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Arora, Vipin

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Estimates of the Price Elasticities of Natural Gas Supply and Demand in the United States [*†]

Vipin Arora

U.S. Energy Information Administration

Abstract

I estimate short and long-run price elasticities of U.S. natural gas supply and demand. For robustness, the estimates are based on data of varying frequencies and samples, some of which include the recent U.S. shale gas boom. Aside from the numbers themselves, there are two main conclusions. As expected, U.S. price elasticities of natural gas supply are higher in both the short and long-run when the effects of shale are included in the sample (post-2007). The calculated price elasticities of natural gas demand are also more responsive than recent estimates, but in-line with earlier ones.

JEL Classification: C32, E37, Q41.
Keywords: Natural gas, sign restriction, shale, elasticity, long-run, short-run

Introduction

Price elasticities of supply and demand are key inputs for many projections of energy consumption and production. They are also a simple way to check and validate model results and responses. Recent estimates of both short and long-run price elasticities in the U.S. natural gas market are limited, particularly those that include shale gas as a major component of U.S. natural gas production.

In this paper I estimate price elasticities of U.S. natural gas supply and demand. The primary goal is to update earlier estimates with data that include shale. Unlike many earlier estimates, I use a

[*]The analysis and conclusions expressed here are those of the author and not necessarily those of the U.S. Energy Information Administration.

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multivariate approach that explicitly differentiates between changes in supply and demand. This allows calculation of price elasticities of supply based on shifts in natural gas demand and calculation of price elasticities of demand based on shifts in natural gas supply. A common simplification in estimating short-run price elasticities of demand has been to equate natural gas consumption to natural gas production, thereby eliminating the need to account for inventories. The method used here allows for incorporation of inventories into the calculation of short-run price elasticities of demand.

The elasticity calculations are based on series of weekly, monthly, and quarterly frequencies whose sample periods both exclude and include shale. The weekly estimates are based on data from 2008-2013W20 and the monthly and quarterly estimates use both 1993-2007 and 1993-2013. The long-run is defined as one year in the weekly case, five years for the monthly series, and fifteen years for the quarterly sample. The short-run is defined as one week, one month, and one quarter in the weekly, monthly, and quarterly model variants, respectively. The different frequencies are used to gauge the robustness of model results and for comparisons within results of the same frequency, and may not necessarily be comparable between frequencies.

Results for the price elasticities of supply lead to two main conclusions. First, values in both the short and long-run are higher when the shale gas boom is included in the sample period. This holds for data estimated at both a monthly and quarterly frequency. For example, using monthly data, the median long-run estimate through 2007 is 0.10, rising to 0.42 when the sample extends into early 2013. The supply responses are calculated as natural gas demand changes in response to economic activity. The corresponding short-run estimates are 0.03 and 0.07.

The second conclusion regarding price elasticities of supply is that the reason why demand changes is important in determining their magnitude. The results show that the price elasticities of supply which change the most when the sample extends into 2013 respond to variations in either economic growth or inventory demand. This is not surprising, as each of these reflect possible variations in future expectations about natural gas supply and demand. In contrast, the price elasticity of supply does not show a substantial movement with the extended sample if energy demand varies. Presumably such changes in energy demand are viewed as temporary phenomenon.

The price elasticity of demand results are more responsive than recent estimates, but are similar to earlier ones (reviewed in the next section). For example, the median long-run estimate through early 2013 is -0.24, with a short-run estimate of -0.11 when natural gas production is equated to consumption, and -0.13 when inventories are included in the calculation. These results are for the monthly series in response to changes in natural gas supply.

Recent Elasticity Estimates

This section surveys recent estimates of U.S. price elasticities of natural gas supply and demand. These are either empirically determined or implied based on simulations from structural macro or energy models.

Supply

Recent empirical estimates of the price elasticities of natural gas supply are limited [for a review of earlier estimates see Dahl (1993)]. In unpublished work based on data that ranges from August 1997 to October 2012, Ponce and Neumann (2013) find that both the short and long-run price elasticities of natural gas supply are negative. The negative short-run elasticity is consistent with Krichene (2002), who calculates two different U.S. short-run prices elasticities of supply of -0.59 and -0.14 based on data ranging from 1918-1999. However, the value of the long-run price elasticity of supply over this time is 0.28.

In contrast to these scarce empirical estimates, many structural macroeconomic and energy models have implied U.S. price elasticities of natural gas supply. These structural models are primarily built for long-run analysis, and they are either annual or work in five-year increments. A comparison table of such supply elasticities was recently generated from models participating in the 26th Energy Modeling Forum (EMF-26). These values were calculated by comparing the same pre-specified cases across models and backing out the elasticities. In terms of a long-run elasticity, the median implied U.S. price elasticity of natural gas supply in 2030 across models is 1.46, with values ranging from 0.11 to 6.0. The median U.S. short-run elasticity, based on calculation for 2015, is 0.24, with a range from -0.41 to 7.2. The EIA's National Energy Modeling System (NEMS) gives values of 0.11 and 0.50 for the short and long-run U.S. price elasticities of natural gas supply, respectively.

In summary, there are few recent empirical estimates of U.S. natural gas price elasticities of supply. And there is a wide range of values for such elasticities when implied from structural models. However, conventional beliefs are that both the short and long-run price elasticities of supply are positive, and the long-run values are larger than the short-run values.

Demand

Recent empirical estimates of U.S. price elasticities of natural gas demand are more numerous than in the case of supply, but a comparison of implied values from different structural models is unavailable [see the energy demand database of Carol Dahl at `http://dahl.mines.edu/courses/dahl/dedd/` for an extensive overview, particularly of older estimates]. Recent estimates focus primarily on the U.S. price elasticities of residential natural gas demand, while older estimates are based on residential, commercial, and industrial natural gas demand. For example, Bernstein and Madlener (2011) find that the long-run U.S. price elasticity of residential natural gas demand is -0.16 and the short-run equivalent is -0.04. These are consistent with the estimates of Joutz et al. (2009), who find the U.S. long-run elasticity to be -0.18 and compute a short-run value of -0.09.

In earlier work, Maddala et al. (1997) find the average long-run price elasticity of residential natural gas demand across 49 U.S. states is -0.273, while the corresponding short-run estimate is -0.001. Dahl (1993) surveys many studies and finds a wide range of estimates, with many showing price elasticities of natural gas demand in the residential, industrial, and commercial sectors above -0.30 in absolute value. More recently, Bernstein and Griffin (2006) find a larger value of -0.36 for the long-run elasticity of residential natural gas demand and -0.12 for the short-run. In recent non-U.S. estimates, Asche et al. (2008) compute a long-run elasticity of -0.10 and a short-run elasticity of -0.03 for the EU12. Similarly for the Netherlands, Berkhout et al. (2004) estimate a long-run price elasticity of residential natural gas demand of -0.19.

In summary, recent estimates of the U.S. price elasticities of residential natural gas demand are generally consistent. Both the short and long-run values appear to be negative, and the long-run value is more negative than the short-run one.

Model and Identification

This section overviews the model used in calculating U.S. natural gas price elasticities of supply and demand. The data and identifying assumptions are also outlined. Full mathematical details and estimation procedures are provided in the appendix.

Model Overview

The model used in estimation of the elasticities is a vector-autoregression (VAR) identified with sign-restrictions. An autoregressive (AR) model is one which specifies that the current value of a variable depends only on its own past values and the current value of an error. This can be extended to a VAR by writing multiple variables in terms of their own current values and lags and the current values and lags of other variables and error terms. One can think of a VAR model in terms of multiple equations, where each equation has a different variable on the left-hand side and other variables and an error term on the right-hand side.

The structural form of a VAR model specifies each endogenous variable in terms of the current and past values of all endogenous variables and the current value of all error terms. The error terms in the structural form are called innovations or structural shocks, and are assumed to be independent, identically and normally distributed with mean zero. However, for technical reasons the structural form is rearranged to the reduced form for estimation, and this reduced form has the current value of each endogenous variable only in terms of lagged values of the endogenous variables and a reduced form error term. This error term is not the structural shock, but due to the rearrangement is some function of multiple structural shocks.

The goal in many VAR-based analyses is to isolate the impact of the original structural shocks on the variables of interest. Because the structural shock is exogenous, in the sense that is it unpredictable and uncorrelated with anything else in the system, the resulting movements in other endogenous variables are interpreted as due to the original shock. Because of the transformation from the structural form to the reduced form, there are not enough variables in the reduced form to uniquely determine the values of the variables in the structural form. To get around this, the modeler must restrict the value of a certain number of variables in the structural system before making inferences about how the structural shocks impact variables in the system. This is called identification of the system.

There are many different ways to identify a VAR system. The approach used here is based on sign-restricted identification, which works by making assumptions about the direction, or sign, of responses of model variables to the structural shocks. Specifically, the sign of the response of one variable to a structural shock in others is specified. Once these assumptions have been made, the model is simulated many times to gauge the responses of model variables to structural shocks. The model runs which meet the pre-specified assumptions are kept, while the others are discarded.

There will generally be multiple VAR model simulations that meet the sign-restrictions. In the current context these have been narrowed down further by excluding those that imply counterintuitive elasticities (positive price elasticities of natural gas demand, etc.) as in Kilian and Lee (forthcoming).[1] See the appendix for full details on the model and estimation. There are still multiple models which meet the sign restrictions after the ones with counterintuitive elasticities have been removed. These are used to generate a distribution of results for the elasticities, and the median and 16th and 84th percentiles are reported below.

Data

The model is estimated on series of weekly, monthly, and quarterly frequencies which range from 1993M01-2013M05. The quarterly and monthly variants use the annual log differences of each series except for inventories to remove both trends and seasonality. The inventory series is first-differenced and seasonally adjusted using dummy variables, as the first-differences are needed in calculating short-run elasticities. The weekly model uses seasonally-adjusted first-differences for each series because weeks do not line up in the same manner each year. Each estimation has a different number of lags, which are chosen based on the Akaike information criterion.

[1] Choosing the "best" of these successful candidates is a topic of considerable research interest [see Fry and Pagan (2011) or Inoue and Kilian (2013)].

The model variables encompass the supply, demand, and price of U.S. natural gas.[2] The variables used in the quarterly and monthly variants of the model are the same, and mostly differ from those used in the weekly variant. The monthly/quarterly supply variable is the change in marketed U.S. natural gas production (Δngs). Marketed production is used instead of gross production to exclude any gas which is consumed in extraction or in processing operations. With weekly data the supply variable is the change in U.S. dry natural gas production, as marketed production is unavailable at this frequency.

The demand for natural gas is separated between three variables. The first in the monthly/quarterly variants, total U.S. industrial production (Δipd), encompasses demand for use in the production of goods and services. This is the type of demand associated with U.S. economic activity, such as feedstock demand from a chemical firm. Because this variable is not available at higher frequencies, the weekly model uses natural gas demand in the industrial end-use sector to proxy for demand in the production of goods and services.

The second demand variable, residential natural gas demand (Δend), represents natural gas energy demand. Changes in this variable reflect variations in the demand for natural gas for heating and power purposes (possibly due to changes in the weather). This same variable is used at each of the three frequencies. Residential natural gas demand is preferred as a proxy for energy demand to the alternatives because it does not reflect changes due to economic activity. Other possible variables such as the sum of non-industrial natural gas demand do reflect changes in economic activity. For example, commercial demand for natural gas may rise because of colder weather, but it may also be higher because of overtime that requires additional electricity consumption. Using only residential natural gas demand avoids this problem.

The third demand variable is changes in natural gas inventories (Δinv), which reflect storage demand for natural gas that are linked to expectations of future supply and demand. This is also the same for each of the three frequencies. The final variable in the model is the natural gas price. In the monthly/quarterly case the producer price index (PPI) of natural gas (Δrpg) is the reference price. The PPI is used instead of other natural gas prices such as Henry Hub because it is an index of different U.S. natural gas prices, it has a longer history than other prices, and because it does not need to be deflated. The nominal Henry Hub price is used in the weekly case because the PPI for natural gas is not available at this frequency. This price is nominal because of concern with deflating a weekly variable using price indices that are only available monthly.

[2] See Appendix 1 for full details on the data.

Identification

For clarity, quotations are used around the description of each shock, and the sign restrictions are summarized in Table (1).[3] The first shock, a "Supply" shock, is an unexpected change in U.S. marketed natural gas supply.[4] As is standard, it is assumed that such increases in supply lead to greater natural gas production, demand for use in the production of goods and services, and the demand for energy. The first is a direct consequence of the shock, while the second and third follow from lower natural gas prices. These lower prices are the final sign restriction on the "Supply" shock, and are due to the greater production. The restrictions on the "Supply" shock are assumed to be dynamic, in that they are required to hold for at least one year in all models.

	$\epsilon^{\text{"Supply" Shock}}$	$\epsilon^{\text{"Economic Activity" Shock}}$	$\epsilon^{\text{"Energy Demand" Shock}}$	$\epsilon^{\text{"Speculative Demand" Shock}}$
Δngs	+	+	+	+
Δipd	+	+		-
Δend	+		+	
Δppi	-	+	+	+
Δinv			-	+

Table 1: Imposed sign restrictions. The variables are listed top to bottom and structural shocks across the top. Each column summarizes the required sign of the impact of the structural shock on the respective variables in the initial period. For the supply shock the restrictions are assumed to hold for one year in all models.

The second shock, an "Economic Activity" shock, is an unexpected change in the demand for natural gas due to changes in economic activity. The restrictions in column 3 of Table (1) hold only during the period of impact. This shock is assumed to raise natural gas production, the demand for natural gas for use in the production of goods and services, and also the price of natural gas. The price rises because of higher demand, and such higher demand implies higher production, assuming the short-run price elasticity of demand is positive. The third shock, an "Energy Demand" shock, is an unexpected movement in the demand for natural gas as an energy source. As shown in column 4 of Table (1), it is assumed that supply is greater, as are energy demand and the price, but inventories fall. The price rises because of higher demand, and supply follows because of a positive short-run price elasticity of supply. Inventories are assumed to fall because these are generally drawn down in the face of unexpected demand from the energy sector, usually because of extreme weather.

[3]Although the structural shocks on the right-hand side and the variables on the left-hand side of each equation are usually related, they are not the same thing. The structural shock is anything which changes the value of the left-hand side variable, but itself is unpredictable and uncorrelated with other shocks or variables in the VAR system. The modeler labels this unexpected movement and then makes assumptions about how it impacts the variables in the system.

[4]One concern with interpreting this as a "Supply" shock is that the supply of natural gas from storage is omitted.

The fourth shock, a "Speculative Demand" shock, is an unexpected change in the demand for natural gas due to inventories. This shock reflects the expected shortfall of future natural gas supply relative to future natural gas demand (Kilian and Murphy, 2013). Column 5 of Table (1) shows that these shocks are assumed to lead to higher natural gas production, lower demand for natural gas for use in the production of goods and services, and higher prices and inventories. As before, prices are assumed to rise because of greater demand, and increased supply follows the higher prices. The demand for natural gas for goods and services is assumed to fall because of the higher prices, which are not expected to be as short-lived as those from an "Energy Demand" shock. The final shock, an "Other" shock represents the impact of other demand or non-demand factors on the natural gas price. There are no assumptions made about the response of model variables to this shock.

Elasticity Estimates

The long and short-run price elasticities of supply and demand are presented in this section. The weekly estimates are based on data from 2008-2013W20 and the monthly and quarterly data from 1993-2013M05 and 1993-2013Q1. In the latter two cases, additional estimations are performed on a sample ranging from 1993-2007 to account for a possible break in the data due to the U.S. shale gas boom.[5] The long-run is defined as one year in the weekly case, five years for the monthly series, and fifteen years for the quarterly sample. The short-run is defined as one week, one month, and one quarter in the weekly, monthly, and quarterly model variants. The different frequencies are used to gauge the robustness of model results and for comparisons within results of the same frequency, and may not necessarily be comparable between frequencies.

In each case, the long-run elasticities are defined as the cumulative responses of either supply or demand to the cumulative changes in the price due to a specified shock. The specific long-run elasticities are:

1. The long-run price elasticity of supply due to an "Economic Activity" shock (E^{ea})
2. The long-run price elasticity of supply due to an "Energy Demand" shock (E^{ed})
3. The long-run price elasticity of supply due to a "Speculative Demand" shock (E^{sd})
4. The long-run price elasticity of total demand due to a "Supply" shock (E^{s})

For example, the long-run price elasticity of supply in response to an "Economic Activity" shock (E^{ea}) in the monthly model is the cumulative response over five years of changes in natural gas supply relative to the cumulative responses of the natural gas price for the same shock. The calculated

[5]Arora and Lieskovsky (forthcoming) show that this is an appropriate break date.

long-run price elasticity of demand is for total natural gas demand, which is assumed to be equal to supply in the long-run.

The short-run elasticities are defined as the instantaneous responses of either supply or demand to the instantaneous changes in the price due to the specified shock. These include:

1. The short-run price elasticity of supply due to an "Economic Activity" shock (e^{ea})
2. The short-run price elasticity of supply due to a "Energy Demand" shock (e^{ed})
3. The short-run price elasticity of supply due to a "Speculative Demand" shock (e^{sd})
4. The short-run price elasticity of total demand in use due to a "Supply" shock (e_u^s)
5. The short-run price elasticity of total demand in production due to a "Supply" shock (e_p^s)

A common simplification in estimating short-run price elasticities of demand has been to equate natural gas consumption to natural gas production, thereby eliminating the need to account for inventories. The method used here allows for incorporation of inventories into the calculation of short-run price elasticities of demand. As in Kilian and Murphy (2013), the short-run price elasticities of demand are differentiated between those in use (e_u^s) and in production (e_p^s). The short-run elasticity of demand in use incorporates inventories into its calculation by using the fact that in the short-run natural gas consumption does not necessarily equate to natural gas supply. The use of natural gas in this case is defined as the sum of changes in supply and depletion of inventories [see Appendix A in Kilian and Murphy (2013) for a definition]. The short-run elasticity in production is the response of supply relative to the response of the price due to a demand shock, which implicity assumes that inventories turn over quickly in the short run.

The estimated U.S. price elasticities of natural gas supply [top panels] and demand [bottom panels] are shown in Tables (2)-(5). Table (2) displays the median values from the models which meet the sign and elasticity restrictions at different frequencies over the specified samples, while the remainder of tables provide the 16th and 84th percentile values for the elasticities from those distributions. These particular boundaries are chosen because 68 percent of calculated elasticities from the posterior distribution of responses fall between the values.

Supply

In terms of median values for the long-run price elasticities of supply, those which are in response to "Economic Activity" and "Speculative Demand" shocks are between 0.3-0.5 when the full sample is considered. These are on the higher end of recent empirical estimates, but on the lower end of elasticities used in structural models. Supply elasticities in response to "Energy Demand" shocks are even lower, around 0.2. In all monthly and quarterly cases the short-run elasticities are calculated to

Sample	LR/SR	E^{ea}	E^{ed}	E^{sd}	e^{ea}	e^{ed}	e^{sd}
2008-2013W20	1Y/1W	0.21	0.07	0.43	0.29	0.02	0.39
1993-2007M12	5Y/1M	0.10	0.14	0.13	0.03	0.02	0.03
1993-2013M05	5Y/1M	0.42	0.18	0.31	0.07	0.05	0.07
1993-2007Q4	15Y/1Q	0.08	0.09	0.45	0.01	0.03	0.10
1993-2013Q1	15Y/1Q	0.40	0.17	0.48	0.05	0.04	0.13

(a) Long and short-run price elasticities of natural gas supply

Sample	LR/SR	E^s	e^s_u	e^s_p
2008-2013W20	1Y/1W	-0.70	-0.46	-0.57
1993-2007M12	5Y/1M	-0.38	-0.26	-0.25
1993-2013M05	5Y/1M	-0.24	-0.13	-0.11
1993-2007Q4	15Y/1Q	-0.40	-0.21	-0.14
1993-2013Q1	15Y/1Q	-0.29	-0.16	-0.14

(b) Long and short-run price elasticities of natural gas demand

Table 2: Median natural gas price elasticities based on VAR model estimated on different frequency data over specified sample periods.

be below 0.15, with most less than 0.1. These are consistent with the standard belief that price elasticities of natural gas supply in the short-run are positive, but small.

The top panels of Tables (3) and (4) show that the range of possibilities grows along with the median values when shale is fully included into the sample. In fact, the monthly model shows ranges from 0.08 to 0.96 and the quarterly model 0.08 to 1.3. The elasticities calculated based on “Energy Demand” shocks determine this lower bound, but the upper bound is in response to “Economic Activity” shocks for the monthly data and “Speculative Demand” shocks in the quarterly data. The short-run price elasticities of supply over the full samples range from 0.0 to 0.15 in the monthly case to 0.01 to 0.26 in the quarterly case.

Panel (a) of Table (5) shows the distribution of supply elasticities calculated for weekly data after 2008. Considering that the long-run is defined as one year here, these show a substantially increased responsiveness to price, in both the long and short-run, for the “Economic Activity” and “Speculative Demand” shocks. However, these are based on different data because of the frequency, and this may play a part in the differentials.

Two points stand out from the results shown in Panel (a) of Table (2). The first is that the median price elasticities of natural gas supply in both the short and long-run are higher when the shale gas boom is included in the sample period. This holds for data estimated at both a monthly and quarterly frequency. The second point is that the long-run supply elasticity in response to “Economic Activity” shocks appears to have changed the most, and the long-run price elasticity of supply in response to

Sample	LR/SR	Percentile	E^{ea}	E^{ed}	E^{sd}	e^{ea}	e^{ed}	e^{sd}
1993-2007M12	5Y/1M	16th	0.06	0.06	0.06	0.00	0.01	0.02
		50th	0.10	0.14	0.13	0.03	0.02	0.03
		84th	0.13	0.27	0.67	0.05	0.09	0.17
1993-2013M05	5Y/1M	16th	0.27	0.08	0.11	0.05	0.03	0.00
		50th	0.42	0.18	0.31	0.07	0.05	0.07
		84th	0.96	0.51	0.86	0.15	0.06	0.08

(a) Long and short-run price elasticities of natural gas supply

Sample	LR/SR	Percentile	E^s	e^s_u	e^s_p
1993-2007M12	5Y/1M	16th	-0.52	-0.29	-0.34
		50th	-0.38	-0.26	-0.25
		84th	-0.31	-0.05	-0.06
1993-2013M05	5Y/1M	16th	-0.71	-0.18	-0.16
		50th	-0.24	-0.13	-0.11
		84th	-0.19	-0.07	-0.04

(b) Long and short-run price elasticities of natural gas demand

Table 3: Natural gas price elasticities based on VAR model estimated on monthly data over specified sample periods. Percentiles correspond to those from the posterior distribution of the model which meet the sign and elasticity restrictions.

"Energy Demand" shocks the least.

Both of these results are unsurprising and consistent with conventional wisdom. The nature of shale gas wells and their method of extraction makes producers more responsive to prices, as extraction can take place faster. Also, most unexpected increases in natural gas demand for use as energy are temporary in nature, which would give producers less of a reason to increase production. It is more likely that inventories are drawn down in such a scenario. The higher responses to "Economic Activity" and "Speculative Demand" shocks likely occur because these are longer-lived shocks, which would give producers more of a reason to ramp up production in the face of higher prices.

Demand

The median estimates for price elasticities of U.S. natural gas demand are shown in panel (b) of Table (2). For the full sample, the long-run values are -0.24 for monthly data and -0.29 for quarterly. The short-run values for the full sample vary between -0.10 and -0.16. However, in this case it appears that the elasticity estimates when shale is included fully into the sample get larger, i.e. there is less responsiveness to price both in the short and long-run.

One possible explanation for this is a well known issue when using elasticity estimates, that the

Sample	LR/SR	Percentile	E^{ea}	E^{ed}	E^{sd}	e^{ea}	e^{ed}	e^{sd}
1993-2007Q4	15Y/1Q	16th	0.02	0.04	0.14	0.00	0.01	0.01
		50th	0.08	0.09	0.45	0.01	0.03	0.10
		84th	0.23	0.35	0.84	0.05	0.12	0.36
1993-2013Q1	15Y/1Q	16th	0.29	0.08	0.19	0.04	0.01	0.03
		50th	0.40	0.17	0.48	0.05	0.04	0.13
		84th	0.92	0.61	1.30	0.10	0.17	0.26

(a) Long and short-run price elasticities of natural gas supply

Sample	LR/SR	Percentile	E^{s}	e^{s}_{u}	e^{s}_{p}
1993-2007Q4	15Y/1Q	16th	-0.76	-0.31	-0.35
		50th	-0.40	-0.21	-0.14
		84th	-0.24	-0.07	-0.08
1993-2013Q1	15Y/1Q	16th	-0.53	-0.37	-0.17
		50th	-0.29	-0.16	-0.14
		84th	-0.17	-0.10	-0.08

(b) Long and short-run price elasticities of natural gas demand

Table 4: Natural gas price elasticities based on VAR model estimated on quarterly data over specified sample periods. Percentiles correspond to those from the posterior distribution of the model which meet the sign and elasticity restrictions.

Sample	LR/SR	Percentile	E^{ea}	E^{ed}	E^{sd}	e^{ea}	e^{ed}	e^{sd}
2008-2013W20	1Y/1W	16th	0.05	0.03	0.16	0.08	0.01	0.12
		50th	0.21	0.07	0.43	0.29	0.02	0.39
		84th	1.11	0.18	0.98	1.22	0.04	0.41

(a) Long and short-run price elasticities of natural gas supply

Sample	LR/SR	Percentile	E^{s}	e^{s}_{u}	e^{s}_{p}
2008-2013W20	1Y/1W	16th	-1.28	-0.72	-1.17
		50th	-0.70	-0.46	-0.57
		84th	-0.54	-0.27	-0.34

(b) Long and short-run price elasticities of natural gas demand

Table 5: Natural gas price elasticities based on VAR model estimated on weekly data over specified sample period. Percentiles correspond to those from the posterior distribution of the model which meet the sign and elasticity restrictions.

percentage changes in price after 2008 reflect level changes that are smaller in size than before. For example, the nominal Henry Hub price drops from a high of over 12 dollars per MMBtu in early 2008 to around 4 dollars per MMBtu for the remainder of the sample period. And the responses of households in a low-price environment may simply be different than a higher-price one, in that they are less concerned with price changes when prices are low.[6]

Still, the median values before shale is included show more responsiveness than many recent empirical estimates (which also do not include shale). One reason for this is likely that the other estimates were based on the price elasticity of residential natural gas demand. A large portion of this is heating demand, which one would expect to be relatively insensitive to price. The estimates here include all demand. Also, the price elasticities of demand in production, which are generally used in the literature, are lower than the price elasticity of demand in use. Recall that the price elasticity of demand in use includes natural gas inventories in its calculation, taking account of the fact that natural gas production does not necessarily equate to consumption on a monthly or even quarterly basis.

The bottom panels of Tables (3) and (4) show relatively wide distributions in either the monthly or quarterly case, particularly for the short-run price elasticities of demand. For example, the quarterly price elasticity of demand in use shows a range from -0.10 to -0.37 over the full sample, although this is tighter in the monthly case at -0.07 to -0.18. The weekly data show an even larger range and higher median values than the monthly/quarterly estimates. This likely reflects data differences between the weekly and other samples.

The main conclusion from the estimates of the U.S. price elasticity of natural gas demand is that they are more responsive, both in the long and short-run, than other recent estimates, although they are closer to earlier estimates. Considering inventories make them more responsive still.

Conclusion

The supply results indicate that natural gas producers are more sensitive to prices if the period after 2007 is included in the sample, both in the short and long-run. This underlines the importance of shale gas for elasticity estimates. The demand elasticities are in-line with conventional estimates, but including inventories into the short-run calculations raises their responsiveness.

Although they are based on slightly different data, comparing the weekly samples, which only include data after 2007, and the monthly and quarterly series provides interesting contrasts. In particular, the range of possible supply elasticity values, both for the short and long-term is much larger for the weekly data. This might be due to the fact that there is not enough data, or even to the differences in data between the samples. But it also raises the possibility that there have been very large changes in

[6] The relationship between competitive fuels in electric power can also vary under different natural gas price ranges.

the price elasticities of U.S. natural gas supply since 2008 that are not showing up in the lower frequency series. The question in that case is around the permanence of such changes.

References

Arora, Vipin and Jozef Lieskovsky, "Natural Gas and U.S. Economic Activity," *The Energy Journal*, forthcoming.

Asche, Frank, Odd Bjarte Nilsen, and Ragnar Tveteras, "Natural Gas Demand in the European Household Sector," *The Energy Journal*, 2008, *29* (3), 27–46.

Berkhout, Peter H.G., Ada Ferrer-i-Carbonell, and Jos C. Muskens, "The Ex Post Impact of an Energy Tax on Household Energy Demand," *Energy Economics*, 2004, *26* (3), 297–317.

Bernstein, M.A. and J. Griffin, "Regional Differences in the Price-Elasticity of Demand for Energy," Subcontract Report SR-620-39512, NREL 2006.

Bernstein, Ronald and Reinhard Madlener, "Residential Natural Gas Demand Elasticities in OECD Countries: An ARDL Bounds Testing Approach," Working Paper 15/2011, FCN 2011.

Dahl, Carol, "A Survey of Energy Demand Elasticities in Support of the Development of NEMS," Contract Report De-AP01-93EI23499, U.S. Department of Energy 1993.

Fry, Renee and Adrian Pagan, "Sign Restrictions in Structural Vector Autoregressions: A Critical Review," *Journal of Economic Literature*, 2011, *49* (4), 938–960.

Inoue, Atsushi and Lutz Kilian, "Inference on Impulse Response Functions in Structural VAR Models," *Journal of Econometrics*, 2013, *177* (1), 1–13.

Joutz, Frederick, Bruce McDowell, David Shin, and Robert Trost, "Estimating Regional Short-Run and Long-Run Price Elasticities of Residential Natural Gas Demand in the U.S.," Working Paper 09-021, USAEE 2009.

Kilian, Lutz, "Structural Vector Autoregressions," in N. Hashimzade and M.A. Thornton, eds., *Handbook of Research Methods and Applications in Empirical Macroeconomics*, Edward Elgar, 2013, pp. 515–554.

_ **and Daniel P. Murphy**, "The Role of Inventories and Speculative Trading in the Global Market for Crude Oil," *Journal of Applied Econometrics*, 2013.

_ **and Thomas K. Lee**, "Quantifying the Speculative Component in the Real Price of Oil: The Role of Global Oil Inventories," *Journal of International Money and Finance*, forthcoming.

Krichene, Noureddine, "World Crude Oil and Natural Gas: A Demand and Supply Model," *Energy Economics*, 2002, *24* (6), 557–576.

Maddala, G.S., Robert P. Trost, Hongyi Li, and Frederick Joutz, "Estimation of Short and Long-Run Elasticities of Energy Demand From Panel Data Using Shrinkage Estimators," *Journal of Business & Economic Statistics*, 1997, *15* (1), 90–100.

Ponce, Micaela and Anne Neumann, "Estimating Price Elasticities of Supply for the U.S. Natural Gas Market," 2013. Poster Presentation USAEE 2013.

Appendix

Model and Estimation

This section provides more detail on the specification and estimation of the VAR model. The general approach follows Kilian (2013).

Model

Assume a general VAR process:

$$\mathbf{B}_0\mathbf{y}_t = \mathbf{B}_1\mathbf{y}_{t-1} + ... + \mathbf{B}_p\mathbf{y}_{t-p} + \boldsymbol{\epsilon}_t \tag{1}$$

where $\mathbf{y}_t$ and lags are $N \times 1$ vectors of variables, the $\mathbf{B}_j$ are N x N matrices of coefficients, and $\boldsymbol{\epsilon}_t$ is an N x 1 vector of structural innovations. The structural errors are white noise processes with $E(\boldsymbol{\epsilon}_t, \boldsymbol{\epsilon}_t^{'}) = \mathbf{S}_\epsilon$. The matrix $\mathbf{S}_\epsilon$ is assumed to be diagonal, implying that each structural shock is uncorrelated with all others. To estimate the model both sides of equation (1) are pre-multiplied by $\mathbf{B}_0^{-1}$ to give the reduced form representation:

$$\mathbf{y}_t = \mathbf{A}_1\mathbf{y}_{t-1} + ... + \mathbf{A}_p\mathbf{A}_{t-p} + \mathbf{u}_t \tag{2}$$

Here, the $\mathbf{A}_i = \mathbf{B}_0^{-1}\mathbf{B}_i$ and $\mathbf{u}_t = \mathbf{B}_0^{-1}\boldsymbol{\epsilon}_t$. The impulse response function, which summarizes the impact of the errors on the variables in the VAR model, is the moving average form of equation (2):

$$\mathbf{y}_t = \sum_{j=0}^{\infty} \mathbf{A}_j\mathbf{u}_{t-j} \tag{3}$$

Recovering the impact of the structural shocks on the variables of interest from the impulse response function requires additional identifying assumptions on the VAR model. Normalizing the variance of the structural shocks to one, so that $\mathbf{S}_\epsilon = \mathbf{I}_N$, allows the variance of the reduced form errors ($\mathbf{u}_t$) to be written as:

$$\mathbf{S}_u = \mathbf{B}_0^{-1}\mathbf{B}_0^{-1'} \tag{4}$$

With additional identifying assumptions, the system of equations represented by equation (4) can be used to recover the coefficients of $\mathbf{B}_0^{-1}$, and thus the impacts of the structural shocks on model variables.

A common method to impose these restrictions is by defining a lower-triangular $N \times N$ matrix $\mathbf{P}$ such that $\mathbf{PP}' = \mathbf{S}_u$. The matrix $\mathbf{P}$ is the Cholesky decomposition of $\mathbf{S}_u$ and is a unique solution to equation (4) when $\mathbf{B}_0^{-1} = \mathbf{P}$. The assumption of a lower-triangular structure for $\mathbf{B}_0^{-1}$, however, may imply strong restrictions on when structural shocks impact model variables. Such strong restrictions can be hard to justify in many cases, and the sign-restricted identification procedures applied here are one alternative.

Sign-restricted identification works by making assumptions about the direction, or sign, of impulse responses of model variables to the structural shocks. As above, $\mathbf{P}$ is a lower triangular matrix that satisfies $\mathbf{PP}' = \mathbf{S}_u$. With this Cholesky decomposition, setting $\mathbf{B}_0^{-1} = \mathbf{P}$ solves equation (4) and fully identifies the model. But it is also the case that any orthogonal $N \times N$ matrix $\mathbf{D}$ can be chosen such that $\mathbf{PD} = \mathbf{B}_0^{-1}$ also solves $\mathbf{S}_u = \mathbf{B}_0^{-1}\mathbf{B}_0^{-1'}$. Unlike with the Cholesky decomposition, $\mathbf{PD}$ is not necessarily lower triangular, and this may lead to identifying restrictions that are more plausible in certain cases.

The general procedure when identifying a VAR through sign restrictions is to find the matrix $\mathbf{P}$, and then to draw many different $\mathbf{D}$ matrices. One can then check if the impulse responses from $\mathbf{PD}$ match the pre-specified sign-restrictions. Those that match the restrictions are kept and the others are discarded. After a large number of candidate $\mathbf{D}$ matrices have been evaluated there will generally be many different $\mathbf{PD}$ combinations which match the sign restrictions. Choosing the "best" of these successful candidates is a topic of considerable research interest [see Fry and Pagan (2011) or Inoue and Kilian (2013)]. One way to further narrow down these successful candidates in the current context is by excluding those that imply counterintuitive elasticities as in Kilian and Lee (forthcoming).

Estimation

As described in the main text, the model is estimated on series of weekly, monthly, and quarterly frequencies which range from 1993M01-2013M05. The quarterly and monthly variants use the annual log differences of each series except for inventories to remove both trends and seasonality. The inventory series is first-differenced and seasonally adjusted using dummy variables, as the first-differences are needed in calculating short-run elasticities. The weekly model uses seasonally-adjusted first-differences for each series because weeks do not line up in the same manner each year. Each estimation has a different number of lags, which are chosen based on the Akaike information criterion.

The elasticity estimates are generated as values from the posterior distribution of impulse responses using the Bayesian procedure of Kilian and Murphy (2013). Specifically, the VAR model is first solved to find the posterior distribution of the reduced-form parameters (assuming a Gaussian-inverse Wishart prior distribution). A draw is then taken from this posterior distribution, the Cholesky decomposition of the corresponding variance-covariance matrix of the reduced-form errors is calculated, then a large number of different combinations of this Cholesky decomposition with orthogonal matrices (**PD** above) are used to generate impulse responses, and these are checked to see if sign-restrictions are met.

The successful candidates matrices are further narrowed down by imposing restrictions on the size of various elasticities, leaving the combinations which meet both sign and elasticity restrictions. In all cases price elasticities of demand which are positive and price elasticities of supply which are negative are ruled out, consistent with earlier estimates. In addition, the long-run price elasticity of supply is constrained to be below 2, while the long-run price elasticity of demand is constrained to be above -2. These values encompass the large majority of previous estimates summarized above. Finally, short-run elasticities of supply or demand which are larger in absolute value than their long-run counterparts are not allowed.

The various elasticity estimates are then summarized by using different percentiles of the posterior distribution of impulse responses from successful candidate matrices. The posterior distribution of responses is generated with 2500 different draws from the posterior distribution of the VAR reduced form parameters and 20,000 different candidate orthogonal matrices for each of those draws.

Data

Data on natural gas production and demand are taken from the EIA. Natural gas production is marketed U.S. natural gas withdrawals in millions of cubic feet, and is available at a monthly frequency from 1980M01 at `http://www.eia.gov/dnav/ng/hist/n9010us2m.htm`. End-use consumption of natural gas is available from the EIA's Monthly Energy Review. Data on consumption of natural gas by end-use sector is available in Table 4.1 of this document, and the monthly historical data can be found at `http://www.eia.gov/totalenergy/data/monthly/#naturalgas` in billions of cubic feet. In calculating the natural gas demand for use as energy, natural gas consumed in the residential end-use sector is used. The inventory data is U.S. demand for underground storage from the EIA in billions of cubic feet, and can be found at `http://www.eia.gov/naturalgas/data.cfm#storage`.

The total U.S. industrial production index is taken from the Board of Governors of the Federal Reserve, and is available at `http://www.federalreserve.gov/releases/g17/download.htm` at a monthly frequency from 1967 onwards. The total index includes manufacturing, mining, and utilities. The real natural gas price is the U.S. producer price index (PPI) for fuels and related products and power, natural gas (WPU0531). The PPI is available at a monthly frequency from 1967M01 and comes from the Bureau of Labor Statistics (BLS) at `http://data.bls.gov/timeseries/WPU0531`. In the models which have a quarterly frequency the data from the sources above are aggregated as appropriate to a quarterly frequency: summation for the EIA data and averages for the industrial production and natural gas price data.

The models estimated with weekly data use supply and demand numbers from EIA's natural gas weekly update http://www.eia.gov/naturalgas/weekly/ and natural gas storage report http://ir.eia.gov/ngs/ngs.html. In this case the supply numbers are for dry production, the demand for economic activity is demand in the industrial end-use sector, energy demand is demand in the residential end-use sector, and inventory demand is as before. The weekly nominal Henry Hub price is the natural gas price.