The Shale Gas Phenomenon: Utilizing the Power of System Dynamics to Quantify Uncertainty

La Tonya N. Walker, Sandia National Laboratories[1], lnwalke@sandia.gov
Leonard A. Malczynski, Sandia National Laboratories
Peter H. Kobos, Sandia National Laboratories
Garrett Barter, Sandia National Laboratories

Abstract

Abundance of shale gas and less expensive extraction techniques led to a boom of natural gas (NG) supply in U.S. with a corresponding drop in prices. This investigation captures a multitude of economic, technological, geoscience factors that impact production. A few of the key findings include the ability to more accurately model the shale gas behavior on top of the conventional and coalbed methane-based systems within the system dynamics environment. This is especially noteworthy given the recent rapid increase in production within the U.S. The objective is to quantify the key technical and economic drivers in the United States' (U.S.) Natural Gas exploration markets. The analysis does this by quantifying conditions in the NG exploration system that can lead to innovations and transitions in U.S. NG supplies.

Importance

The low prices spurred increased use of natural gas (NG) in electric power generation, industrial and commercial uses, as well as heavy-duty transportation. With its intrinsic thermal efficiency, and low carbon-hydrogen ratio, there are also engineering and environmental benefits to using NG. However, growing the market share of NG is dependent on consumers, producers, and infrastructure stakeholders having confidence that low prices will continue in the future. If the U.S. economy becomes more dependent on NG, it also becomes more dependent and more vulnerable to its price or supply volatility as illustrated in Figure 1. Also, reducing reliance upon petroleum imports from countries that view the U.S. unfavourably would extricate foreign and military policy from energy dependencies. The increase in known, domestic NG reserves, coupled with extraction innovations, could realize such a future.

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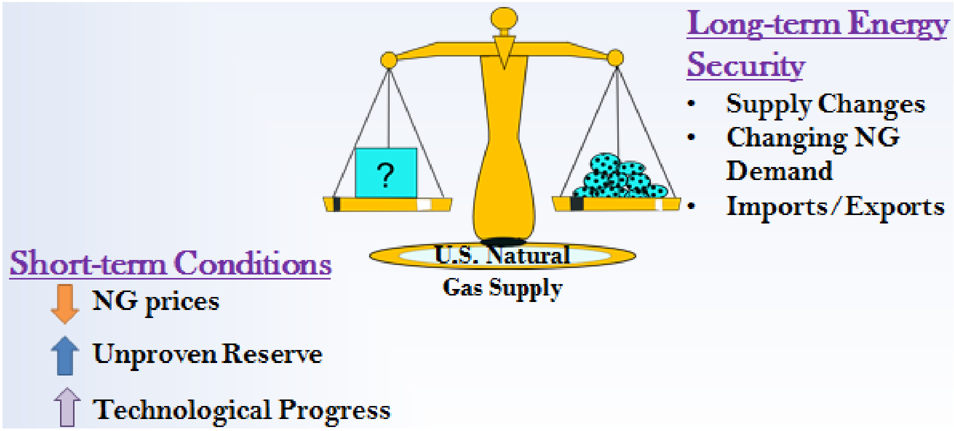

Figure 1. Natural Gas Exploration Market Factors involved in Short-term Conditions and Long-term Energy Security

Dynamic Modelling Effort

This project therefore is developing capabilities to identify the propagation pathways of NG supply shocks through the economy. By doing so, we can highlight the risks, vulnerabilities, and mitigation strategies across the NG value-chain. Hence, we could begin to assess the feasibility of using NG heavily in all economic sectors and/or of becoming a net NG exporter. This project has three primary tasks; quantifying the uncertainty in the supply, infrastructure constraints, and demand dynamics. The supply-side investigation captures the multitude of economic, technological, geoscience factors that impact production. This analysis' effort utilizes a system dynamics methodology to forecast NG production, and incorporates shale gas extraction and discovery developments, which can be leveraged to conduct sensitivity studies of future technological and economic changes.

Methodology

This quantitative modelling project began through a literature review of the NG exploration process, regulations, and history, which led to the discovery of Roger F. Naill's "The Discovery Life Cycle of a Finite Resource" model. Naill's work provides the basic understanding of NG market dynamics. The translation of Naill's model from DYNAMO syntax to Powersim© Studio syntax was an iterative, intensive effort. Once the conversion of the model was deemed accurate, a model calibration phase began to test parameters and restructure the model to reflect the current NG regulatory environment. Additional salient modeling efforts in the research community focusing on natural gas systems include Moniz et al. (2011), Medlock (2012), NPC (2011), Abada et al. (2013), Chi et al. (2009), Managi et al. (2005), and Sterman and Richardson (1985).

Natural Gas Exploration Process

Natural gas exploration is a process of characterizing sites for its potential gas output through geoscience factors (e.g. thermal maturity, TOC, reserves' areal and thickness distributions, etc.) as well as technological and economic evaluations. A site is initially refined by its geoscience characteristics, and then the assessment of technological feasibility of recovery is performed. This helps determine the breakeven price for profitable production. Then regulatory and economic environments are assessed for any additional constraints and added costs to determine if the reserve is proven to be economically producible.

Understanding the Nomenclature of NG Industry

The naming convention of natural gas quantities among the different data sources has inconsistencies. Throughout the last 50 years there have been many attempts to categorize the natural resource stocks including natural gas. A prominent attempt includes the joint effort of the Society of Petroleum Engineers and the World Petroleum Council (SPE and WPC, 2005). One early attempt is the USGS Principles of the Mineral Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey (1976). All classification systems examine two characteristic axes of a resource, knowledge of the quantity and cost of extraction. A recent attempt from the Massachusetts Institute of Technology (Moniz et al., 2011) supports the basic idea (Figure 2). This work classifies NG into Unproven Reserves (UPR) and Proven Reserves (PR). This classification preserves the general ideas expressed in more formal classification work by simplifying the supply space.

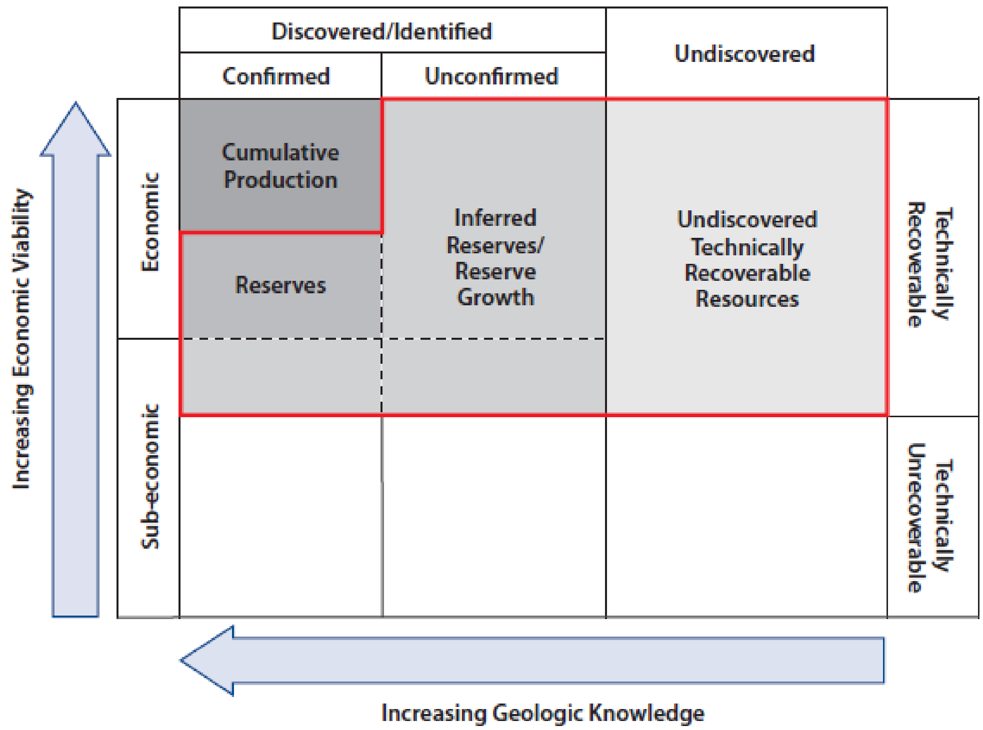

Figure 2. Adopted from Moniz et al. 2011 Figure 2.3 Modified McKelvey Diagram, Showing the Interdependencies between Geology, Technology and Economics and Their Impacts on Resource Classes

Data Collection of Publicly Available Sources

After Naill's model was converted from DYNAMO, the simulated results for price and Proven Reserves were compared to historical cumulative data from U.S. Energy Information Administration (EIA) (Walker et al., 2014). Data collection on NG industry is no small task. Collection is further complicated by the naming convention and aggregation approaches used by different sources. Therefore, the primary data sources utilized were EIA and the United States Geological Survey (USGS), and data from other sources such as Oil & Gas Journal and Potential Gas Committee were used. Acquiring shale gas time series datasets on proven reserves, production, and consumption on national and shale play aggregated levels has been a challenging task.

Basis for Model

Since the focus of the effort is to identify the potential for supply volatility, the model assumes the United States' NG industry has three main source types: Shale gas, Coalbed Methane, and Conventional with Tight gas, and all these sources are assumed to be producing a non-renewable, undifferentiated product that require a similar production process and can be used interchangeably. Each source type is assumed to be discovered and produced based on the rate of return on investments and cumulative quantity demanded. The supply-demand dynamics within the model determines the NG price at the wellhead as a weighted average of the total costs of all three sources. This assumption of undifferentiated product is similar to one used by Naill (1973) and Sterman and Richardson (1985).

The model considers effects of recognizing increases in the potential reserve based of technically feasible NG unlike the models of Naill (1973) and Sterman and Richardson (1985), which have a single fixed initial value for technically-recoverable reserve. The technologically-recoverable reserve increases due to the recognition of gaseous hydrocarbons developed from source rocks (i.e., shale gas and coalbed methane) (USGS 2013 and NPC 2011). The recognition of these formation types as a technically-recoverable, economically profitable possibility was caused by the technological breakthroughs of using horizontal drilling with hydrologic fracturing. The reserve increase estimates were acquired from the USGS. Currently, the model simulates this as a discrete and exogenous input process, but technology improvements are not explicitly modelled. A future direction of the model is to have technology improvements be an endogenous process based on some internal thresholds.

Additional core model assumptions are:

- No interdependencies between gas and oil.
- Total production cost for each source type is a proportional to its cost of exploration.
- The cost of exploration is assumed to rise as resources are depleted.
- Quantity demanded is a function of current price and exponential growth in usage over time.
- Investments in exploration are determined by sales revenue generated.

The initial insights into the basic dynamics of NG industry were derived from Naill's work (1973). The objective of Naill's NG discovery model is to "represent and analyse the implications of the factors that control the supply of non-renewable resources, in order to determine the nature of the turning point in supply, and examine the effectiveness of various policies in alleviating the [shortage] problem" (Naill 1973). The main focus of the model is to determine trends that would answer the question of what are the effects of governmental policies such as ceiling price regulations or tax incentives on the short-term and long-term supply of NG resources. The motivating processes in the model are the economic processes that cause the transfer of NG from unknown resource to proven reserve category and subsequent exploitation of those reserves. There are two feedback loops in the Naill's NG discovery model, which are:

Discovery) Negative feedback loop, that symbolizes the long-term effects of unproven reserves depletion on the exploration cost and discovery rate, which relates unproven reserves, cost of exploration, discovery rate together.

Market Demand) Goal-seeking loop, that dictates the need for new discoveries though proven reserves, usage rate, and price, and is the system's equilibrium mechanism via Reserve-Production ratios (R/P) to desired R/P.

Though Naill's model provided valuable insights, it does not address supply volatility issues without modifications. The substantial increase in the technically-recoverable reserves (unproven reserves) caused by technological advance is not possible in this model structure. Also, Naill's model does not track different NG source types and their associated parameter differences.

In addition, Naill's model contained price policies for regulations that were no longer applicable for the time period of interest (shale gas boom of early 2000's and beyond), which complicated understanding the system's behavior. Therefore, price ceiling and control structure was removed from the model. Prior to 1992, price controls regulation existed, which caused hindrances via suppressed production and restricted real demand (Joskow 2013). The model begins in 1993 to eliminate those complications.

Arraying Model by Source Types

Then the model was arrayed to include producing and potential shale gas plays, cumulative coalbed methane, and cumulative conventional gas. The model produced results that were difficult to explain given the understood dynamic behavior. Thus, the modelers decided to go back to the pre-arrayed model to make the problem more tractable. The model was arrayed using three categories: Conventional, Shale, and Coalbed Methane. The national datasets became more important at this stage of the research to calibrate the model for shale gas and coalbed methane.

With this change in model structure, the modelers recognized that the different NG source types have inherent differences in normal cost of exploration and discovery delays. This alteration was deemed necessary because the production behavior for shale gas and coalbed methane differ substantially from conventional natural gas.

The considerations identified in the decision to array by source types:

- *How NG price is determined.* The NG price is a singular value as a weighted average function of all three natural gas types' costs and could be comparable to Henry Hub Price. The current structure may allow the proven reserves of a specific type to decrease while another increases due to the individual prices being different. The price and total cost influence investments in explorations which directly influences discovery rate. The individual total costs were maintained to influence investments in exploration for specific types (e.g., percent invested in exploration (PIIE) and sales revenue (SR)).

- *How usage rate is handled.* The total usage rate is the cumulative NG quantity demanded. The total usage rate is distributed among the source types based on their exploration costs (i.e., the highest portion of total usage rate taken from the source with lowest exploration cost). One important aspect is the restructure to redistribute total usage when a source type's proven reserve is depleted. The quantity demanded is determined by price and exponential growth in potential usage.

- *How initial technically-recoverable (unproven) reserves is determined.* The U.S. Unproven Reserves estimate (2203.3 tcf) was obtained from the EIA for 2009, but three historical values for end of 1992 were better initiating parameters. This process took two phases: estimate 1992 cumulative production prior to arraying the model, and then estimate individual initial unproven reserve parameters.
    - In the first stage for non-arrayed model, a value for the end of 1992 was approximated based on Naill's Gas-in-Place[2] estimate (1040 tcf) assumed be accurate in 1962 (Naill 1973) subtracted by end of 1992 proven reserve and estimate cumulative production from 1900 to 1992. The initial cumulative Unproven Reserves amount was incrementally increased to estimate suitable initial values and optimized using Powersim Solver, an evolutionary search algorithm built-in the Powersim© Studio software.
    - In the second stage for the arrayed model, initial unproven reserves for each source type were calculated. The 1992 cumulative Gas-in-Place value was distributed between the three source types based on their approximate percent contribution to the EIA 1992 cumulative NG production. It was assumed the production distribution reflects the unknown, but assumed distribution in unproven reserves. Then individual unproven reserves subtracted by three source type 1992 proven reserve estimates and their entire, historical individual production from 1900 to 1992 reported by EIA.

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[2] Gas-in-Place is the NG original quantity regard as technically-recoverable before production started in 1900. Naill obtained this Gas-in-Place estimate from Hubbert (1969).

Current Model

Our model structure allows understanding the motivations that caused shale gas boom in the early 2000's, which will lead to providing forecasts and variability in the unconventional resource estimation. The model simulates from 1993 to 2035. The casual loop diagram (Figure 3) is the aim of the model structure.

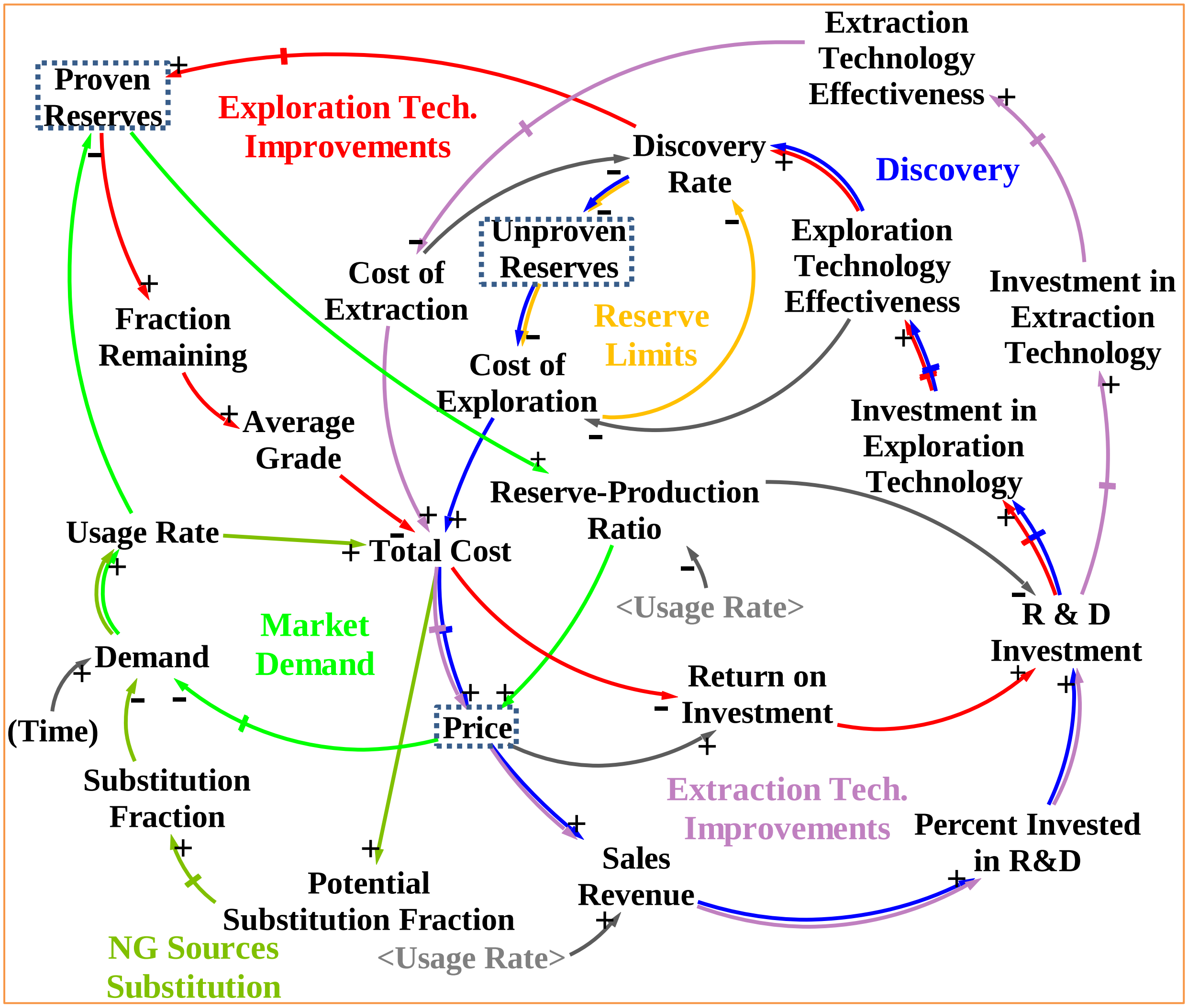


Figure 3. Causal Loop Diagram illustrating the conceptual intersections of Naill's natural gas discovery model and Behrens's natural resource Utilization Model (Meadows and Meadows, 1973) with the addition of exploration and extraction technologies for NG exploration market. (Note: An influence arrow with a minus sign at the end refers to the underlying inverse nature of the relationship between the variable at the beginning of the arrow and the end. Thus, if the beginning variable increased, the minus sign suggests the variable at the end of the arrow will decrease by some relationship. The dashed boxes highlight the major stocks in the model.)

Several loops in Figure 3 offer topic-specific information that is salient to the underlying operations of the model. The 'Exploration Technology Improvements' loop (shown using red lines) was developed to motivate the proven reserves by quantifying the relationship between new exploration technology's ability to potentially increase proven reserves. From there, if the 'Proven Reserves' increase, this increases the 'Fraction Remaining' of the available proven reserves of natural gas. If the 'Fraction Remaining' increases, there is a potential for the 'Average Grade' of natural gas available to increase, but this part of the model is largely available as a placeholder when expanding the model to site-specific gas fields. From the 'Average Grade', if this increases then the ability to maintain a similar output (of BtUs, for example) could translate into a reduced 'Total Cost' for that amount. When 'Total Cost' increases, the 'Return on Investment' would decrease which would decrease the amount of 'R&D Investment' available to the system. If 'R&D Investment' increases, this might manifest itself in terms of increasing the 'Investment in Exploration Technology' and thereby increase the potential to increase 'Exploration Technology Effectiveness'. When the 'Exploration Technology Effectiveness' increases, so might the 'Discovery Rate' of new natural gas which then affects (increases) the 'Proven Reserves' to complete the 'Exploration Technology Improvements' loop.

Similarly, the influential and subject-specific loops exist in the model shown in Figure 3 that include 'Extraction Technology Improvements', 'Reserve Limits', 'Natural Gas Sources Substitution', as well as the two previously describe including the 'Market Demand' and 'Discovery'. It is worth mentioning the 'Natural Gas Sources Substitution' represents the trade-offs between the three reserves types within the model including shale gas, conventional and tight gas and coalbed methane.

Confidence Building
'Did you build the **RIGHT Model**? Did you build the **MODEL Right**?'

To address these questions, the confidence building process was performed using five testing levels. These levels, illustrated in Figure 4, include System Mapping (correct structure & actors), Quantitative Modeling (observed behavior modes), Hypothesis Testing (feasible decision rules & boundaries), Uncertainty Analysis (realistic sensitivities), and Forecasting & Optimization (quantitative & predictive).

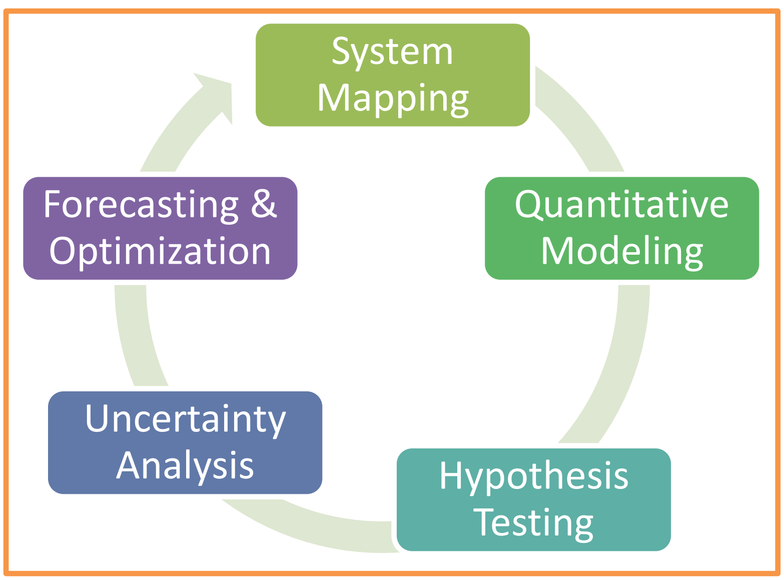


Figure 4. Levels of Confidence in the Pragmatic Approach (Zagonal and Corbet 2006), Built Confidence in the Model's Structure and Parameters.

Calibration and Sensitivity Analysis

The calibration and sensitivity analysis are iterative processes. The calibration was implemented using literature review to define a probable range of suitable values for the constant in the model (e.g. discovery delay and normal cost of exploration), and then using optimization to reduce the squared residuals between simulated and historical EIA proven reserve data.

The singular sensitivity analyses were performed using two approaches to assess the potential risks: Tornado diagram (Figure 5) and a triangular distribution to develop the probability distribution plot (Figure 6). The model tested for its sensitivity to 50% increase and decreases to all the initial and constant parameters. In the risk assessment approach, estimates of the specific parameters were tested by using a combination of optimization and risk analysis via evolutionary search and Latin Hypercube methods, tools within Studio software.

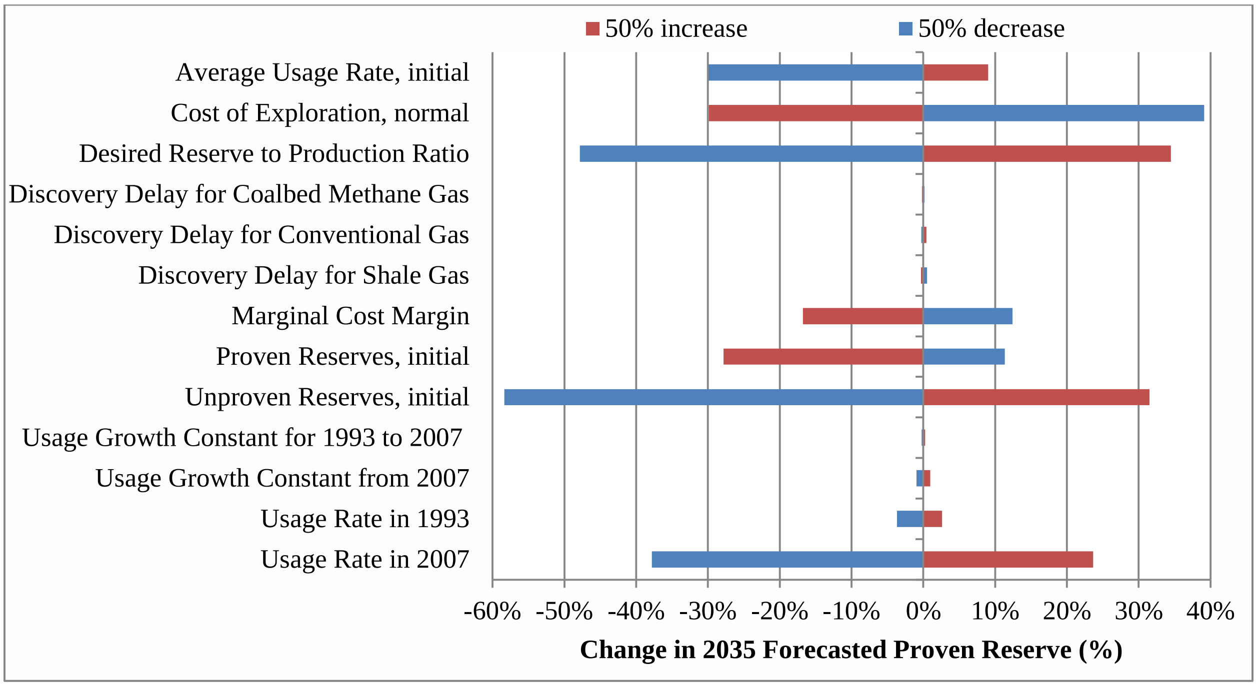
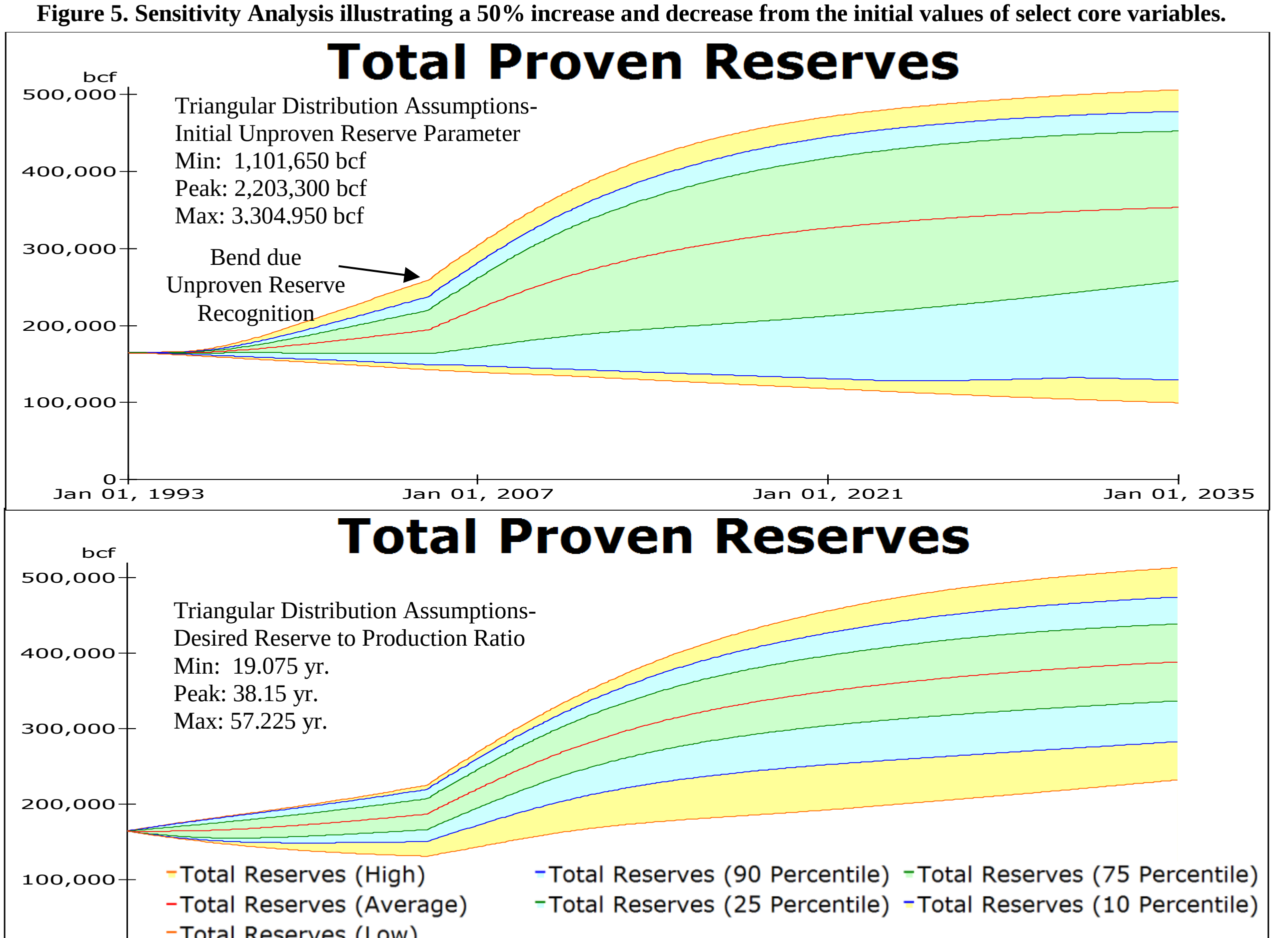
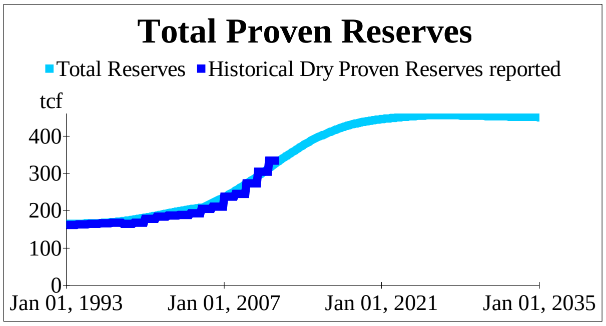


Figure 5. Sensitivity Analysis illustrating a 50% increase and decrease from the initial values of select core variables.

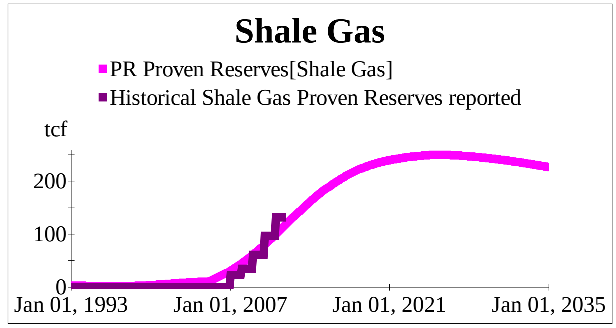


Preliminary Results

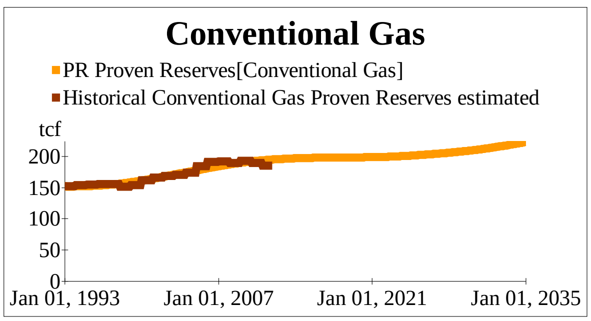
The simulated results of this model were compared to historical estimates of NG reserves and extraction rates, in order to build confidence in the model. Figure 7 illustrates the simulated and historical natural gas reserves.



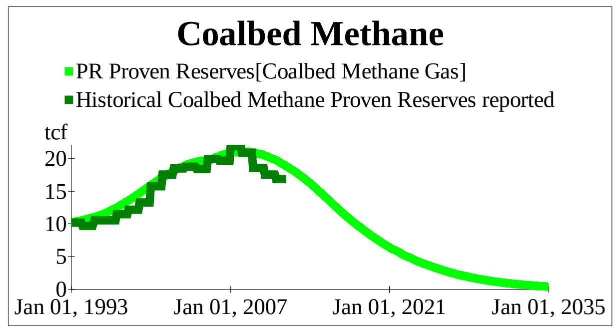
Comparison of Simulated Results to EIA Historical Results for Total Proven Reserves.



Comparison of Simulated Results to EIA Historical Results for Shale Proven Reserves.



Comparison of Simulated Results to EIA Historical Values for Conventional Gas Proven Reserves.



Comparison of Simulated Results to EIA Historical Values for Coalbed Methane Gas Proven Reserves.

Figure 7. Simulated and EIA Historical Proven Natural Gas Reserves.

Figure 7 illustrates the close correspondence between the general shapes of the simulated results to the historical data. This is encouraging due to the fact the underlying model framework is reflective of the underlying dynamics. Specifically, as shown in Figure 8, the Reserve-Production (R\P) ratio helps drive the underlying behaviour of the NG investments which then influences the available supply. These in turn influence the ultimate price of NG within the representative market.

In the shale NG graphic within Figure 7, it is noteworthy to point out that using the original Naill model with several modifications, his underlying framework proved to be useful. The shale component of Figure 8 illustrates the large increase in the R/P ratio accurately reflecting the substantial increase in proven reserves seen in the U.S. in recent years.

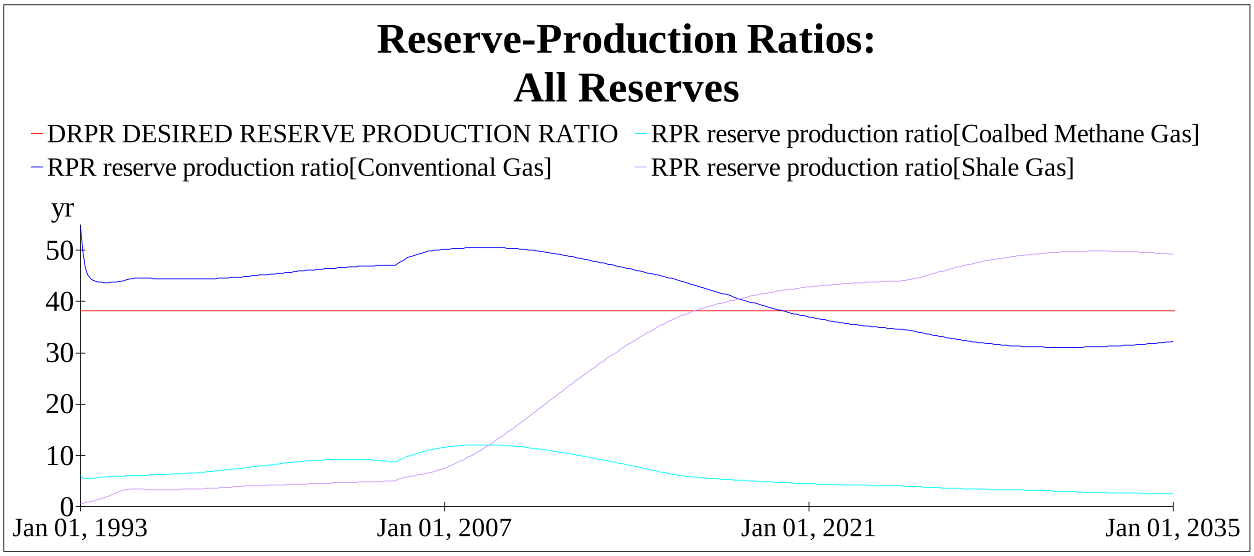


Figure 8. Comparison of Simulated Results among three source types and desired state for Reserve-Production Ratios.

Discussion and Future Research

Much of the research showed successful matching of the underlying model's results to historical shale gas data. This is a unique and novel approach to capturing the geologic, technological and economic considerations of the NG market during recent surges in shale gas production. The next stage of this project is to incorporate policy design and evaluations.

- Shale gas model:
    - Explore the behavior, possibly introduce an exogenous variable based on threshold analysis (based on reserve to production ratio) and related items.
- Delivery Constraint:
    - How do current infrastructure limitations constrain available supply to meet demand in regions of the U.S.?
- Introduce more technology:
    - Using fewer resources to extract shale gas
    - Potentially use learning curve calculations to lower normal cost of exploration
    - Introduce competition among source types in reserve exploration investments
- Policy considerations:
    - Environmental costs or benefits of increased NG extraction and consumption
    - Potential exporting of NG

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