

US Natural Gas Price Determination: Fundamentals and the Development of Shale

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Abstract: This paper uses a structural vector autoregression (SVAR) to model the US natural gas market. Domestic natural gas production has dramatically increased in the late 2000's as producers implemented improved horizontal drilling and hydraulic fracturing techniques to extract natural gas from shale deposits. This paper applies techniques developed in the crude-oil literature that incorporate time-varying parameters (TVP), which more realistically model a changing market. Results suggest the supply curve associated with aggregate demand shocks, residential demand shocks, and other natural gas market demand shocks has become more elastic during the latter part of the sample. This latter period corresponds to the recent rapid expansion in shale gas production. By contrast, the curvature of the supply curve associated with precautionary inventory demand shocks has remained at a stable level for most of the sample since 2000, and has not changed significantly even with the rapid growth of shale gas production. Furthermore, it appears that in the new era of ample natural gas supply, the demand curve has also become more elastic, partly reflecting greater flexibility in fuel use substitution.

1. Introduction

Natural gas is a critical component of the energy industry in the US. The Energy Information Administration (EIA) estimated that in 2014, about 26.8 trillion cubic feet of natural gas was consumed in the US, which supplied roughly 27% of electricity generation and 19% of all residential heating. In commercial manufacturing, natural gas is widely used as both a primary fuel source and raw material. For instance, as a major input in the production of nitrogenous fertilizers such as urea and ammonia, the cost of natural gas typically accounts for 40% to 70% of the fertilizer price. On a macro-scale, natural gas is of significant importance as well, as economic development, employment, and industrial output are all closely tied to energy prices. Natural gas is seen as a way to both reduce foreign oil dependence as well as a 'bridge' fuel to a lower-carbon future. Bistline (2014) explains how future climate uncertainties could significantly disrupt both supply and demand of natural gas. Its relevance in almost every aspect of the economy highlights the critical importance of understanding the driving factors behind the supply and demand of natural gas in the US, shedding light on better understand these potential disruptions.

Much change has occurred to the natural gas market since 2007 with the popularization of the combined use of horizontal drilling and hydraulic fracturing techniques. Although these techniques are not new, a long history of private and government investment led to producers in the Barnett area to combine them in a cost-effective manner (see Trembath, et al., 2012). This triggered a major increase in the production of natural gas in the US. In 2006 shale production represented less than 5% of US dry natural gas production, while in 2013 it was 47% (EIA, 2015). With this dramatic rise, the EIA currently predicts that the US will be a net exporter of natural gas in 2017 (EIA, 2015).

Various studies have attempted to understand the supply-and-demand structure in the natural gas market. One stream of literature focuses on the regional relationship in the natural gas markets. Mohammadi (2011) demonstrates that while prices of oil and coal are determined globally and by long term contracts respectively, natural gas prices are determined regionally. This conclusion is consistent with the extensive effort devoted by economists aiming to understand the pricing relationship among regional natural gas markets. For instance, Olsen, et al. (2014) find cointegration between North

American natural gas markets, though the degree of integration varies depending on their locations. Siliverstovs, et al. (2005) find integration within European and US markets, but not between them. A similar conclusion is reached in Renou-Maissant (2012), who also finds cointegration within the European market. Park, et al. (2007) find non-linear adjustments between seven US markets, driven by location, season, and inventories.

A second stream of literature investigating the natural gas market focuses on the pricing relationship between natural gas and crude oil. For many applications, natural gas and crude oil are substitutes. Although the potential for fuel-switching exists, it can be limited in the short-run by technological constraints (Qin, et al., 2010). There has been significant research in the integration of the two markets. While general consensus is that the two markets are cointegrated, recent work has suggested that regional variation in natural gas markets, direction of crude oil supply movements, and exchange rates help further explain the relationship (see Atil, et al. (2014), Brigida (2014), Hartley and Medlock (2014), Ramberg and Parsons (2012)). For a more detailed discussion of the interaction between crude oil and natural gas markets, see Ji, et al. (2014).

A third stream of literature attempts to disentangle the supply and demand shocks in driving natural gas prices using various structural or reduced-form models. Nick and Thoenes (2014) analyze the German natural gas market, and the impact that three significant supply shocks have had on prices. Woo et al (2014) find that end-use prices of natural gas generally reflect cost of wholesale. Mu (2007) highlights the importance of weather on natural gas prices, as demand is influenced both directly by cold weather for heating as well as indirectly by warm weather through increased electricity demand. Given that the market for natural gas has been recently shown to evolve, studies have also attempted to include structural breaks when modeling natural gas prices. Qin, et al. (2010) find that the importance of fundamentals change depending on market regime, playing a larger role in bull markets. They further contend that natural gas price behavior is far more complicated than that predicated by fundamentals, and that volatility unexplained by fundamentals plays an essential role in natural gas price behavior.

While results from these studies are informative, none of them considered the effects of booming shale gas production on the natural gas market. With the incredible increase in shale gas production, it is likely that the relative importance of demand and supply shocks in natural gas price dynamics has changed significantly. One exception in the literature is the paper by Arora (2014) that uses a structural model to estimate the supply and demand elasticity of US natural gas prices. He finds that both the short- and long-run natural gas supply becomes more elastic when the effects of a shale development are included, while the demand becomes less responsive to prices after accounting for shale production (post-2007). Another exception is Wakamatsu and Aruga (2013), who model the US and Japanese natural gas markets using a one-time structural break from the shale boom.

Our analysis is closely related to a third stream of literature, focusing on the time-variation and structural breaks in the natural gas supply and demand dynamics. This work is of particular importance given the recent expansion of shale production that took off in 2006 and the large volatility that has existed in the natural gas market since then. The studies of Wakamatsu and Aruga (2013) and Arora (2014) both impose a one-time structural break to account for the shale gas boom. However, as suggested by Primiceri (2005), imposing a one-time structural break might not be an appropriate way of dealing with time variations in the parameter estimates as aggregation in the private sector can smooth changes. Further, increased heteroskedasticity from exogenous shocks are likely, as the market for natural gas is much more volatile today than the past. Overlooking this heteroskedasticity could generate spurious inference from the estimated coefficients (Cogley and Sargent, 2005).

The purpose of this paper is to disentangle supply and demand shocks on US natural gas prices and investigate how these effects have changed over time. Whereas most previous studies have only used reduced-form analyses, this paper will use a structural vector autoregressive model (SVAR) to examine price dynamics under a theoretically-driven structural framework. The SVAR model has been widely applied in recent literature to evaluate price dynamics in the crude oil market (e.g., Kilian, 2009, Kilian and Murphy, 2014). Unlike Wakamatsu and Aruga (2013) and Arora (2014), who both impose a one-time arbitrary structural break, we generate a time-varying parameter model that allows the data to determine

when and how any changes may have occurred. To this end, we construct a long sample period that not only includes both pre-and post- shale boom (1976-2014), but also uses a new identification strategy recently developed by Baumeister and Peersman (2013), which allows for drifting coefficients and stochastic volatility in the SVAR model. Estimation results suggest that the short-run supply curve associated with aggregate demand shocks, residential demand shocks, and other natural gas market shocks becomes more elastic after the shale boom, a conclusion that is consistent with Arora (2014). However, we find that the demand curve become more elastic as well, which is in contrast to the conclusion of Arora (2014).

The remainder of this paper is organized as follows. The next section describes the econometric procedure used in the analysis. Section 3 presents data used in this paper. Section 4 describes results from an initial recursive model of the natural gas market, as well as the results from a time-varying model that allows for stochastic volatility. Section 5 concludes the paper and discusses possible policy implications.

2. Econometric Procedure

Consider the following vector autoregression (VAR) model with a lag length of p :

$$(1) \quad y_t = C_t + B_{1,t} y_{t-1} + \dots + B_{p,t} y_{t-p} + u_t = X_t' \theta_t + u_t$$

where y_t is a $[5 \times 1]$ vector of endogenous variables consisting of the total physical availability of natural gas in the US (Q_t), the demand of natural gas from industrial use (I_t), the demand of natural gas from residential use (R_t), the precautionary inventory demand (V_t), and the real price of natural gas (P_t). The term u_t is a $[5 \times 1]$ vector of residuals that are assumed to be independently and identically distributed (*iid*). C_t is $[5 \times 1]$ vector of intercepts and $B_{1,t}, \dots, B_{p,t}$ are $[5 \times 5]$ matrices of coefficients on the lags of the endogenous variables, all of which need to be estimated. The right-hand side of equation (1) can be simplified as $X_t' \theta_t + u_t$, where θ_t consists of both intercept C_t and coefficients on the lags of the endogenous variables $B_{1,t}, \dots, B_{p,t}$. In essence, equation (1) imposes a recursive structure of the

endogenous variables in the VAR system such that the preceding variable affects the following variable at contemporaneous time, but not vice versa.

Three problems exist with the reduced-form VAR(p) structure in equation (1). First, all parameters are assumed to be constant throughout the sample period in a recursive VAR. This assumption is unlikely to hold, as changes to various aspects of the economy could potentially influence supply and demand dynamics in the natural gas market. Shale production, in particular, has fundamentally revolutionized the natural gas market since 2006. Second, the error terms in the recursive VAR system are assumed to be independently and identically distributed, which may not hold in practice. Heteroskedasticity is likely to be of concern when dealing with real data, particularly when it comes to the natural gas market in the US, which has exhibited rather volatile prices over the past decades. Finally, since shocks from the reduced-form VAR are not structural shocks, we cannot use the estimation results to infer the response of natural gas price and supply to various structural shocks. In other words, we are still left with the task of identifying structural shocks after the reduced-form VAR for innovation accounting.

2.1 Bayesian VAR with time-varying parameters and stochastic volatility

To resolve the first two problems, we follow Baumeister and Peersman (2013) and consider a Bayesian VAR model with time-varying parameters and stochastic volatility. Specifically, instead of assuming constant parameters throughout the sample period in equation (1), we let both the intercept C_t and coefficient matrices $B_{1,t}, \dots, B_{p,t}$ to vary in time (i.e., θ_t is allowed to be time-varying). Further, the error term u_t is assumed to be normally distributed with mean zero and a time-varying covariance matrix Ω_t :

$$(2) \quad \Omega_t = A_t^{-1} H_t (A_t^{-1})' ,$$

where A_t is a 5×5 lower triangular matrix that models the contemporaneous correlations among the five endogenous variables and H_t is a 5×5 diagonal matrix that models the stochastic volatility in the residuals.

$$(3) \quad A_t = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \alpha_{21,t} & 1 & 0 & 0 & 0 \\ \alpha_{31,t} & \alpha_{32,t} & 1 & 0 & 0 \\ \alpha_{41,t} & \alpha_{42,t} & \alpha_{43,t} & 1 & 0 \\ \alpha_{51,t} & \alpha_{52,t} & \alpha_{53,t} & \alpha_{54,t} & 1 \end{bmatrix} \quad H_t = \begin{bmatrix} h_{1,t} & 0 & 0 & 0 & 0 \\ 0 & h_{2,t} & 0 & 0 & 0 \\ 0 & 0 & h_{3,t} & 0 & 0 \\ 0 & 0 & 0 & h_{4,t} & 0 \\ 0 & 0 & 0 & 0 & h_{5,t} \end{bmatrix}.$$

The specification above allows for time variation in both coefficient estimates and the variance-covariance matrix of the residuals. The time-varying coefficient estimates can capture possible nonlinearities and time variation in the lag structure of the endogenous variables, while time variation in the variance-covariance matrix enables us to model not only the heteroskedasticity in the residuals but also changes in the contemporaneous relationships among the five endogenous variables. These two features combined allow the data to determine whether the time variation in the structural relationship among endogenous variables are due to changes in the size of the shock and its contemporaneous impact or the lag structure. Now let $\alpha_t = [\alpha_{21,t}, \alpha_{31,t}, \alpha_{32,t}, \dots, \alpha_{53,t}, \alpha_{54,t}]'$ be a vector of elements from A_t that are both nonzero and non-unity; and $h_t = [h_{1,t}, h_{2,t}, h_{3,t}, h_{4,t}, h_{5,t}]'$ be the diagonal elements of H_t . Following Primiceri (2005) and Baumeister and Peersman (2013), we assume that both the parameters in equation (1), θ_t and the non-zero and non-one elements from A_t , α_t evolve as random walks without drift, and that each element of the vector of volatility h_t follows a geometric random walk that is independent from each other. The three time-varying processes that determines the VAR system can therefore be written as:

$$(4) \quad \theta_t = \theta_{t-1} + v_t, \quad v_t \sim N(0, Q)$$

$$(5) \quad \alpha_t = \alpha_{t-1} + \zeta_t, \quad \zeta_t \sim N(0, S)$$

$$(6) \quad \ln h_{i,t} = \ln h_{i,t-1} + \sigma_i \eta_{i,t}, \quad \eta_t \sim N(0, 1)$$

where the error terms of the above three equations are independent of each other. Further, a block-diagonal structure is imposed for S which equals to the variance of the error term ζ_t , as in equation (7)

$$(7) \quad S \equiv \text{Var}(\zeta_t) = \text{Var} \left(\begin{bmatrix} \zeta_{21,t} \\ \zeta_{21,t} \\ \zeta_{21,t} \\ \vdots \\ \zeta_{21,t} \end{bmatrix} \right) = \begin{bmatrix} S_1 & \mathbf{0}_{1 \times 1} & \mathbf{0}_{1 \times 2} & \mathbf{0}_{1 \times 3} \\ \mathbf{0}_{2 \times 1} & S_2 & \mathbf{0}_{2 \times 3} & \mathbf{0}_{2 \times 4} \\ \mathbf{0}_{3 \times 1} & \mathbf{0}_{3 \times 2} & S_3 & \mathbf{0}_{3 \times 4} \\ \mathbf{0}_{4 \times 1} & \mathbf{0}_{4 \times 2} & \mathbf{0}_{4 \times 3} & S_4 \end{bmatrix}$$

where $S_1 \equiv \text{Var}(\zeta_{21,t})$, $S_2 \equiv \text{Var}([\zeta_{31,t}, \zeta_{32,t}]')$, $S_3 \equiv \text{Var}([\zeta_{41,t}, \zeta_{42,t}, \zeta_{43,t}]')$, $S_3 \equiv \text{Var}([\zeta_{41,t}, \zeta_{42,t}, \zeta_{43,t}]')$, and $S_4 \equiv \text{Var}([\zeta_{51,t}, \zeta_{52,t}, \zeta_{53,t}, \zeta_{54,t}]')$. This implies that the nonzero and non-unity elements in matrix A_t in each row evolve independently from elements of other rows. Since A_t are the parameters that model the contemporaneous correlations among the five endogenous variables, imposing a block-diagonal structure on S essentially implies that the shocks of the contemporaneous correlations are correlated within, but not across, equations.

Following Baumeister and Peersman (2013), the VAR model with time-varying parameters and stochastic volatility can be estimated using the Bayesian methods of Kim and Nelson (1999). Details of the estimation procedure can be found in Baumeister and Peersman (2013).

2.2 Identifying structural shocks with sign restrictions

The third problem associated with the recursive VAR system as in equation (1) is that the response of endogenous variables y_t to the error term u_t are in general not structural shocks. By construction, a structural VAR system requires the recovery of parameters in the matrix that specifies the contemporaneous relationship among endogenous variables. Kilian (2011) summarizes various approaches that can be used to identify structural shocks, including institutional knowledge, economic theory, other extraneous constraints on the model responses, sign restrictions, etc.

Following Arora (2014), we impose the following sign restrictions to identify the structural shocks (table 1):

Table 1. Sign Restrictions

	Q	P	I	R	V
Natural gas supply shock	+	-	+	+	
Residual shock		+			
Industrial demand shock	+	+	+		
Residential demand shock	+	+		+	-
Precautionary inventory demand shock	+	+	-		+

Notes: Q is the total available natural gas supply in the US, P is the price of natural gas, I is the industrial demand, R is the residential demand, and V is the precautionary inventory demand. All shocks are assumed to be positive.

A positive shock in the available natural gas supply is likely to induce a negative response in natural gas prices. A readily available example is the recent expansion of shale gas production that has shifted the natural gas supply curve to the right, and moving the real price of natural gas to the opposite direction. The response of natural gas price to positive supply shocks is thus restricted to be non-positive. On the other hand, positive supply shocks are associated with increased supply of natural gas in the market, as well as increased residential and industrial demand. We do not impose any sign restriction for the impact of supply shocks on the precautionary demand of inventory.

A positive shock on industrial demand driven by the aggregate economic activity in the US is assumed to increase the total supply of natural gas in the market, the real price of natural gas, as well as the industrial demand. No sign restrictions are placed on the response of residential demand or precautionary inventory demand to a positive shock on industrial demand. Similarly, a positive shock on residential demand of natural gas is expected to induce a positive response at contemporaneous time on the total supply of natural gas, the real price of natural gas, and the residential demand. It should also result in a negative response to the precautionary demand as inventory is likely to decline when more natural gas is used for residential consumption.

For storable commodities, the level of inventory available in the system partly reflects how quickly firms can respond to unexpected demand and supply shocks. The theory of storage (e.g., Brennan,

1958, Kaldor, 1939, Working, 1949, Working, 1948) states that firms earn a convenience yield by holding inventory at hand, which prevents disruptions in the flow of goods and services, and in turn reduces production uncertainty. A number of studies have investigated the relationship between prices and inventories (e.g., Miranda and Fackler, 2004, Wright, 2011, Wright and Williams, 1991), showing that inventories can help absorb price fluctuations. During periods of high prices, storage holders can sell out inventories that incur high opportunity costs, effectively lowering price levels. On the other hand, storage holders can replenish inventories when prices are low, helping again to buffer prices. The implication is that a positive unanticipated shock on precautionary demand of inventory will induce a positive response in the real price of natural gas, as there is a greater demand of natural gas during the current period. Supply and inventory are also assumed to increase after a positive shock on precautionary demand of inventory, while the response of industrial demand driven by aggregate economic activity is assumed to be negative. The latter sign restriction implies that the demand for natural gas used in industrial production is likely to decline following a positive shock on the speculative demand.

Finally, we assume that a positive residual shock will induce a positive response of real natural gas prices. We do not, however, impose any sign restrictions on the response of other variables.

3. Data

The data used in this study follows Arora (2014) closely. Natural gas prices are from the Producer Price Index published by the Bureau of Labor Statistics, and October 1982 is used as the baseline.¹ To model the supply of natural gas, we use the marketed US natural gas production published by the EIA.² In the process of natural gas production, marketed natural gas refers to the gas produced before associated liquids such as propane and butane are extracted. The definition should be distinguished from dry natural

¹ Under the Fuels and related products and power group on the Bureau of Labor Statistics website, the item Natural gas is used. See <http://data.bls.gov/timeseries/WPU0531>

² The marketed US natural gas production data is published by the EIA in monthly intervals in millions of cubic feet. See <http://www.eia.gov/dnav/ng/hist/n9010us2m.htm>

gas, which refers to the gas when these liquids are removed. Here the marketed amount is used rather than the gross amount as a measure of natural gas supply so that any gas consumed either in extraction or processing is ignored.

We model the demand of natural gas using three variables, total demand of natural gas from industrial production, residential demand, and precautionary inventory demand of natural gas. Total industrial production measures the demand for natural gas driven by changes in US economic activity, and thus provide a measure of the business cycle driven by the aggregate economic activity. As such, shocks to the industrial demand of natural gas may be interpreted as the aggregate economic activity shock. The Federal Reserve publishes an index of industrial production and capacity utilization (G.17), which is used as a proxy for the industrial demand of natural gas in the US.³ A second dimension of natural gas demand comes from the residential side. Residential demand accounts for a substantial fraction of the natural gas in the US. Using data from EIA, it is estimated that in 2013 over 20 percent of the total natural gas use in the US was for residential purposes. Data on residential natural gas demand are obtained from the EIA as well.⁴ Lastly, we use the EIA natural gas inventory data as a measure of precautionary inventory demand.⁵ For storable commodities like natural gas, inventory reflects expectation of future supply and demand and storage expands when the expected future price exceeds the current period price plus storage cost and convenience yield. Kilian and Murphy further argue that the inventory demand may also be interpreted as speculative demand as speculators tend to put more commodity into storage if they expect a substantial rise in future prices.

The data period begins on January 1976 and ends on August 2014, and is sampled at a monthly frequency. In the US, the federal government has regulated the natural gas market for many years. The Natural Gas Act of 1938 gave the Federal Power Commission the authority to regulate gas rates. This

³ Available at <http://www.federalreserve.gov/releases/g17/download.htm>

⁴ See <http://www.eia.gov/totalenergy/data/monthly/#naturalgas>

⁵ See <http://www.eia.gov/naturalgas/data.cfm#storage>

continued until passage of the Natural Gas Policy Act (NGPA) of 1978, which created the Federal Energy Regulatory Commission (FERC). The NGPA was the first effort to deregulate the natural gas market, but Congress passing the Natural Gas Wellhead Decontrol Act was the main driver. All price regulations were eliminated by January 1993. Combined with FERC order 636, mandating the unbundling of pipeline services (previously pipelines were able to combine sales and transportation), this act of Congress effectively ended all government control over the market.

Given the history of federal regulation of the natural gas market, we use data from 1976 to 1992 for burn-in iterations in the Bayesian VAR model with time-varying parameters and stochastic volatility as outlined in section two, and use the data from January 1993 to August 2014 for time series analyses.

Figure 1 plots the five variables used in the analysis. As can be seen, the supply of natural gas was relatively stable between 1990 and 2005, after which the production quickly took off, growing more than 40 percent from 2006 to 2014. This rapid growth largely reflects the expansion of shale gas production due to the popularization of the combined use of horizontal drilling and hydraulic fracturing techniques. The natural gas producer price index (panel (b) of figure 1) shows that much variation in natural gas prices has occurred since 1993, when all price regulations on natural gas in the US were eliminated. Further, the expansion of shale gas production has resulted in a rather low level of natural gas prices. Panel (c) of figure 1 shows the US industrial production index. With one setback in 2002 and another in 2008, the industrial production index, reflecting the aggregate economic activity in the US, has been growing at a rather steady rate. Both residential demand (panel (d) of figure 1) and precautionary inventory demand (panel (e) of figure 1) show a significant degree of seasonality, partly due to the fact that natural gas is used primary in winter seasons for space heating in residential homes.

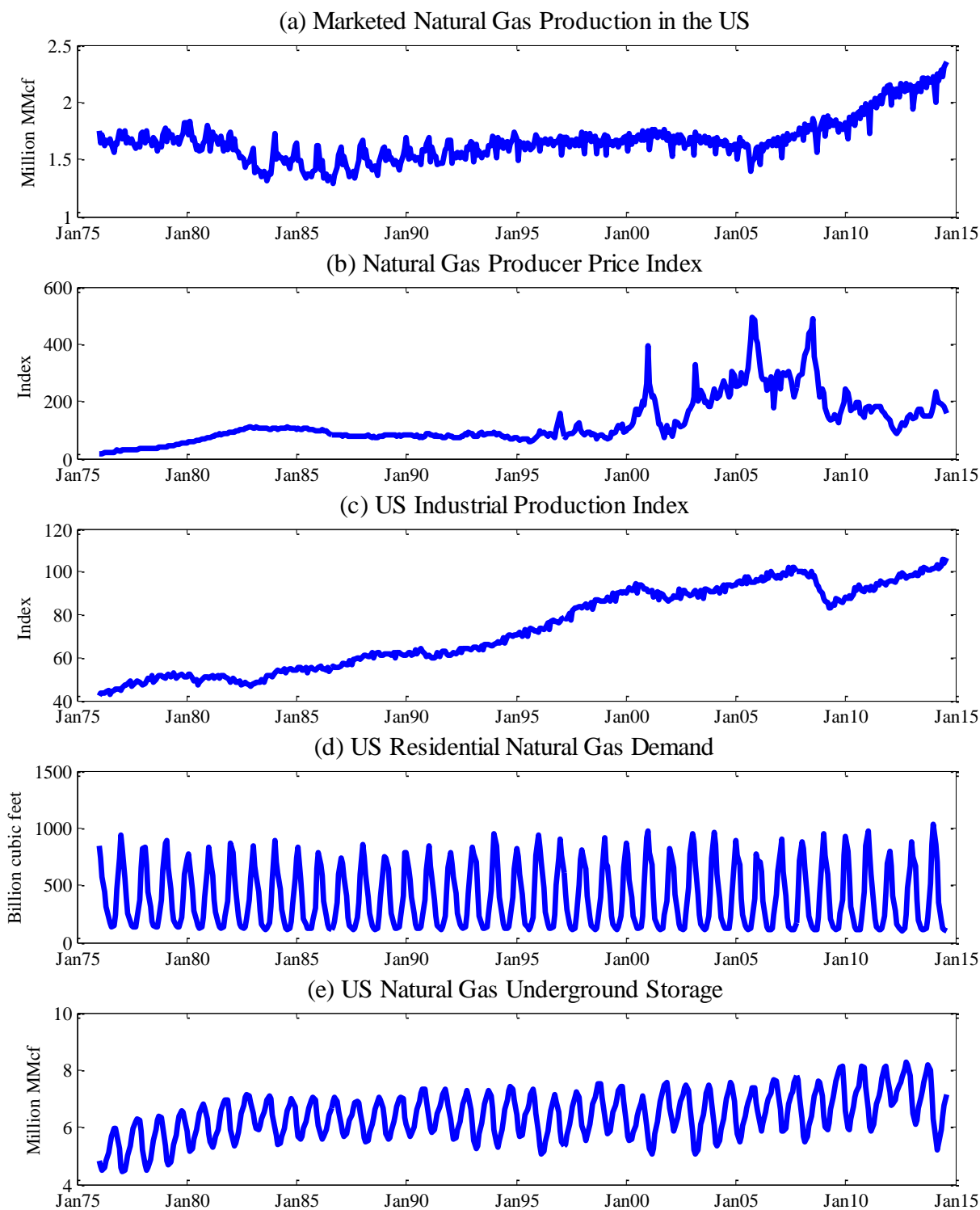


Figure 1. US Natural Gas Supply and Demand, January 1976 – August 2014

Table 2 reports the results from augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests both with and without a trend for the five variables used in the analysis. All variables have been transformed to logarithmic form. The lag length of the ADF test is selected using the Akaike information criterion (AIC). As can be seen, with the exception of industrial demand, all of the other four variables appear to be non-stationary in levels using the ADF test both with and without a trend. Using the PP test without a trend, the industrial demand and inventory demand are considered to be stationary. In addition to these two variables, the real price of natural gas is also considered to be stationary when using the PP test with a trend. All five variables appear to be stationary in first differences.

Table 2. Unit Root Test Results

	-----In Logarithmic Levels-----				--First Diff--	
	<u>No Trend</u>		<u>With Trend</u>			
	ADF	PP	ADF	PP	ADF	
Supply	-2.21	-2.32	-2.44	-2.72	-7.04	***
Real Price	1.15	-2.34	-0.21	-5.98	-6.65	***
Industrial Demand	-14.86 ***	-6.84 ***	-12.29 ***	-6.85 ***	-17.50	***
Residential Demand	-2.20	-2.06	-2.13	-2.27	-4.47	***
Inventory Demand	-1.53	-6.05 ***	-1.77	-6.42 ***	-11.95	***

Notes: ADF refers to augmented Dickey-Fuller test, PP refers to Phillips-Perron test. One, two, and three asterisks refers to a significance level at 10, 5, and 1 percent, respectively.

Given the mixed results from the unit root test for the five variables in levels, we consider their first differences, which essentially measure the monthly growth rate of each variable.

4. Empirical Results

In this section, we report results from the VAR analysis. First, we use the recursive structure to obtain the constant-coefficient point estimates, and then discuss the results of the Bayesian VAR model with time-varying parameters and stochastic volatility. A comparison between the results from these two models highlights the importance of accounting for time-variation, stochastic volatility, and sign restrictions when modeling natural gas prices.

4.1 Recursive VAR results

The key assumption underlying a recursive VAR model is that no variable is affected by the variable that follows at contemporaneous time. We impose the recursive structure as in equation (8):

$$(8) \quad u_t \equiv \begin{pmatrix} u_t^Q \\ u_t^I \\ u_t^R \\ u_t^V \\ u_t^P \end{pmatrix} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} \times \begin{pmatrix} \varepsilon_t^{\text{natural gas supply shock}} \\ \varepsilon_t^{\text{aggregate demand shock}} \\ \varepsilon_t^{\text{residential demand shock}} \\ \varepsilon_t^{\text{precautionary demand shock}} \\ \varepsilon_t^{\text{residual shock}} \end{pmatrix}$$

where u_t are the residuals from the reduced-form model as in equation (1) associated with each individual equation, Q , I , R , V , and P are the total supply of natural gas, industrial demand, residential demand, inventory demand, and real natural gas prices, respectively. ε_t are the structural shocks.

The recursive structure imposes a vertical short-run supply curve of natural gas such that natural gas supply is not affected contemporaneously by any demand-side shocks but by unanticipated natural gas supply shocks only. The justification of placing natural gas supply as the first variable in the system follows from Kilian (2009, 2011) who argues that the supply of natural gas is unlikely to respond to demand shocks in an instantaneous fashion (here, within one month) as it takes certain amount of time for natural gas producers to react to any unanticipated change in industrial, residential, or inventory demand. Such an exclusion restriction has been frequently used in the literature as a way to identify structural shocks (e.g. Kilian 2009).

Innovations to aggregate economic activity that cannot be explained by natural gas supply shocks are referred to as shocks to the aggregate demand for industrial commodities in the US, and are considered to contemporaneously affect residential demand and inventory demand in addition to the real price of natural gas, but not vice versa. This means that increases in the residential demand and inventory demand of natural gas, as well as the real price of natural gas, are unlikely to induce an instantaneous response (here, within one month) in the aggregate economic activity in the US.

Residential demand is the third variable in the system. Innovations to residential demand that cannot be explained by either natural gas supply shocks or aggregate demand shocks are referred to as shocks to the residential demand of natural gas. As residential demand only represents a small portion of the US market for natural gas, and that residential demand has remained stable during the sample period (effect of energy efficiency is offset by the increase in total number of consumers), an unexpected shock in the precautionary inventory demand or the real price of natural gas is unlikely to induce a response in the residential demand within one month.

The final two variables are ordered as inventory demand and real price of natural gas. These are innovations to inventory demand and real price of natural gas that cannot be explained by the previous three structural shocks, namely supply shocks, aggregate demand shocks, and residential demand shocks. We assume that in the short-run, an unexpected shock in the real price of natural gas will not induce an immediate response in the precautionary inventory demand. One possibility is that the storage facility is not readily available at the time the shock in the real price occurs.

The recursive VAR as postulated in equation (8) can be consistently estimated using conventional estimation procedures. A lag length of two is selected based on AIC, and to account for seasonality, we also include monthly dummies as exogenous variables in the system. We first report the impulse response functions, focusing on the response of supply and price of natural gas to the five structural shocks, and then report the forecast error variance decomposition.

Impulse response functions display reactions of each variable to unexpected shocks to the model, and for how long those effects persist. Figure 2 shows the cumulative responses of total natural gas supply and prices to the five structural shocks considered in this study at a two-year horizon, where the 95 percent confidence intervals are obtained through bootstraps with 1,000 replications. Focusing first on the response of supply to various structural shocks (top row of figure 2). As can be seen, an unanticipated supply shock has a large positive impact on total natural gas supply in the US. Speculative demand shocks induce a negative response in the total supply of natural gas in the US. The responses of natural gas supply to other three shocks are not statistically significant.

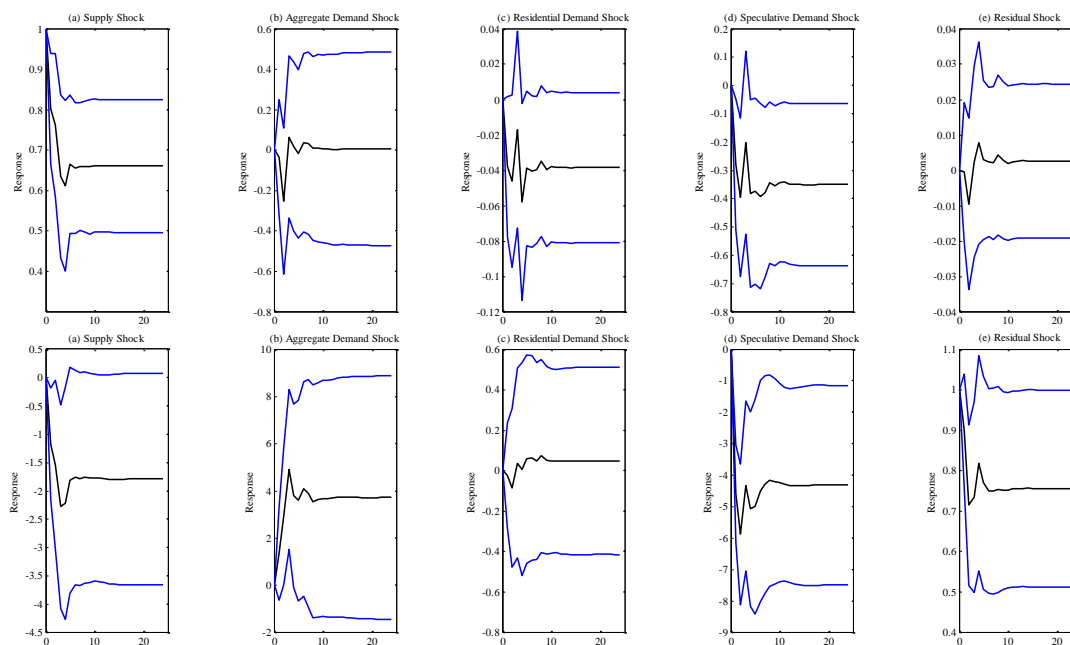


Figure 2. Cumulative Response of Natural Gas Supply (Top Row) and Natural Gas Prices (Bottom Row) to a Structural Shock

Responses of natural gas prices to various structural shocks (bottom row of figure 2) show a rather different pattern. Shocks to residential demand have only a small effect on prices, and the cumulative response of prices is never statistically significant. Industrial production shocks have a large and positive effect on prices, as higher macro-economic activity increases demand. Inventory shocks have a large and negative effect on prices. One possibility is that as inventory increases, the expected future supply of natural gas increases as well, thus effectively lowering the prices in subsequent periods. Natural gas production shocks overall have a negative effect on prices. However, the cumulative response is not significant after five months.

Table 3 presents the forecast error variance decomposition for supply and real price of natural gas. Each cell in the table represents the percentage of the forecast error in one variable induced by developments in another variable. As can be seen, the majority of the forecast error variance of supply can be explained by shocks to the supply. Even at the two-year horizon, shocks to the supply contribute to as much as 90 percent of the total forecast error variance. Speculative demand shocks come as the second most important variable, accounting for 4.5 percent of the forecast error variance for supply. Industrial

demand shocks contribute to 3.2 percent of the error variance at the end of the two-year horizon. Residual and residential demand shocks appear to explain only a negligible portion of the forecast error variance.

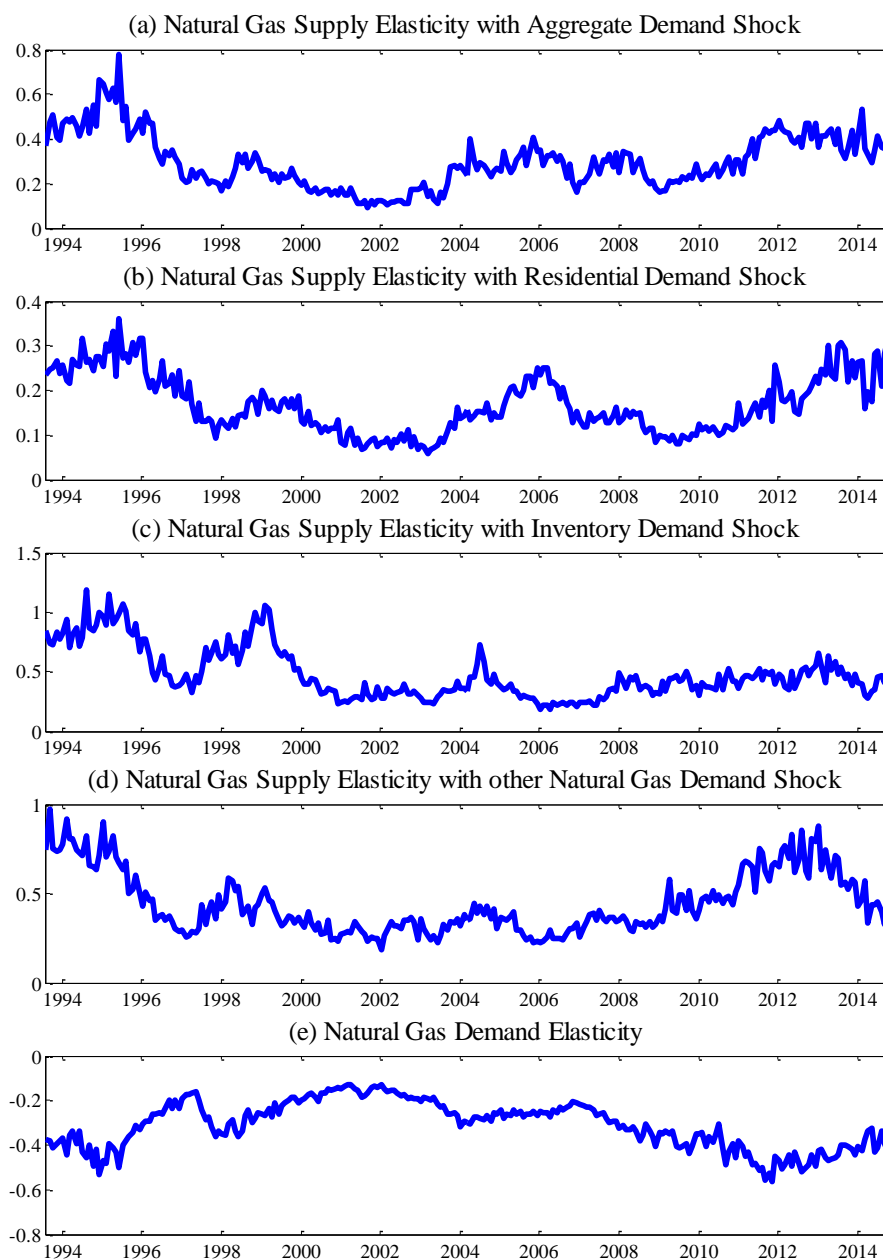


Figure 3. Median Short-Run Price Elasticities of Natural Gas Supply and Demand from 1993 to 2014

Results of forecast error variance decomposing on real natural gas prices show a bigger contribution from other structural shocks. Innovations in industrial production explain a small share of

price variations. This suggests producing firms have some degree of flexibility in their production. When changes in industrial production occur, they appear to have some ability to adjust their production to match economic output. Natural gas production changes explain the some variation in prices, which is a predictable result consistent with economic theory. Innovations in residential demand have a non-trivial effect on prices, explaining approximately 6-8% at the end of each time period. Inventories account for a large share of price variation, between 11-13%. Capacity constraints could be one possible explanation, in that if inventories were high (indicating a high utilization capacity of available storage inventories), a sudden rise in the amount of natural gas stored in inventories could account for a much larger share of price variation than if inventories were lower. Finally, at the end of a two-year horizon, residual shocks account for approximately two thirds of the total forecast error variance of real prices.

Forecast error variance decomposition on other variables (results not presented) shows that innovations in natural gas prices have only small effects on residential demand, supporting the well-established theory of inelastic demand for energy sources. Prices do have a larger effect on industrial production, suggesting a strong dependence on commodity prices. Inventories are effected by other natural gas market shocks (residual shocks), but only after a lag-time of two months.

Overall, results from the recursive VAR model suggest that unanticipated supply shocks are the primary driver of the total supply of natural gas in the US, followed by speculative demand shocks and aggregate demand shocks from 1993 to 2014. Shocks to residential demand and residual shocks only contribute minimally to the supply of natural gas. Results on natural gas prices showed a much bigger role of other variables, in that the response of prices to aggregate demand, speculative demand, and supply shocks are all statistically significant. The role of residential demand shocks, however, remains negligible.

Table 3. Forecast Error Variance Decomposition from the Recursive VAR Model

Months	Supply Shocks	Aggregate Demand Shocks	Residential Demand Shocks	Inventory Demand Shocks	Demand Shocks	Other Natural Gas Demand Shocks
Panel A. Natural Gas Supply						
1	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	95.80%	1.07%	0.10%	2.72%	0.31%	
5	90.57%	3.13%	0.89%	4.51%	0.91%	
9	89.91%	3.20%	1.39%	4.51%	1.00%	
12	89.87%	3.19%	1.41%	4.51%	1.01%	
15	89.87%	3.20%	1.41%	4.51%	1.01%	
18	89.87%	3.20%	1.41%	4.51%	1.01%	
21	89.87%	3.20%	1.41%	4.51%	1.01%	
24	89.87%	3.20%	1.41%	4.51%	1.01%	
Panel B. Real Price of Natural Gas						
1	2.47%	5.15%	1.06%	0.18%	91.15%	
3	3.96%	5.40%	8.03%	12.25%	70.36%	
5	4.07%	6.54%	7.93%	13.22%	68.24%	
9	4.41%	6.61%	8.03%	13.24%	67.72%	
12	4.41%	6.61%	8.04%	13.24%	67.71%	
15	4.41%	6.61%	8.04%	13.24%	67.70%	
18	4.41%	6.61%	8.04%	13.24%	67.70%	
21	4.41%	6.61%	8.04%	13.24%	67.70%	
24	4.41%	6.61%	8.04%	13.24%	67.70%	

4.2 Structural Model

In this section, we discuss the results from the Bayesian VAR model with time-varying parameters and stochastic volatility.

Figure 3 presents the evolution of median short-run price elasticities in natural gas supply and demand over the sample period. Given that we include three dimensions of oil demand, namely industrial demand driven by aggregate economic activity, residential demand, and precautionary inventory demand, we trace the curvature of the natural gas supply elasticity with all these three shocks, as well as the

residual shocks associated with the real price of natural gas. As can be seen, the median supply elasticity associated with aggregate economic demand ranges from 0.09 to 0.78, with the largest value occurring at the beginning of the sample period (1993-1995). The supply elasticity gradually declines starting from mid-1995. It is not until 1998 that the natural gas supply curve becomes more elastic. During 1999-2004, the median supply elasticity associated with aggregate demand shock ranges from 0.09 to 0.25, indicating a rather insensitive supply response to industrial demand shocks driven by aggregate economic activity. The implication is that natural gas supply is unlikely to significantly increase even with rapid economic growth. One possible explanation is that, due to technology constraints, producers are unable to increase production significantly and take advantage of the fast-growing economy, but have to instead maintain the current level of production. With the popularization of the combined use of horizontal drilling and hydraulic fracturing techniques, supply has apparently become much more responsive to aggregate demand shocks, with the median impact elasticity ranging from 0.2 to 0.6 between 2004 and 2014. In particular, a particularly rapid increase in supply elasticity is observed starting from 2009, when the economy in the US starts to recover from the 2008 financial crisis.

A rather similar pattern exists for the supply elasticity associated with residential demand shock, though with much smaller magnitudes. The median supply elasticity ranges from 0.1 to 0.38, suggesting that the supply of natural gas in the US is much less responsive to residential demand shock, as compared to industrial demand shock driven by aggregate economic activity. This is consistent with the observation that residential demand accounts for a much smaller portion of the total natural gas use compared to industrial demand. The supply curve appears to be more elastic for the first few years of the sample period, with the median impact elasticity ranging from 0.2 to 0.38. Starting from 1998, the supply elasticity associated with residential demand shock remained at a low level until 2004, often fluctuating between 0.1 and 0.2. 2006 marks the first time over the past decade that the supply elasticity has gone beyond 0.3. Though it subsided a bit afterwards, the supply elasticity quickly increases starting from 2008, a pattern similar to the supply curve with aggregate demand shocks.

The evolution of supply elasticity with inventory demand shocks over the sample period are presented in panel (c) of figure 3. As can be seen, much larger variations are observed for the first ten years of the sample (1993-2003), with the median supply elasticity ranging from 0.2 to 1.2. By contrast, the curvature of the supply curve associated with precautionary inventory demand has remained somewhat steady starting from 2005, ranging from 0.3 to 0.6. The implication is that with one percentage of unanticipated precautionary inventory demand shock, the supply of natural gas is likely to increase by 0.3 to 0.6 percent from 2005 to 2014.

The fourth panel of figure 3 shows the supply elasticity with other natural gas demand shocks that cannot be explained by unanticipated supply shocks, aggregate demand shocks, residential demand shocks, or speculative demand shocks. It appears that the supply curve is most elastic during the beginning and end of the sample period. The supply elasticity associated with this type of residual shock ranges from 0.3 to 1.0. For most months in the 1995-2011 sample period, the supply elasticity appears to fluctuate around 0.5.

Panel (d) of figure 3 plots the natural gas demand elasticity. The demand elasticity ranges from -0.5 to -0.1 over the sample period. Notably, while the demand elasticity remained rather steady from 1998 to 2008 (fluctuating around -0.2), the demand curve becomes much more elastic after 2008. One possible explanation is that there is a greater flexibility in energy substitution such that industrial, commercial, and residential users can switch among different fuel sources much more easily.

Given the short-run price elasticities presented in figure 3, we further compute the average underlying shocks associated with each variable, the results of which are shown in figure 4. As can be seen from the graph, much larger structural shocks are observed for the three demand side variables (industrial demand, residential demand, and precautionary inventory demand shocks) during the latter part of the sample period (2008-2014). The magnitude of each structural shock peaks between 2008 and 2010, after which a gradual decline is observed. By contrast, the size of other natural gas market demand shocks (or residual shocks) has become smaller in the latter part of the sample, partly reflecting a lower natural gas price level due to the shale boom that took off in 2006.

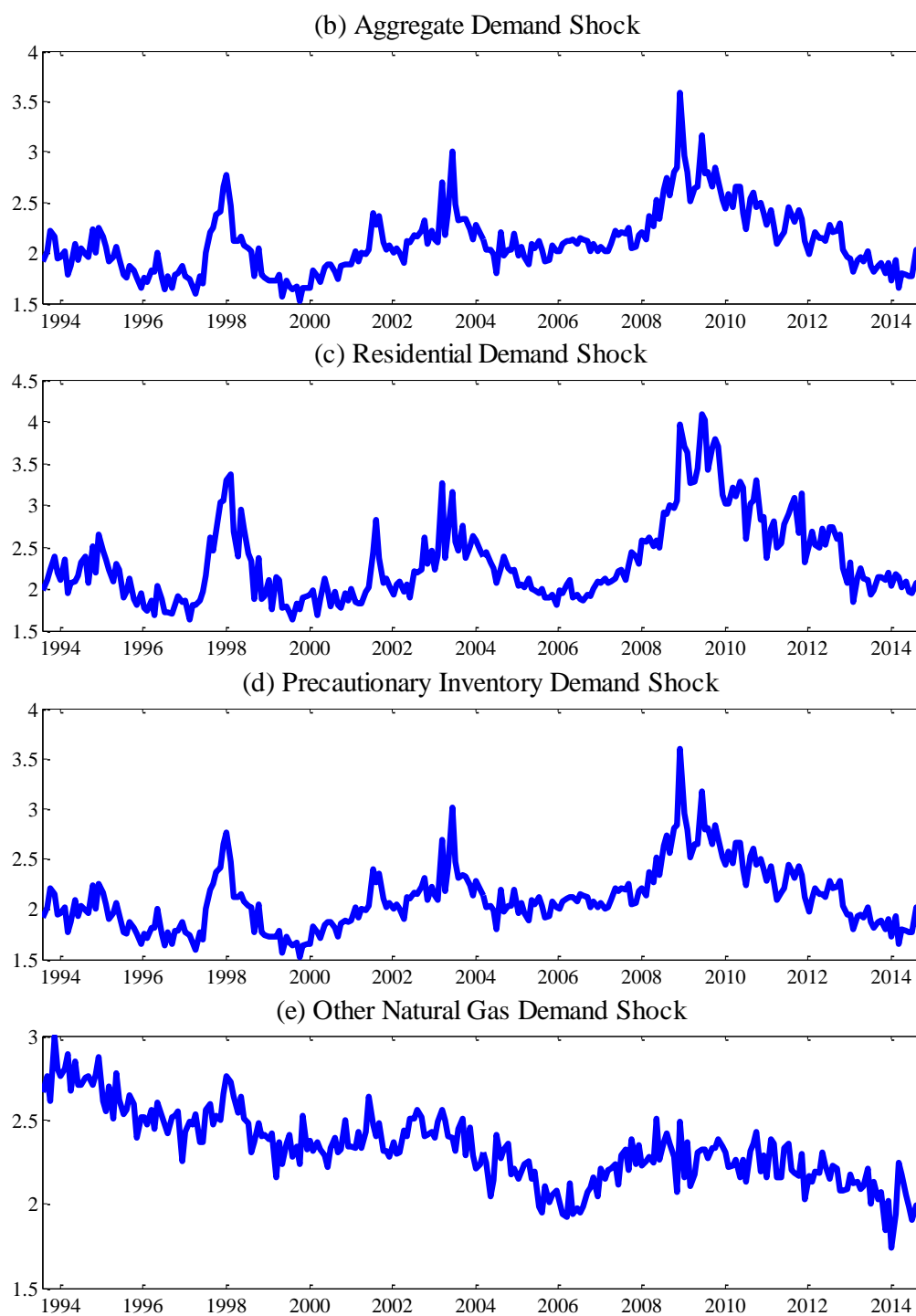


Figure 4. Median Magnitude of Structural Shocks

Overall, our estimation results from the VAR model with time-varying parameters and stochastic volatility suggest that the supply curve associated with aggregate demand shocks, residential demand

shocks, and other natural gas market demand shocks has become more elastic during the latter part of the sample. This is also the period that marks the rapid expansion in shale gas production. By contrast, the curvature of the supply curve associated with precautionary inventory demand shocks has remained at a stable level for most part of the sample since 2000, and has not changed much even in the face of rapid production growth driven by the shale gas boom. Furthermore, it appears that in the new era characterized with ample natural gas supply, the demand curve has also become more elastic, partly reflecting the fact that there is a greater flexibility of substitution in fuel use.

5. Conclusions

In this paper, we disentangle supply and demand shocks on US natural gas prices and investigate how these effects have changed over time. Whereas most previous studies have only used reduced-form analyses, this paper uses a structural vector autoregressive model (SVAR) to examine price dynamics under a theoretically-driven structural framework. Unlike Wakamatsu and Aruga (2013) and Arora (2014), who all impose a one-time arbitrary structural break, we generate a time-varying parameter model that allows the data to determine when and how any changes may have occurred. To this end, we construct a long sample period that not only includes both the pre-and post- shale boom (1976-2014), but also uses a new identification strategy recently developed by Baumeister and Peersman (2013), allowing for drifting coefficients and stochastic volatility in the SVAR model.

Results from the recursive VAR model suggest that unanticipated supply shocks is the primary driver of the total supply of natural gas in the US, followed by speculative demand shocks and aggregate demand shocks during 1993-2014. Shocks to residential demand and residual shocks only contribute minimally to the supply of natural gas. In fact, results on natural gas prices show that other variables play a much bigger role, in that the response of prices to aggregate demand, speculative demand, and supply shocks are all statistically significant. The role of residential demand shocks, however, remains negligible.

Our results from the VAR model with time-varying parameters and stochastic volatility suggest that the supply curve associated with aggregate demand shocks, residential demand shocks, and other natural gas market demand shocks has all become more elastic during the latter part of the sample. This is commensurate with the period of rapid expansion in shale gas production. By contrast, the curvature of the supply curve associated with precautionary inventory demand shocks has remained at a stable level for most of the sample since 2000, and has not changed much even with the rapid growth of shale gas production. Furthermore, it appears that in the new era characterized with ample natural gas supply, the demand curve has also become more elastic, partly reflecting the fact that there is a greater flexibility of substitution in fuel use.

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