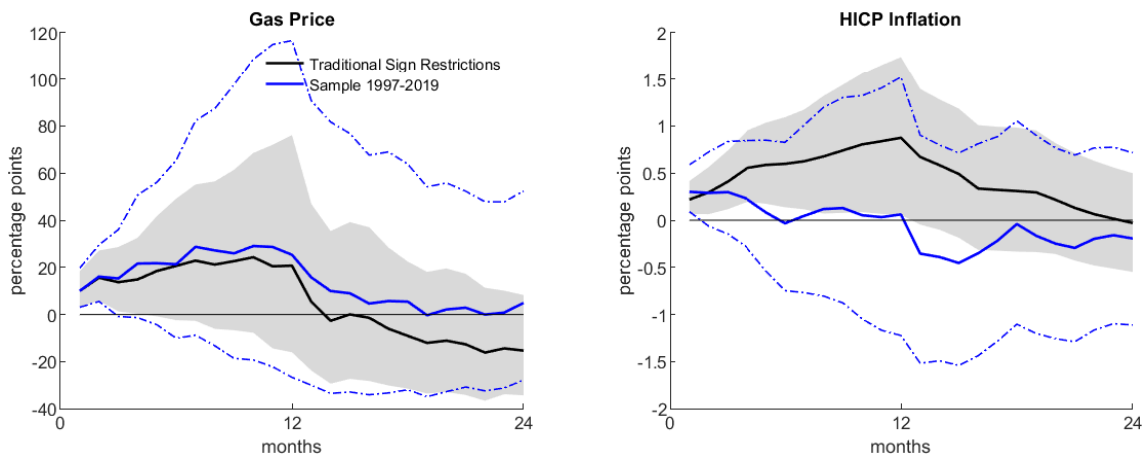
Figure A.4: Sample: 1997 to 2010

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 1997 m1 to 2010m12.
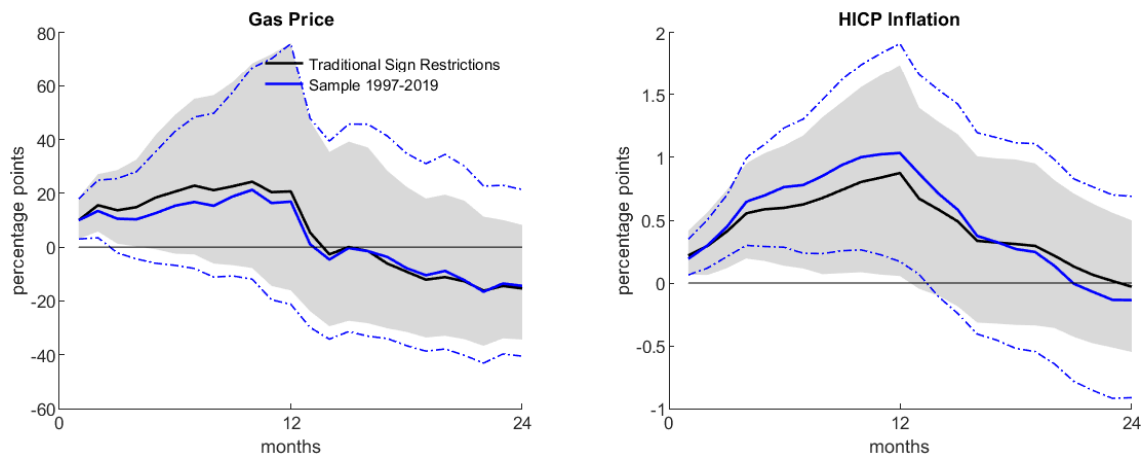
Figure A.5: Sample: 2010 to 2022

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 2010 m1 to 2022 m12.
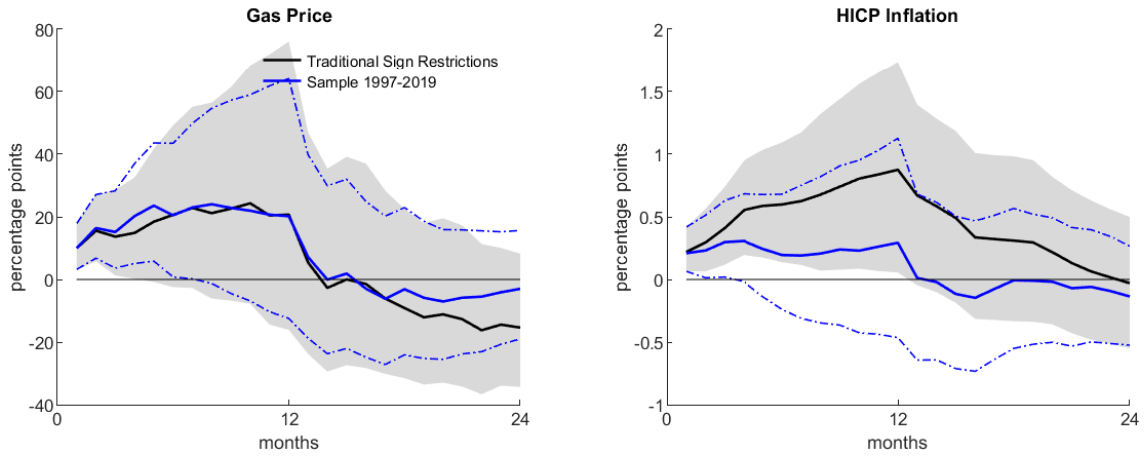
Figure A.6: Sample: 1997 to 2019

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 1997 m1 to 2019m12.
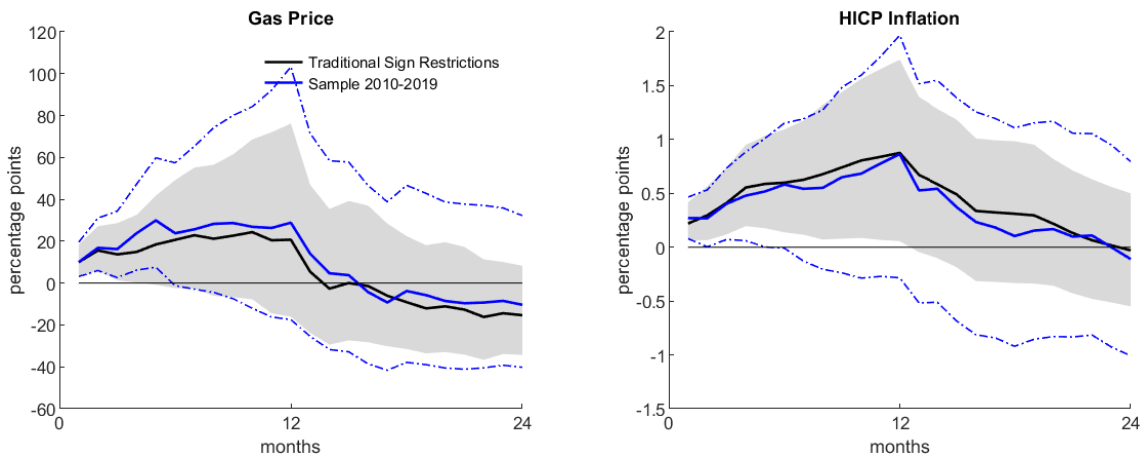
Figure A.7: Sample: 2010 to 2019

Notes: The figure shows median impulse response functions to a 10% increase in the price of gas, together with 68% credibility intervals. Sample 2010 m1 to 2019m12.

B   Month-on-Month Estimates
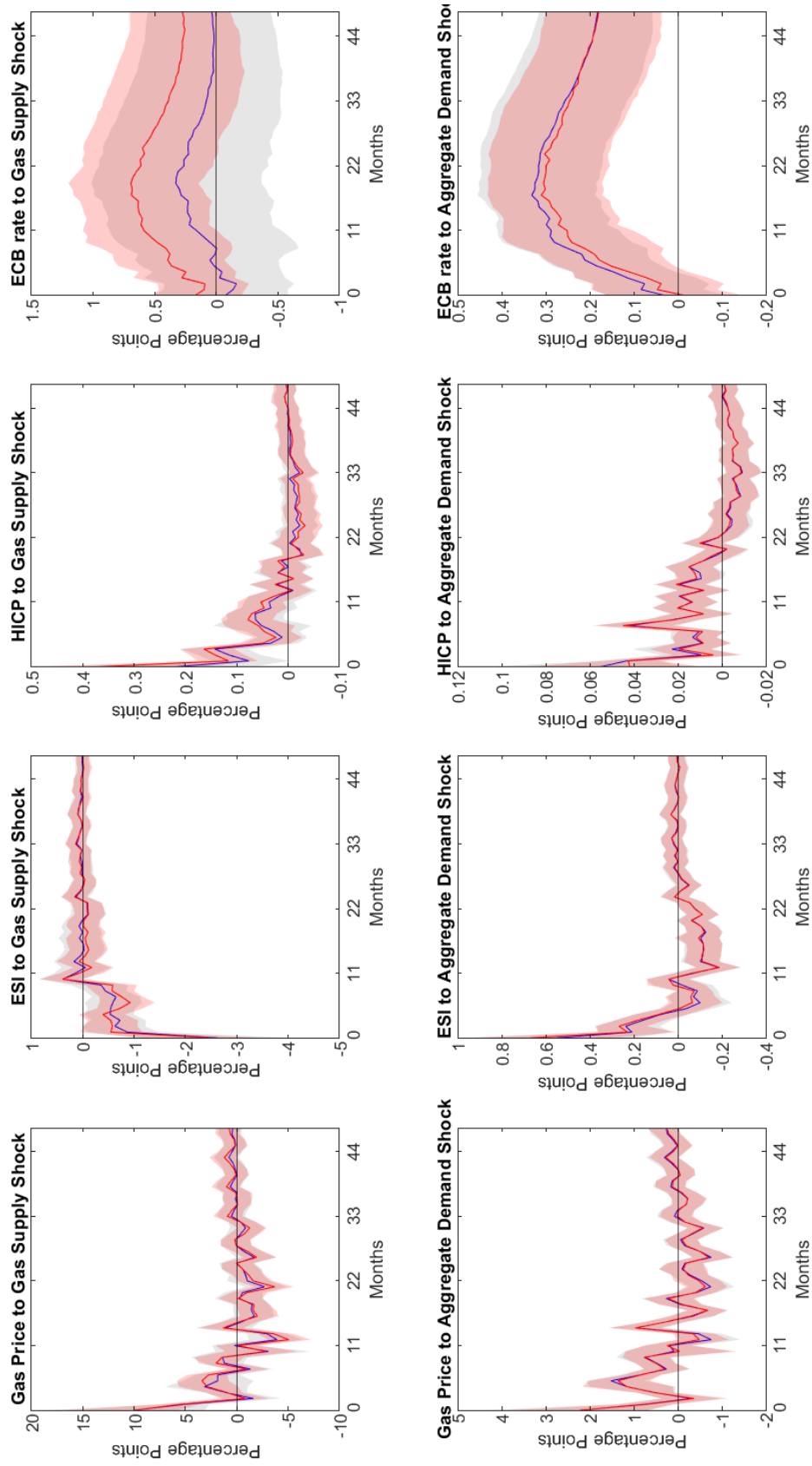
Figure B.8: Baseline BVAR Results - month-on-month growth rates

C   Alternative Narrative Sign Restrictions
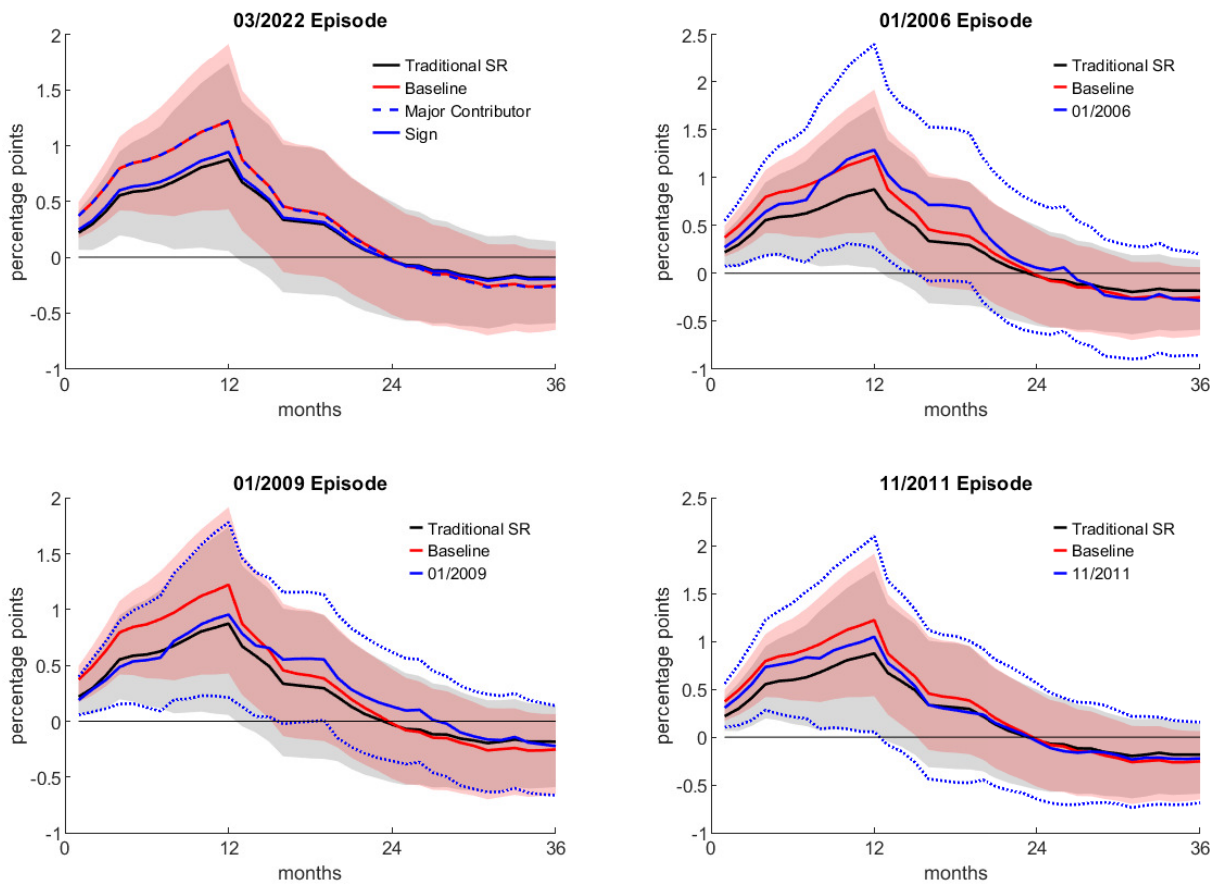
Figure C.9: Gas Prices Pass Through to HICP in the Euro Area for Alternative Narrative Sign Restrictions

Notes: The figure shows annualized median impulse response functions to a 10% increase in the price of gas. 68% credibility intervals. Sample 1997 m1 to 2022 m12.

D   HICP Energy Components Weights
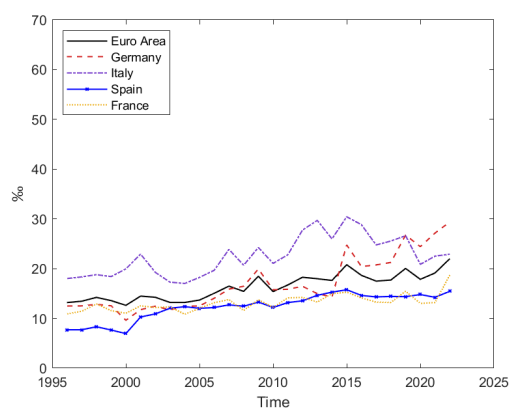
(a) HICP Weight of Gas
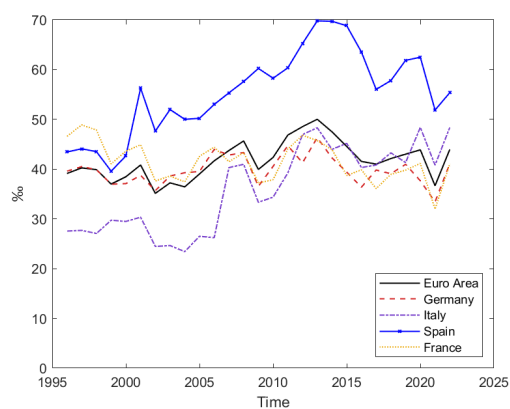
(b) HICP Weight of Fuels for Personal Transport Equipment
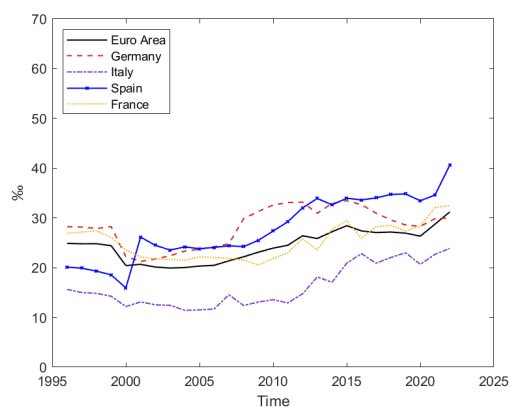
(c) HICP Weight of Electricity

Figure D.1: HICPS Energy Components Weights

E Historical Shock Decomposition of Real GDP Growth
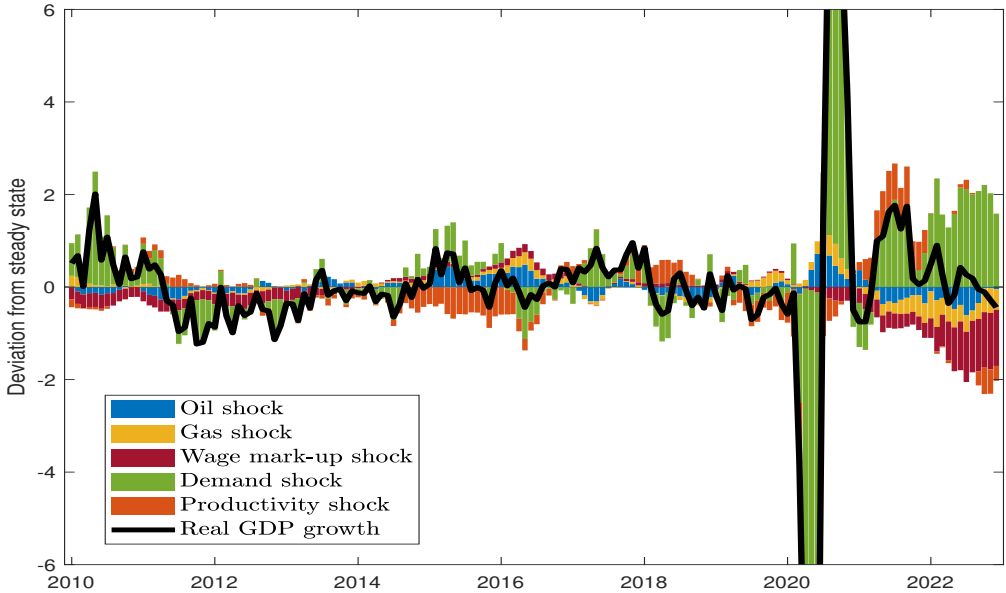
Figure E.1: Historical shock decomposition of real GDP growth in the euro area
Note: Horizontal axis: months. Vertical axis: percentage-point deviations from the steady state.

The historical shock decomposition for real GDP exhibits lower uncertainty from 2010 to 2020. However, from 2020 onward, the contribution of different structural shocks to output dynamics is clearly more uncertain. On the one hand, we observe a positive contribution of aggregate demand shocks, potentially influenced by the reopening of the economies after the Covid lockdowns. At the same time, we note persistent and negative contributions from energy shocks (especially natural gas) and wage mark-up shocks.

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