A Policy Framework for Evaluating North American Natural Gas Exports

EMF SR 11

Hillard Huntington, Stanford Department of Management Sciences and Engineering and the Energy Modeling Forum

John Weyant, Stanford Department of Management Sciences and Engineering and the Energy Modeling Forum

Michael Wara, Stanford Law School

October 2016

Abstract: Policy makers need robust decision tools for evaluating changes to US natural gas law and regulation. Among the most critical policy debates in recent times has been whether and to what degree the US and Canadian governments should approve licenses for export of newly abundant natural gas. Also critical are numerous state-level debates on if and how to increase regulatory oversight of drilling and its environmental impacts. Vast improvements in hydraulic fracturing have ushered in a wave of less expensive natural gas that might meet gas demands both overseas and in the U.S. market There exists, however, a range of views among energy experts about how competitive North American sources will be globally and how such energy exports might strain domestic natural gas markets through higher domestic prices. We develop a transparent and tractable framework for evaluating the opportunities, challenges and impacts of LNG exports from North America to Europe, Asia and eventually South America. The framework emphasizes the need to make policy choices that are robust to the large uncertainties within natural gas markets.

Acknowledgements: The authors wish to acknowledge valuable financial support from the Stanford Natural Gas Initiative, research assistance from Maria Roumpani, Xianling Long, and Fangmingyu Yang on organizing the data and constructing the policy framework, and additional discussion with Lauren Culver. Any remaining errors or omissions remain with the authors.

Introduction and the Problem

Large differences in regional natural gas prices in 2015 provide attractive incentives for building the infrastructure to transport natural gas long distances over water in the form of liquefied natural gas (LNG). The need for these investments has attracted strong commercial interests as well as a very active policy debate about licensing these facilities within North America as well as elsewhere. Corporations and government agencies must make these private and public decisions in an energy market fraught with major uncertainties.

This report reviews a research effort at Stanford University to develop a policy framework for improving decisions about exporting North American natural gas, where the ultimate market outcome will not be known for a number of years. Section 2 describes the problem and documents previous efforts to evaluate the prospects for expanding natural gas exports from North America. Section 3 explains how the United States government evaluates proposals for licensing LNG export facilities. Section 4 provides our preliminary framework for evaluating how policy analysts might evaluate major uncertainties in market conditions. This initial analysis is a simplified version of the ultimate framework that was developed in the project. Section 5 describes the analytical structure and data that was used eventually to incorporate international natural gas markets. The framework captures the key market responses but also maintains sufficient simplicity and flexibility to incorporate critical uncertainties in evaluating different options. Concluding comments and recommendations for future research are contained in the final section.

Opportunities for Rising U.S. Gas Exports

Although liquefaction and regasification terminals and LNG shipping remain expensive, companies are investing strongly in these facilities in order to move natural gas from high-resource areas in Russia, the Middle East, Africa and North America to high-consumption markets in Europe and Asia. Many experts anticipate that global LNG trade will grow strongly under these conditions. Optimism remains high within North America that domestic supplies will share in this growing market. The U.S. Department of Energy is currently processing a number of different applications to build the facilities to export LNG. Once these licenses are approved, an important strategic issue for many companies will be whether future conditions will support the current flurry in investment activity.

At the same time, policy makers need robust decision tools for evaluating changes to US natural gas law and regulation. Among the most critical policy debates in recent times has been whether and to what degree the US and Canadian governments should approve licenses for export of newly abundant natural gas. Also critical are numerous state-level debates on if and how to increase regulatory oversight of drilling and its environmental impacts. Vast improvements in hydraulic fracturing have ushered in a wave of less expensive natural gas that might meet gas demands both overseas and in the U.S. market (Credit Suisse, 2012; Citi GPS, 2012; EIA, 2014). There exists, however, a range of views among energy experts about how competitive North American sources will be globally and how such energy exports might strain domestic natural gas markets through higher domestic prices. Some analysts expect domestic prices to be only marginally higher with an expansion in exports while others expect price increases that would exceed $1 per thousand cubic feet (Ebinger et al, 2013). Current natural gas wellhead prices within North America are slightly less than $3.00 per thousand cubic feet, higher than the recent historic low prices but still relatively depressed in inflation adjusted terms.

Various expert teams have evaluated these possibilities with detailed structural economic models that incorporate multiple dimensions of natural gas production, technology, policy and end use. One prominent modeling effort was the analysis by Paltsev et al (2011), which formed the basis of the influential natural gas study performed by the MIT Energy Initiative (2011). Other studies include those done by Medlock (2012) at the Baker Institute of Rice University, EIA (2012) and NERA Economic Consulting (2012, 2014), where the latter three were developed to support or influence government decisions about approving export licenses. Although these modeling efforts have significantly improved the analytical capability for evaluating future natural gas market outcomes, they make very different assumptions about the nature of the resource base and how energy consumers will replace coal, nuclear and renewable energy sources with more prevalent shale gas resources. These differences contribute importantly to major disagreements about the market potential for North American exports and the impact that these exports will have on domestic natural gas markets. Without careful evaluations of the reasons for these differences, such as those conducted by the Energy Modeling Forum (2013) in a recent comparison of major energy models, many policy makers are often very confused by the range of possibilities offered by these studies – or worse, simply pick the modeling study that confirms their idiosyncratic policy bias.

We develop in this paper a transparent and tractable framework for evaluating the opportunities, challenges and impacts of LNG exports from North America to Europe, Asia and eventually South America. The framework emphasizes the need to make policy choices that are robust to the large uncertainties within natural gas markets. By explicitly focusing on a range of outcomes, it produces new, more robust methods for communicating energy model-based evidence to key energy policy stakeholders. Previous policy studies (Eisenberg, Wara, Morris, Darby and Minor, 2014; and Wara, Cullenward, Wilkerson and Weyant, 2013) have emphasized the significant advantages for improving public policy decisions when the full range of outcomes is properly communicated. Moreover, its flexibility allows the integration of various strands of scientific, engineering, legal, policy and economic research that may shape this topic. Researchers within one discipline can understand how their research interests influence critical policy decisions. The flexibility of our framework will allow for incorporation and modification as new information about shale gas resources and gas markets emerges in the coming decades.

The LNG Licensing Process

As specified and amended under the Natural Gas Act of 1938, LNG and other natural gas sources cannot be imported into or exported away from the United States without an authorization from the Department of Energy.[1] Some countries operate under existing free trade agreements (FTA) with the United States that allows them to have equal access to U.S. natural gas as do domestic users. This principle, termed national treatment, is a key concept in many international treaties establishing economic ties between countries. If a project plans to export volumes to a country that does not operate under an FTA, these owners must apply for a license. The Department of Energy will review these applications to determine whether the export project can be considered as being in the public interest.

Authorizations can be on a short-term or spot market basis for a period less than two years or for a longer period under a contract. The Department's Office of Fossil Energy evaluates each proposal on the basis of the project's impact on the domestic need for natural gas, its effect on the security of domestic natural gas sources, and its implications for fostering market competition. A typical application for a license from the Department often focuses on several critical issues: whether natural gas prices will be affected, the availability of U.S. natural gas supplies, whether it will detract from natural gas consumption, its direct or indirect implications for the local, regional, and national economies in terms of jobs and domestic product, whether international trade will be improved, and the global environmental

[1] The regulatory approach is described at http://www.energy.gov/fe/services/natural-gas-regulation.

and U.S. national security effects. Often, the applying company will provide the Department with a range of simulation results from one or more models on many of these issues. In addition, the Department has requested the U.S. Energy Information Administration and an economic consulting firm (NERA) to conduct independent analysis on the impact of various export levels on U.S. energy markets and the economy.

The Department has recently decided that it will act on applications for licenses only after the project has been approved by an environmental assessment. This rule has been effective since August 2014. Prior to that date, the Department would provide conditional decisions prior to the environmental assessment.[2]

Many of these issues relate to the market impacts of expanding U.S. exports by a given amount. These impacts focus principally upon changes in the amount of domestic natural gas produced, in the domestic need for these natural gas volumes if they were not exported, and in the price paid by domestic consumers. For this reason, the research project described in this report focuses upon the range of possible exports and wellhead prices that can be expected under a variety of different market conditions. In particular, metrics are developed to report the likelihood that export levels and wellhead prices will reach a certain level. These ranges are derived from a modeling framework that ensures that any natural gas sold to another country must be cost-competitive at the end-use level with sources that are available from other world regions. If the gas exports from the United States are not cost competitive, they are not allowed to be exported and must be used domestically.

A Basic Framework

We begin with a small model of regional consumption and production in different areas of the world to demonstrate how the one can report results on the uncertain nature of

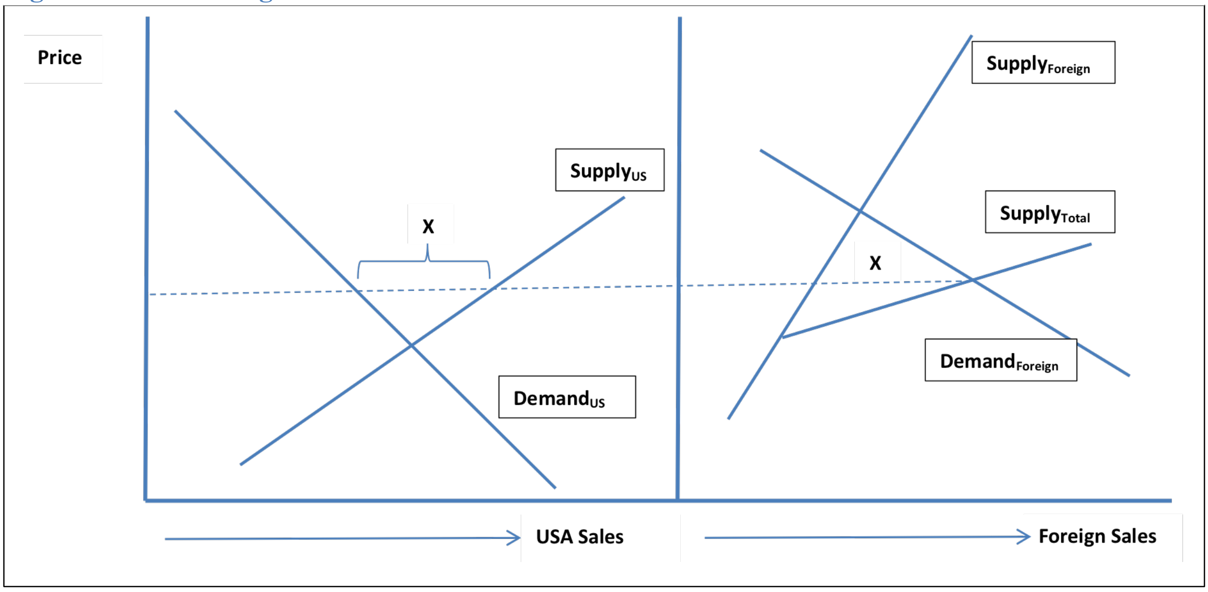
[2] Federal Register, Vol. 79, No. 158, Friday, August 15, 2014, Notices, pp. 48132-6.

eventual market outcomes for natural gas trade. This discussion will provide a useful perspective for explaining the more developed framework that the project is ultimately undertook, as described in the next major section.

Market forces allocate supplies and balance them with end-use consumption both domestically and abroad in the basic approach. By maintaining a broad definition of different regions, types of natural gas sources and end-use sectors, the model can be simulated multiple times with little additional effort. As such, it is particularly well suited to explore the range of uncertainty about how much U.S. natural gas will be exported and at what price. For both exports and price, we show a distribution of possible outcomes that provides some guidance for decision makers in both the private and public sector. The major uncertainties explored in the current analysis relate to the cost and availability of natural gas due to geologic and "above-ground" conditions, economic growth, trends in fuel-switching within end-use markets, and world oil market conditions.

The framework tracks the interactions between the North American natural gas markets and other major regional natural gas markets where US exports may be competitive. Pipeline and overseas LNG shipping corridors link supply and demand conditions in the key regions. Supply and demand conditions are calibrated initially to prices and quantities currently being projected by US Energy Information Administration in their International Energy Outlook (IEO), although there is sufficient flexibility to calibrate these variables to be consistent with other projections, such as the World Energy Outlook provided by the International Energy Agency. It is unlikely that future conditions will match the IEO projections because there exists considerably uncertainty about future resource development costs, climate and energy policy initiatives, and other factors shaping natural gas market conditions. The framework solves for new natural gas price, production and consumption levels by allowing prices to vary from their reference values.

Figure 1. USA-Foreign Market Interactions



The framework includes a mid-term outlook for the year 2025 (ten years from now) that allows sufficient time for the completion of new infrastructure for transporting natural gas across regions. It excludes explicit oil production or the petroleum market details, because oil is used quite differently than natural gas in many energy-consuming countries. An adequate treatment of oil market dynamics would require much more detail on oil refining capacity and transportation end uses than is appropriate in a model of this complexity. See Van Wagener (2014) for a recent discussion about the need for modeling to incorporate the growing exploration for liquids. Similarly, the model does not represent coal market responses that might result from widespread replacement of coal by natural gas in the power sector. In this respect, the model is quite similar in its treatment of other energy sources to other natural gas modeling efforts, such as Medlock (2012), NERA (2014) and Richter and Holz (2015).

Figure 1 contains a useful conceptual framework for incorporating the interactions between US and foreign natural gas markets. The response of US production and consumption decisions to different wellhead price levels are shown in the left-hand panel. At certain price levels at the higher end, producers are willing to offer more natural gas sales than domestic consumers want and for inventory needs. Domestic producers will search for overseas markets to sell their surplus natural gas supplies when prices reach these levels. These exports, labeled X in the figure, will be transported and added to foreign supplies to be sold to foreign consumers. Prices will balance the foreign market at a price where the total foreign supply (including US exports) satisfies the foreign demand. Prices will be higher than where domestic U.S. supply intersects with domestic U.S. demand, as the additional foreign demand for U.S. supplies creates an upward shift in price. Although not shown in the figure for simplicity, a price differential will exist between the two markets, because domestic U.S. supplies cannot be sold in Asia or Europe without adding substantial infrastructure costs for liquefying, shipping and regasifying the gas. In addition, there will be important regional differences in producing and consuming natural gas around the world.

If foreign consumers desire more natural gas or are willing to pay a higher price, the foreign demand curve in the right-hand panel will move outward. Prices will need to rise in order to encourage more foreign supplies or more U.S. exports. The latter increase not only because domestic producers provide more natural gas supply but also because some domestic consumers will reduce their use as prices begin to rise. For somewhat similar reasons, prices will also increase when foreign suppliers provide less production or incur higher finding and drilling costs. These are the major adjustments incorporated in the basic framework described in this section.

Market Responses

When market conditions change the underlying supply and demand conditions, the framework computes a new price level that balances the production and consumption of natural gas. It assumes that wellhead prices need to increase by 10 percent in order to expand natural gas production in 2025 by 7 percent. This estimate is based upon the world resource cost curve for conventional and unconventional natural gas that the Global Energy Assessment (GEA, 2012) prepared under the guidance of resource experts organized by the International Institute for Applied Systems Analysis (IIASA) in Austria. We interpreted data from their Figure 7.16 and estimated an ordinary least squares (OLS) equation that explained total resource recovery as a function of costs. Both variables were converted to logarithms; the equation is displayed in Table 1. This response is somewhat less than those derived for 14 different energy models for the United States by the Energy Modeling Forum (2013, Appendix E), which reported the supply elasticity of price equal to 0.90 and 1.06 in two separate sets of scenarios considered by the EMF. Although different geologic conditions, infrastructure and above-ground political and legal costs may result in different responses in non-USA regions, reliable estimates for other regions are not available. For this reason, this analysis applied the same response to all regions, following the approach of many global modeling systems. The framework, however, is quite flexible and can easily allow different regional responses when reliable estimates become available.

Table 1. Estimates for World Natural Gas Resource Costs

	Value	T-statistic
Constant	8.688	90.28
Price	-0.693	14.67
Adjusted R Square	0.951	
Standard Error	0.155	
Observations	12	

Source: based upon raw data from GEA, 2012, Figure 7.16.

On the demand side, it is assumed that wellhead prices need to increase by 10 percent in order to reduce natural gas consumption in 2025 by 3 percent. This response is consistent with those used in other energy models included in the same Energy Modeling Forum (2013,

Appendix E) study as discussed above. The median demand elasticity of price for 2025 and measured at the wellhead price level equaled -0.32, -0.36 and -0.37 in three separate sets of scenarios considered by the EMF. Once again, this analysis applied the same demand response to all regions, although the flexible structure allows different responses when reliable estimates are available.

This estimate of the demand response was checked by conducting an econometric estimate over the 1968-2012 period relating the growth in U.S. natural gas demand to changes in oil and natural gas inflation-adjusted (real) prices as well as in real U.S. GDP. Lagged values of natural gas demand, both natural gas and oil prices and real GDP were included in the estimation to capture the longer-run responses.[3] The estimated long-run own-price elasticity for natural gas prices was -0.293, while its counterpart cross-price elasticity for crude oil prices was 0.067. (The long-run elasticity was 0.983 for heating degree days and 0.317 for real GDP.) These estimates are shown in Table 2.

Table 2. Estimates for US Natural Gas Demand, 1968-2013

	Value	T-statistic#	
Short-Run Elasticities:			
Per Capita GDP	0.549	2.37	*
Gas Price	-0.096	3.87	**
Oil Price	0.077	3.67	**
Heating Degree Days	0.274	2.84	**
Long-Run Elasticities			
Per Capita GDP	0.317	2.61	**
Gas Price	-0.293	4.28	**
Oil Price	0.067	1.32	
Heating Degree Days	0.983	2.22	*
Adj R-squared	0.551		
F-statistic	6.85**		
Observations	44		

* Significant 5%;** significant 1%

Long-run T-statistics are for lagged coefficients.

[3] Long-run elasticities equal the coefficient for each lagged independent variable divided by the negative of the coefficient for the lagged dependent variable. These long-run relationships result by setting all changes in every variable equal to zero.

Initial Market Conditions

Table 3 lists the world regions used in the framework. The first four columns report natural gas production and consumption in 2014 and 2025 in the IEO reference case. The IEO projections made in 2013 do not reflect the lower oil price path that began emerging in late 2014. Asian and European natural gas consumers operating under oil-indexed pricing contracts are now willing to pay considerably lower natural gas prices than previously. Moreover, consumers in North America and other world regions paying market prices may also reduce their demand if they see the prices of substitute fuels like coal declining with the oil price collapse.

Table 3. Initial Natural Gas Market Conditions

	Supply		Demand		
	Reference		Reference		Low Oil Price
Region	**2014**	**2025**	**2014**	**2025**	**2025**
United States	23.6	28.4	25.0	26.9	26.0
Outside USA	6.6	7.6	5.8	8.3	8.0
OECD Europe	9.2	8.0	19.5	20.8	20.1
OECD Asia	2.5	5.0	7.2	8.5	8.2
Russia	21.4	26.3	14.6	17.0	16.5
Outside Russia	7.2	9.3	6.6	7.9	7.6
China	3.8	5.2	5.2	10.3	10.0
India	1.6	1.8	2.3	3.0	2.9
Other Asian	9.5	10.0	7.9	9.8	9.5
Middle East	19.7	25.2	15.0	19.7	19.1
Africa	7.7	10.3	3.6	4.9	4.8
Central/South America	6.2	7.9	5.2	6.6	6.4
Total World	118.9	145.1	118.0	143.6	139.1

Source: US Energy Information Administration, with Project's Adjustments.

The table's fifth column displays adjusted consumption values for the lower oil price conditions that began emerging in late 2014. Unfortunately, the EIA does not provide a comparable recent case showing the effects of a lower oil price path on international energy markets. This agency, however, does simulate a case with low oil prices in its outlook for the U.S. energy market in their Annual Energy Outlook. The estimates for lower oil prices shown in the table's last column assume that crude oil prices are 45.2 percent lower than the reference value in the year 2025, based upon the Annual Energy Outlook projections. When combined with the estimated cross-price elasticity for the effect of oil prices on natural gas consumption in Table 2, this lower oil prices causes natural gas demands in all regions to decline by 3.2 percent below their IEO reference values.

The analysis leaves the natural gas production estimates unchanged because the effect of lower oil prices is unknown. Lower oil prices would reduce the development and production of "wet" natural gas that includes liquids as a product. Operating to expand natural gas production, however, is the combination of lower rig and other drilling equipment and personnel costs and the effect of producers shifting drilling activity away from oil and towards natural gas. The ultimate effect of lower oil prices will depend upon the relative importance of these three effects. This assumption can be adjusted in future work once relevant research becomes available.

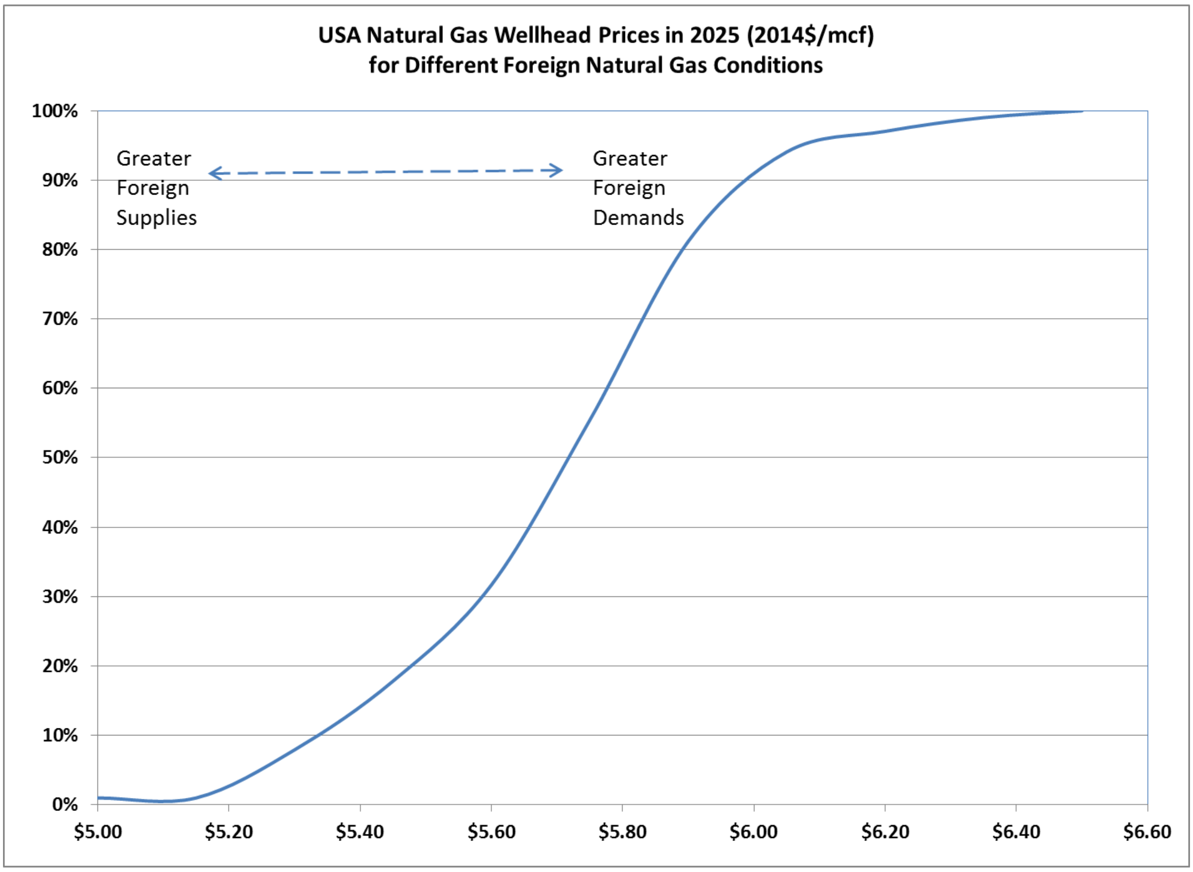
Key Outputs

Key metrics from this framework will be the growth in North American exports to Asia, Europe and possibly other regions both in the mid and long term. Export growth will depend importantly upon how competitive North American supplies are relative to other regional natural gas supply sources around the globe and the degree to which regulatory decisions either reduce or increase supply bottlenecks. Additionally, our framework will provide a range of estimates for how high domestic natural gas prices must be in order to suppress U.S. demand and so divert these supplies from domestic to overseas consumers. Additional price increases will depend upon how costly North American supplies become as production is expanded as well as how large a price increment is needed to shift natural gas away from domestic consumers.

With a relatively small, flexible, and hence computationally efficient framework, the project team is able to report these results in novel and interesting ways to the policy-making community. Instead of providing our "best guess" of what we think will happen, the team can develop new communication products that represent the range of export trade and domestic price increases that are consistent with what experts think about the underlying resource base, end-use trends, and regulatory, legal and policy constraints. For example, resource experts often discuss the different probabilities of having at least a certain volume of ultimately recoverable natural gas. Combined with other assumptions, this framework will be able to convert these probabilities into the chances that export volumes will grow by a certain rate or that domestic prices will be below a certain level. Policymakers will understand that while no one can accurately predict future market conditions, they can bound the results to determine the range of likely outcomes.

Our results also allow policy makers to better understand the robustness of their policy calculus to the fundamental uncertainty and volatility that underlies the fragmented markets for natural gas. We anticipate that this presentation of energy forecast information can elevate the state of the art for policy communication in the energy space and by doing so lead to better informed decision making in Congress and the executive branch, at the FERC and DOE, and at the state level. Finally, the framework we propose will also serve as a lens through which to view and understand the broader implications of other Stanford Natural Gas Initiative research products.

Figure 2. Distribution of Natural Gas Prices (2014$/mcf)



Evaluating Price and Export Uncertainty

This section reports results for repeated simulations of the above framework to determine the range of U.S. wellhead prices and export levels that are likely. The analysis begins with the initial conditions and key market responses discussed above. Net foreign demands are increased or decreased by set amounts and a new market price is computed. The change in initial conditions is computed for 100 different scenarios as a random number with a mean of 0 Tcf and a standard deviation of 4 Tcf. We derived this range of supply and demand conditions by evaluating publicly available forecasts from groups like the US Energy Information Administration, the International Energy Agency, and the Global Energy Assessment. Higher foreign demands will increase the demand for U.S. exports, causing domestic prices and export levels to increase. Lower foreign demands will operate in the counter direction. The responses of production and consumption to price are the same for all domestic and foreign markets in this report to demonstrate the approach, but this assumption can also be relaxed very easily by the user if they have reliable regional estimates.

Figure 2 shows a cumulative probability distribution for the U.S. wellhead natural gas price for these simulations. The chart shows the probability that the price will be at least as high as the amount shown on the horizontal axis moving from left to right. There appears to be a small chance that prices will clear markets at either a price below $5.20 per thousand cubic feet (2013 dollars per mcf) or a price above $6.40 per mcf.

Figure 3. Distribution of U.S. Export Levels (Tcf)

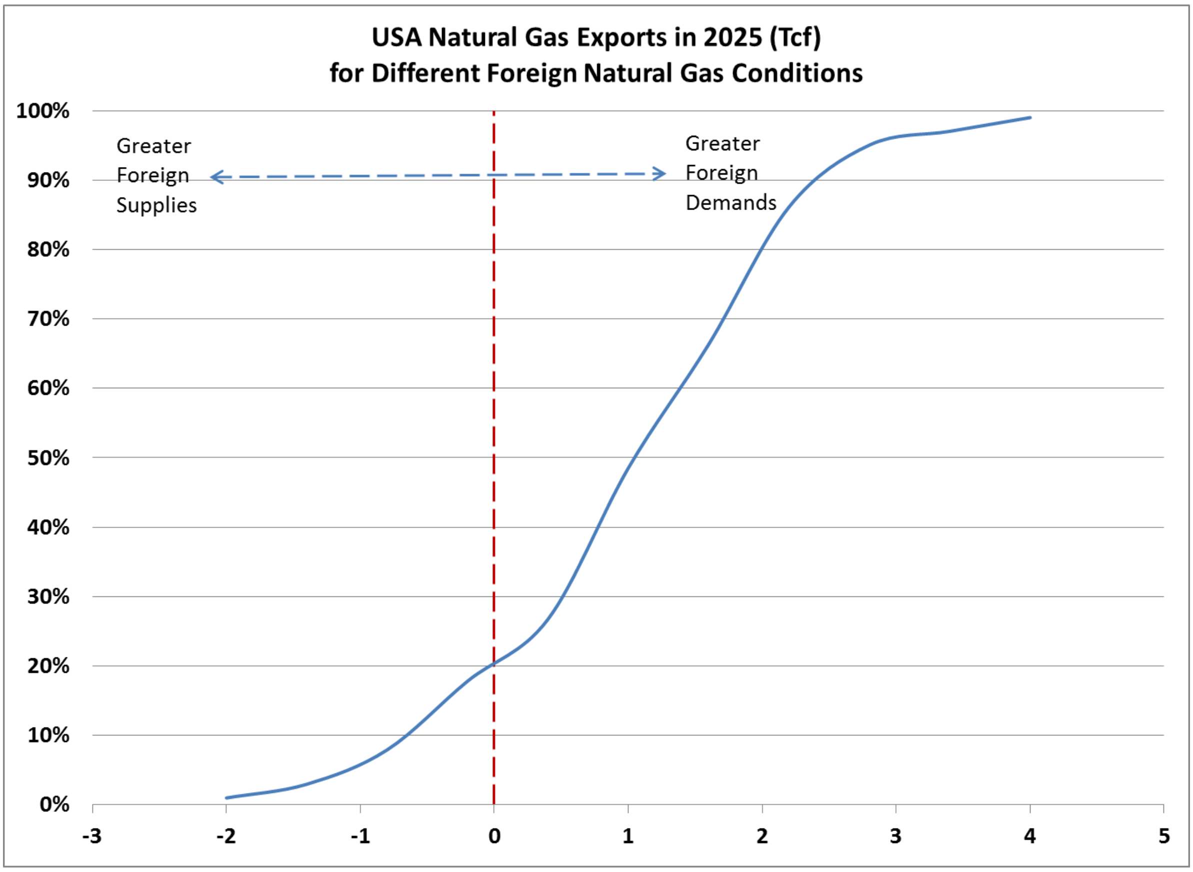


Figure 3 displays the U.S. export levels associated with the same repeated simulations. The chart shows the probability that net U.S. exports will be at least as high as the amount shown on the horizontal axis moving from left to right. There appears to be a 20%

chance that the U.S. will not be a net exporter of natural gas given these conditions. Net exports begin to move in a positive range in the remaining cases, but they do not appear to move much beyond 3 Tcf.

These results underscore the point that there will likely be some opportunities to export natural gas from the United States to other markets, but this window will be limited. It is unlikely that the market will support all the LNG export projects that are currently applying for licenses, although the government should probably allow market forces rather than regulatory review to determine which projects should proceed. Expanding LNG volumes beyond 3 Tcf will likely make these sources uncompetitive with other world regional supplies in the important demand centers.

Regional Competition Between Natural Gas Markets

The project's next step was to incorporate more regional competition into the framework in order to understand better the economic advantages and disadvantages of U.S. exports in meeting overseas demand. A model solving for the spatial competition between foreign sources in individual demand centers appears to be the most informative approach. The project team conducted modeling design and testing activities with the General Algebraic Modeling System software[4] for solving equilibrium conditions and providing consistency across spatial conditions. The GAMS software has become one of the leading programming languages for energy and climate models that trace the interactions between regional markets. GAMS maintains an extensive library of various models used for evaluating a range of different problems. Included in this library are several modeling projects conducted by Prof. Weyant with other colleagues in evaluating international oil and natural gas markets (Manne et al, 1982, 1983; Beltramo et al, 1986). The software is also the primary model architecture

[4] See http://gams.com/.

for the NERA (2014) model that has been developed and used for evaluating U.S. natural gas export policy within the Department of Energy.

Table 4. Data Sources for Regional Competition Framework

Description	Units	Source
Regions	-	2014 NERA Report
Natural Gas Production	Tcf	EIA IEO 2013 Natural Gas Production
Natural Gas Consumption	Tcf	EIA IEO 2013 Natural Gas Consumption
Projected Wellhead Prices	2012$/mcf	projected using data from EIA AEO 2013
Projected City Gate Prices	2012$/mcf	projected using data from EIA AEO 2013
Regional Supply Elasticity	-	2014 NERA Report (also EMF 31 study)
Regional Demand Elasticity	-	2014 NERA Report (also EMF 31 study)
Cost to Move Natural Gas via Pipelines through Intra- or Inter-Regional Pipelines	$/Mcf	2014 NERA Report (also EMF 31 study)
Shipping Rates	2012$/Mcf	2014 NERA Report
Regasification Costs by Region	2012$/Mcf	2014 NERA Report
Liquefaction Costs by Region	2012$/Mcf	2014 NERA Report
Costs to Move Natural Gas from Regasification Plants to City Gates through Pipelines	2012$/Mcf	2014 NERA Report
Costs to Move Natural Gas from Wellheads to Liquefaction Plants through Pipelines	2012$/Mcf	2014 NERA Report
Liquefaction Capacity by Region	Tcf	IGU World LNG Report – 2014
Regasification Capacity by Region	Tcf	IGU World LNG Report – 2014
Pipeline Capacity by Region	Tcf	IEA Statistics (Imports) - Assumption

The project team constructed a framework that operates with the GAMS software. The code for this basic version is included in the appendix. After an extensive search for appropriate and timely data, we have decided to use the sources outlined in Table 4.

Conclusions and Policy Implications

Future efforts will be directed towards applying the General Algebraic Modeling System software to implement the model and provide consistency across spatial conditions. A key consideration will be to maintain a relatively simple and transparent framework that will facilitate numerous simulations required for conducting meaningful uncertainty analysis.

The framework will also adjust drilling costs to overall market conditions so that costs will be higher when drilling and exploration activity is greater in a region. Adjustments will also be made to account for the very important above-the-ground political, legal and infrastructure costs that may augment finding and exploration costs in areas that may discourage drilling. These above-the-ground adjustments can be shifted upward or downward, depending upon the conditions that one wishes to simulate.

With these elaborations, we expect to provide a framework that communicates to the policymaker the inherent uncertainty in natural gas prices and exports. Acknowledging the full range of possible outcomes will help public decisions about licensing exports to be robust to alternative market conditions.

References

Beltramo, Mark A., Manne, Alan S. and Weyant, John P., (1986), "A North American Gas Trade Model (GTM)," *The Energy Journal*, 7(3): 15-32.

Citi GPS: Global Perspectives & Solutions, "Energy 2020: North America, the New Middle East?" March 2012.

Credit Suisse, "The Shale Revolution," Securities Research & Analytics, 13 December 2012. http://www.credit-suisse.com/researchandanalytics

Ebinger, Charles, Kevin Massy and Govinda Avasarala (2012). "Liquid Markets: Assessing the Case for U.S. Exports of Liquefied Natural Gas," Policy Brief 12-01, Brookings Institution, Washington, DC, May.

EIA (2014), *Annual Energy Outlook 2014*, U.S. Energy Information Administration, Washington, DC, Report Number: DOE/EIA-0383(2014), May 7.

EIA (2012), "Effect of Increased Natural Gas Exports on Domestic Energy Markets," U.S. Energy Information Administration, January 2012.

Eisenberg, Samuel D., Michael W. Wara, Adele C. Morris, Marta Darby, and Joel Minor (2014). A State Tax Approach to Regulating Greenhouse Gases Under the Clean Air Act, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2440925.

Energy Modeling Forum (2013), *Changing the Game? Emissions and Market Implications of New Natural Gas Supplies,* EMF 26 Working Group Report, Stanford University, Stanford, CA.

GEA, 2012: Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Manne, A S, Nelson, C R, So, K C, and Weyant, J P (1982), "CPM: A Contingency Planning Model of the International Oil Market," International Energy Program Technical Report, Stanford University.

Manne, A S, and Beltramo, M A (1984), "GTM: An International Gas Trade Model," International Energy Program Technical Report, Stanford University.

Medlock, Kenneth B. (2012), "US LNG Exports: Truth and Consequence," Baker Institute for Public Policy, Rice University, Discussion Paper.

MIT (2011). "The Future of Natural Gas: An Interdisciplinary MIT Study," Report. Massachusetts Institute of Technology Energy Initiative, Cambridge, MA.

NERA Economic Consulting (2012), "Macroeconomic Impacts of LNG Exports from the United States," Washington, DC.

NERA Economic Consulting (2014), "Updated Macroeconomic Impacts of LNG Exports from the United States," Washington, DC.

Paltsev, Sergey, Henry D. Jacoby, John M. Reilly, Qudsia J. Ejaz, Jennifer Morris, Francis O'Sullivan, Sebastian Rausch, Niven Winchester, and Oghenerume Kragha (2011). "The Future of U.S. Natural Gas Production, Use, and Trade, Energy Policy," Volume 39, Issue 9, September, Pages 5309-5321, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2011.05.033.

Richter, Philipp M. and Franziska Holz (2015). "All Quiet on the Eastern Front? Disruption Scenarios of Russian Natural Gas Supply to Europe," *Energy Policy*, 80: 177-189 (May), ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2015.01.024.

Wara, Michael, Danny Cullenward, Jordan Wilkerson, and John Weyant (2013). Analysis of the Climate Protection Act of 2013, Stanford Law and Economics Olin Working Paper No. 459, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2392656.

Van Wagener, Dana (2014), U.S. Tight Oil Production: Alternative Supply Projections and an Overview of EIA's Analysis of Well-Level Data Aggregated to the County Level," in

EIA (2014), *Annual Energy Outlook 2014*, U.S. Energy Information Administration, Washington, DC, Report Number: DOE/EIA-0383(2014), May 7.

Appendix: GAMS Model Code

```
$Title International Gas Trade Model
$Ontext
Adapted from Manne, Weyant and Beltramo and NERA Global Natural Gas Model
$Offtext

Sets
      t   time steps /2018/
      r   regions  /
Africa
Canada
CS_America
ChinaIndia
Europe
FSU
KoreaJapan
Mexico
MidEast
Oceania
Sakhalin
SE_Asia
US
                    /

    zdr(r)   zero demand regions  /
Sakhalin
/
;

alias(r,rr)
$onecho > taskin.txt
par=pr rng=pr!a1:F14
par=cons rng=cons!A1:F14
par=wp rng=wp!A1:F14
par=cp rng=cp!A1:F14
par=es rng=es!A1:F14
par=ed rng=ed!A1:F14
par=pc rng=pc!A1:N14
par=sc rng=sc!A1:J11
par=rc rng=rc!A1:F14
par=lc rng=lc!A1:F14
par=rtc rng=rtc!A1:B13
par=wtl rng=wtl!A1:B13
par=lcap rng=lcap!A1:F14
par=rcap rng=rcap!A1:F14
par=pcap rng=pcap!A1:N14
$offecho

$CALL GDXXRW.EXE data2.xlsx @taskin.txt
```

```
$gdxin data2.gdx

*$CALL GDXXRW.EXE inc_US_prod.xlsx @taskin.txt
*$gdxin inc_US_prod.gdx

*$CALL GDXXRW.EXE dec_US_prod.xlsx @taskin.txt
*$gdxin dec_US_prod.gdx

*$CALL GDXXRW.EXE Inc_KoreaJapan_cons.xlsx @taskin.txt
*$gdxin Inc_KoreaJapan_cons.gdx

Parameters
pr(r,t)       Natural Gas Production (Tcf)
cons(r,t)     Natural Gas Consumption  (Tcf)
wp(r,t)       Projected Wellhead Prices  (2012$ per Mcf)
cp(r,t)       Projected City Gate Prices (2012$ per Mcf)
es(r,t)       Regional Supply Elasticity
ed(r,t)       Regional Demand Elasticity
pc(r,rr)      Cost to Move Natural Gas via Pipelines through Intra- or Inter-Regional
Pipelines ($ per Mcf)
sc(r,rr)      Shipping Rates (2012$ per Mcf)
rc(r,t)       Regasification Costs by Region (2012$ per Mcf)
lc(r,t)       Liquefaction Costs by Region (2012$ per Mcf)
rtc(r,t)      Costs to Move Natural Gas from Regasification Plants to City Gates through
Pipelines (2012$ per Mcf)
wtl(r,t)      Costs to Move Natural Gas from Wellheads to Liquefaction Plants through
Pipelines (2012$ per Mcf)
lcap(r,t)     Liquefaction Capacity by Region (Mcf)
rcap(r,t)     Regacification Capacity by Region (Mcf)
pcap(r,rr)    Pipeline Capacity by Region (Mcf)


$load pr cons wp cp es ed pc sc rc lc rtc wtl lcap rcap pcap
$gdxin


*---------------------Setting up Supply and Demand Functions-------------------------
 Parameters        supa(r,t)  supply constant a
                   supb(r,t)  supply constant b
                   dema(r,t)  demand constant a
                   demb(r,t)  demand constant b ;

  demb(r,t) = 1/ed(r,t) + 1;
  dema(r,t)$(cons(r,t) NE 0) = cp(r,t)/(demb(r,t)*cons(r,t)**(demb(r,t)-1));

  supb(r,t) = 1/es(r,t) + 1;
  supa(r,t) = wp(r,t)/(supb(r,t)* pr(r,t)**(supb(r,t)-1));

*---------------------Scenario Parameters-------------------------------------------
Parameters
```

```
MaxExports
Quota ;
MaxExports = 1;


 Variables
           S(r,t)        regional supply (tcf)
           D(r,t)        regional demand (tcf)
           PG(r,rr,t)    ngas transported through pipelines from s to d (tcf)
           LNG(r,rr,t)   LNG transported from s to d (tcf)
           benefit       consumer and producer surplus minus transportation costs
;
 Positive Variables S, D, PG, LNG;

 Equations
          sb(r,t)           Supply
          db(r,t)           Demand
          lcapacity(r,t)    Liquefaction capacity
          rcapacity(r,t)    Regasification capacity
          pcapacity(r,rr,t) Pipeline capacity
          pcapacity(r,rr,t) Pipeline capacity
*          quotaconstr      Quota constraint
*          shock            Supply shock
          obj               Objective function
;

sb(r,t)..          S(r,t) =g= Sum(rr, PG(r,rr,t)+ LNG(r,rr,t));

db(rr,t)..         D(rr,t) =l= Sum(r, PG(r,rr,t)+ LNG(r,rr,t));

lcapacity(r,t)..       Sum(rr, LNG(r,rr,t)) =l= lcap(r,t);

rcapacity(rr,t)..      Sum(r, LNG(r,rr,t)) =l= rcap(rr,t);

pcapacity(r,rr,t)..       PG(r,rr,t) =l= pcap(r,rr);

*quotaconstr..             Sum(rr, LNG(r,rr,'2018')) =l= quota;

*shock(r,rr,t)..          Sum(rr, LNG(r,rr,'2018')) =l= MaxExports;

obj..           benefit =e= Sum(t,
*consumer surplus
*                Sum( r, dema(r,t)* (D(r,t)**demb(r,t)) )
               Sum( r,
*                Sum( r$(not zdr(r)),
*                    dema(r,t)* ((D(r,t)+0.000000000001)**(demb(r,t)/1000)) )
                  dema(r,t)*D(r,t)**demb(r,t) )
*producer cost
             - Sum( r, supa(r,t)*S(r,t)**supb(r,t) )
*transportation cost
```

```
              - Sum( (r,rr), sc(r,rr)*LNG(r,rr,t) )
              - Sum( (r,rr), pc(r,rr)*PG(r,rr,t)  )
              - Sum( (r,rr), lc(r,t)*LNG(r,rr,t)  )
              - Sum( (r,rr), rc(rr,t)*LNG(r,rr,t) )
  - Sum( (r,rr), rtc(rr,t)*LNG(r,rr,t) )
  - Sum( (r,rr), wtl(r,t)*LNG(r,rr,t)  )
                  )              /10e4

;
*S.lo('Sakhalin','2018')=1;
*lcap('US',t)=5*lcap('US',t);
sc(r,rr)= 1.5*sc(r,rr)  ;
*sc('US','KoreaJapan')= 0.9*sc('US','KoreaJapan')  ;
          d.lo(r,t)$(not zdr(r)) = 0.000001;
*           d.up(r,t)$(not zdr(r)) = 10;
*s.up(r,t)=100

*S.lo('Sakhalin','2018')=0.1
Model gngm global natural gas model /           sb
          db
          lcapacity
          rcapacity
          pcapacity
          obj              /;
solve gngm maximizing benefit using nlp;

parameter report,report2,wprice,cprice;
set value /cs,pcost,sc,pc,lc,rc,rtc,wtl/  ;

report('cs',t)=Sum(r, dema(r,t)* ((D.l(r,t)+0.000000000001)**(demb(r,t))) ) ;
report('pcost',t)=  Sum( r, supa(r,t)*S.l(r,t)**supb(r,t) ) ;
report('sc',t)=Sum( (r,rr), sc(r,rr)*LNG.l(r,rr,t) );
report('pc',t)= Sum( (r,rr), pc(r,rr)*PG.l(r,rr,t)  )  ;
report('lc',t)= Sum( (r,rr), lc(r,t)*LNG.l(r,rr,t)  )  ;
report('rc',t)= Sum( (r,rr), rc(rr,t)*LNG.l(r,rr,t) )  ;
report('rtc',t)= Sum( (r,rr), rtc(rr,t)*LNG.l(r,rr,t) ) ;
report('wtl',t)= Sum( (r,rr), wtl(r,t)*LNG.l(r,rr,t)  ) ;

cprice(r,t)$(not zdr(r))= (D.l(r,t)/cons(r,t))**(1/ed(r,t))*cp(r,t) ;
wprice(r,t)= (S.l(r,t)/pr(r,t))**(1/es(r,t))*wp(r,t) ;
```