Allocation of Natural Gas to Consumption Sectors through Differential Price Paths

Farzaneh Daneshzand[†], Ali Elkamel, Michael Fowler[†], and Mohammad Reza Amin-Naseri[††]
Department of Chemical Engineering, Khalifa University of Science and Technology, SAN Campus, P. O. Box 2533, Abu Dhabi, United Arab Emirates
[†]Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G, Canada
[††]Industrial and Systems Engineering Faculty, Tarbiat Modares University, Tehran, Iran

fdaneshz@uwaterloo.ca, ali.elkamel@ku.ac.ae, mfowler@uwaterloo.ca, amin_nas@modares.ac.ir

Abstract

Reliable energy supply is a vital and crucial role of any country and affects its economic and social development. Energy subsidies in many countries, while enhancing welfare levels, cause over-consumption of energy, lead to supply insecurity and environmental effects. Energy pricing is a key factor in controlling energy demand on one side, and incentivizing supply, on the other side. This paper develops a mathematical model for natural gas supply and demand system to study how differential pricing of natural gas leads to an optimal allocation of it to various demand sectors. The consumer prices of natural gas in each sector affect the sectors' demand according to its elasticity to the price. On the supply side, optimal pricings affects providing financial resources for natural gas development and supply. The optimal price path of each sector, which maximizes the net present value of net income, maximizes the net present value of underground resources value at the end of planning horizon, and minimizes CO_2 emission are proposed using a system dynamics model. The model is applied to a case study. The optimal price paths determine a different allocation of natural gas to demand sectors compared to the Business As Usual case.

Keywords:
Natural Gas, Pricing, Energy Policy, Supply and Demand, System Dynamics

1. Introduction

Energy has an important and vital role in the social and economic development of countries. Ensuring a reliable energy supply and demand system with appropriate growth is the main concern of any country to ensure comprehensive development. Studying the effectiveness of policies for a better performance of the national energy system is very crucial for every country.

Natural gas is an important primary energy resource in different countries and among fossil fuels, has the best prospects of growth until 2035, especially due to its low carbon intensity (Holz et al., 2013; Exxon Mobil 2017). According to the positive prospects about the increase in natural gas consumption in many countries, mathematical models dealing with studying, forecasting and optimizing natural gas supply and demand are very useful at national and international levels. In this paper, a model for natural gas supply and demand system is developed to study the optimal allocation of natural gas resources to demand sectors through pricing policies. Energy prices, their direct effect on energy consumption, and their indirect effect on micro and macro-economic variables have been studied in several researches. These vary from studying the effects of prices on demand and consumption (Wang and Lin, 2014; Dagher, 2012) to the indirect effects on consumer price index, GDP growth, etc. (Zhang et al. 2017, Shahbaz et al., 2014).

Some researches specifically investigate the countries' plans to reform natural gas pricing or to remove regulations or subsidies from their domestic natural gas prices. China, as a big energy consumer with plans to increase the natural gas share in its primary energy mix, has a price reform strategy to help grow natural gas supply (He, Lin 2017). According to this plan, Zhang et al. developed a Computable General Equilibrium model to analyze the effect of domestic natural gas price increase on the overall Chinese economy indexes like GDP, imports, and household, government and enterprises income. They concluded that the chemical industry will be most influenced by any natural gas price increase (Zhang et al. 2017). Zhu et al. used an input-output model to analyze the natural gas price effects on the industrial and residential sectors. They concluded that the Chinese nationwide natural gas pricing reform will have a relatively small effect on general price levels and the country's total economic output (Zhu et al. 2016). Two studies from Russia used a Computable General Equilibrium Model to decide about the optimal domestic price of natural gas and to investigate how that price affects the Russian economy as a whole, household and electricity sector, and greenhouse gas emission (Orlov 2015, 2017).

In this paper, a simulation optimization model is developed to study a natural gas supply and demand system. The relationship between natural gas income and investments in the development of natural gas resources are modeled. On the demand side, various consumers of natural gas are grouped into five categories of residential, industrial, power plants, transportation and injection to oil fields, known as sectors. Export is also considered as a different sector which natural gas can be allocated to. The natural gas demand of all these sectors is modeled as a log-linear regression model using various explanatory variables. The common explanatory variable is the natural gas and natural gas' substitute price for that sector. One of the main aims of the model is to study how differential pricing of natural gas for each sector affects the sector's demand and total natural gas demand each year. On the other hand, how the prices and the natural gas volume consumed by each sector affect natural gas income from that sector, and how this total income will provide financial resources for future developments in natural gas supply. These relationships are modeled using a dynamic simulation method named system dynamics. System dynamics is a simulation method used for analyzing the behaviour of complex systems by identifying the causal structure of a system. This type of modeling focuses on the relationships between various subsystems that cause nonlinear behaviour in the long term. Therefore, they are suitable models to be used for forecasting the long term behaviour of system's variables and to study how various policy options affect them.

2. Modeling

System Dynamics method is used for modeling systems with a lot of endogenous interactions to simulate the long term behaviour of systems variables (Casey, Töyli 2012). The nonlinear interactions of subsystems lead to nonlinear behaviour of variables which is interesting for policy makers to know the long term outcomes of their decisions. The modeling starts with defining the important subsystems, the important variables, their endogenous relationships and the relationships with other exogenous variables. Understanding these relationships helps in developing a *causal loop diagram* which relates variables according to their causalities. This provides a descriptive model which is converted into a quantitative one called stock and flow diagram by differential equations. A stock variable represents the accumulation of inflows and outflows during the time. The stock's value at a moment signifies the state of the system at that time. The inflows and outflows can represent the flow of information, material, etc. in a time unit (Figure 1, Eq. 1).

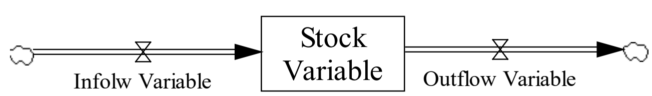

Figure 1. Stock and Flow Variables

$$Stock_t = \int_{t_0}^{t} \left(Inflow_t - Outflow_t\right)dt + Stock(t_0) \qquad \text{Eq.1}$$

The main variables modeled in our problem are, demand consisting of residential and commercial, industrial, power plants, transportation, injection to oil fields and export; natural gas and natural gas substitute price for all of these sectors, the operational and investment costs, the income made from natural gas sold to each sector, CO_2 emission, annual income and the volume of natural gas allocated to and consumed in each sector. Figure 2 represents how each demand sector is modeled. Each demand sector is affected positively by the price of natural gas, and negatively by the price of natural gas' substitute for that sector. Each demand sector has a different elasticity to price. Elasticity is formulated as a percentage of change in the quantity of demand to the percentage of change in price (Eq.2). The more elastic the demand is to the price, the more the demand decreases with the price increase. Some of the other explanatory variables are population, urban percentage, family income, GDP and energy productivity index. The demand equations are formulated as log-linear functions (Eq.3)

$$e_p = \frac{dQ/Q}{dp/p} \quad \text{Eq.2}$$

$$Y = \exp\left(\alpha_0 + \alpha_1 \ln(x_1) + \alpha_2 \ln(x_2) + \cdots\right) \quad \text{Eq.3}$$

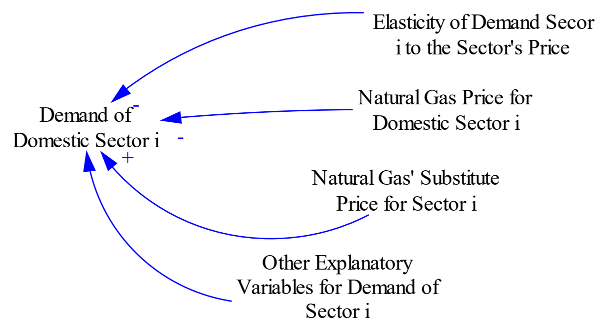

Figure 2. Modeling Natural Gas Demand for Each Sector

Natural gas provider decides about investment in development according to its forecast about future demand. It is assumed that the policymakers decide about the developments required using the previous five-year trend of total demand. This calculation is updated every year to avoid possible distortions. Monetary budgets are important constraints for this investment. The budgets come from the accumulation of yearly natural gas income as shown in figure 3. The yearly income and the operational and investment costs increase and decrease the cumulative budget respectively.

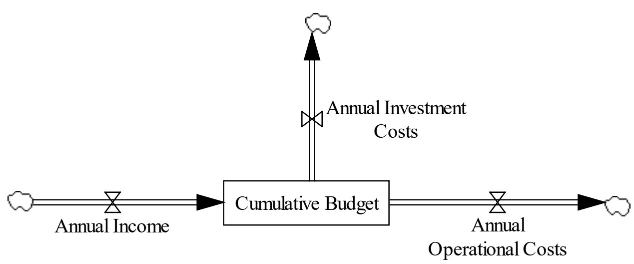

Figure 3. The Cumulative Budget Model (Daneshzand et al. 2018)

Some of the causal relationships and loops are depicted in Figure 4. A positive or reinforcing loop is a relationship between variables that generates feedback to the original source of change and reinforces it. A negative or balancing loop happens if the relationship opposes the original change. The more cumulative budget available, the more investment is possible in natural gas development and more production will be possible in future. More production provides a higher capacity for natural gas export and more export leads to more income which increases the cumulative budget (Loop 5 in Figure 4). The negative loop 1 indicates that with more natural gas production, the volume of developed reserves decreases. The negative loop 2 shows that when production increases, the operational costs increase, and these costs reduce the amount of the cumulative budget. The operational costs are directly related to the production volume. Therefore, less fund will be available for investment in natural gas development, and the volume of developed reserves decreases. Loop 3 indicates the same concept for investment costs.

3. Simulation and Results

The model is simulated on Vensim software using the data of natural gas in Iran from 1985 to 2015. More than 60% of primary energy in Iran is supplied by natural gas (Energy Balance Sheet, 2015). Natural gas production has increased drastically in Iran during the past 30 years and Iran is the third biggest producer of natural gas (BP 2017). However, because of low natural gas prices, the income made from natural gas is minimal. Almost all natural gas produced is consumed domestically, and only 4% of the produced natural gas is exported (Energy Balance Sheet, 2015). Currently, the income from crude oil export, arising from the substitution of domestic oil products with natural gas, has provided the required budget for investments in natural gas development. But there is a hypothesis that by reducing this substitution rate, the required capital for investment in natural gas will diminish. We use the developed model to simulate natural gas supply and demand in Iran, to forecast its future trend, and to study corrective policy options.

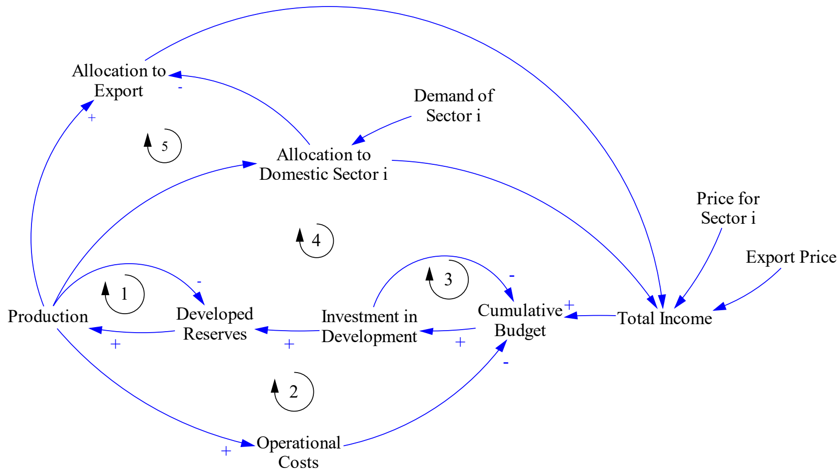

Figure 4. Modeling Supply Side

First, the model is validated to see if it can be used for forecasting future trends. The main model's variables known as policy options that affect natural gas supply and demand are the price of natural gas determined for each demand sector in each year, and the volume of natural gas that is allocated to export. The price for each sector and its effect on demand and supply were discussed earlier. These policy variables ultimately determine the natural gas share consumed by each sector. We first study the business as usual case (BAU), in which all variables continue their past trends. Therefore, in BAU we assume that each domestic sectors' natural gas prices from 2017 to 2035 and natural gas export continue the past trends. The model's result shows that in this case there will be a gap between supply and demand and that the investment in natural gas resources cannot keep up with the growing natural gas demand (Figure 5). This is because of low domestic natural gas prices that do not provide enough financial capital for investment in natural gas development, and cause low levels of developed reserves.

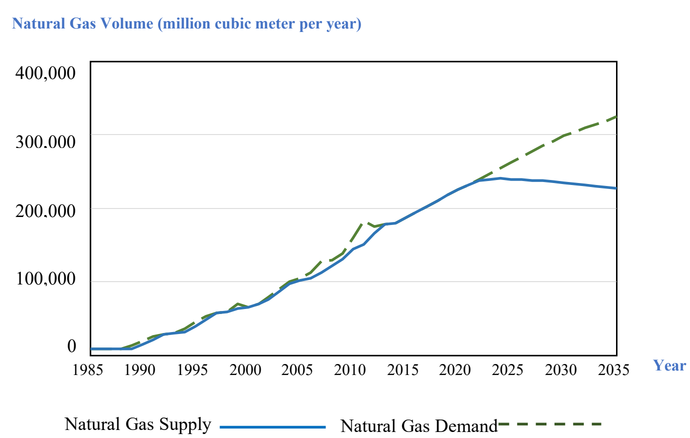

Figure 5. The Forecasted Gap between Supply and Demand

According to this result, different policy options were examined to study how each sector's natural gas price should be annually determined to control natural gas demand on one side and to provide enough capital for investment in development on the other side. Simulation optimization methods were used for searching over various options. The objectives considered in this simulation optimization are listed in equations 4 to 6.

$$\textit{Maximize the net present value of } (\textit{annual income} - \textit{annual operational costs} - \textit{annual investment costs}) \qquad \text{Eq.4}$$

$$\textit{Minimize } CO2 \textit{ emission cost} \qquad \text{Eq.5}$$

$$\textit{Maximize the net present value of } (\textit{underground natural gas value at final period}) \qquad \text{Eq.6}$$

The optimization process traverses over various values of decision variables and selects the best values according to objective functions and their weights, which determine the priorities to the decision maker. Figure 6 and 7 represent a sample result of the model. Figure 6 illustrates each sector's price in each year. These prices indirectly affect the sectors' demand and the amount of natural gas which is allocated to them. Figure 7 also represents the optimum values for the allocation of natural gas to export and injection. For these two sectors, natural gas domestic prices do not affect the demand and consequently the volume allocated to them. Therefore, the allocation of natural gas to these sectors are determined directly.

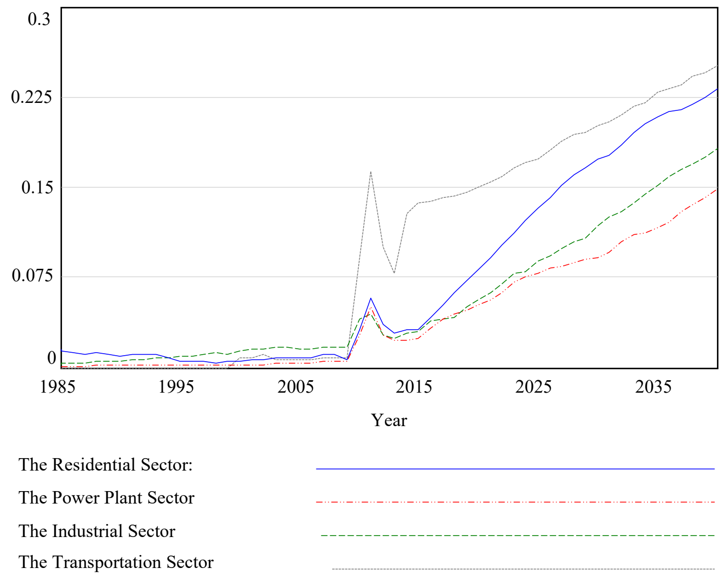

Figure 6. Natural Gas Price Path for Each Domestic Sector

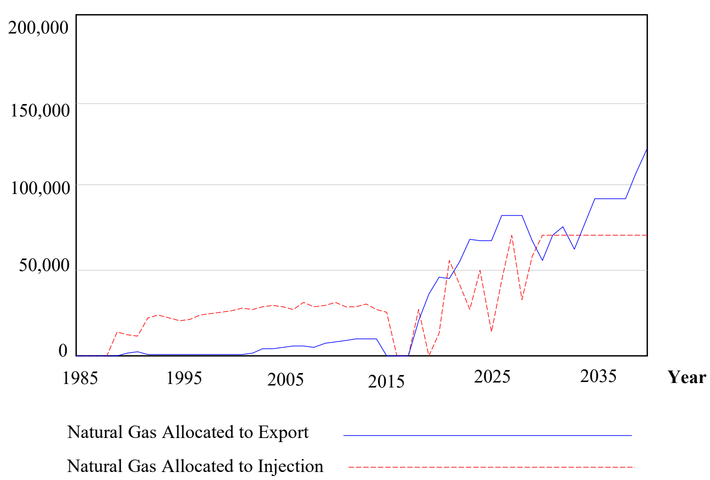

Figure 7. The Annual Natural Gas Allocated to Injection and Export

Figure 8 represents how natural gas allocation to various sectors varies from 2015 to 2040. These changes are due to two reasons, first the business as usual change of demand in each sector according to the function estimated for each, which relates the demand to the explanatory variables, the second reason is due to the changes in each sector's natural gas prices determined in the optimization process. These prices affect natural gas demand. The higher the price is determined for a sector, the lower its demand will be. In figure 6, the natural gas price for the residential sector has the highest growth compared to other sectors. Therefore, the residential sector is the sector with the lowest growth of natural gas consumption in 2040 compared to 2015.

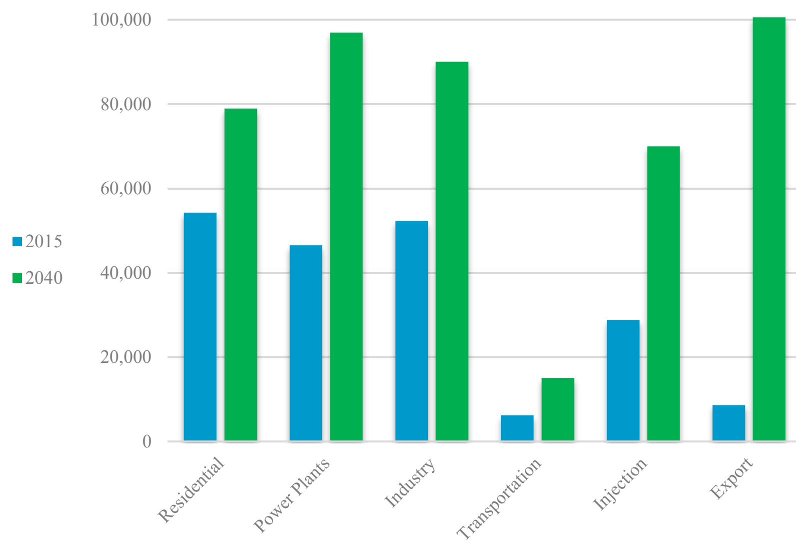

Figure 8. Natural Gas Allocated to Each Sector at the Start and Final Period

Conclusion

Ensuring a reliable energy supply with minimum cost is one of the main priorities of each country, and a prerequisite for economic and social development. Among energy resources, natural gas has the prospects to be one of the most growing energy resources of future and to be replaced with more polluted fuels like coal and oil products due to its lower pollution. In this paper, we presented a system dynamics model to study supply and demand reactions in response to pricing policies for each demand sector. The relationships between price and demand, price and supply, and supply and demand are modeled in a dynamic way. Using simulation optimization methods, the optimum price paths that guarantee supply security, maximize the net annual income, and minimize CO_2 emissions are proposed in the model.

The model is used to forecast the future natural gas supply and demand in the case study of Iran with more than 60% share of natural gas in the primary energy supply mix. The model forecasted a gap between supply and demand before 2025, if the current pricing policies for domestic sectors continued. It is concluded that the current pricing does not provide enough capital for future investments in natural gas development. According to this forecast, the optimum price paths are determined using various objective functions. These price paths indirectly affect how natural gas should be allocated to various demand sectors optimally. The results for the case study show that the highest increase should be for natural gas allocated to export and the lowest growth is related to the natural gas allocated to the residential sector.

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Biographies

Farzaneh Daneshzand is a postdoctoral fellow at the University of Waterloo. Her background is Industrial and Systems Engineering and her main research focuses on techno-economic analysis of energy systems using various optimization and simulation modeling techniques. In her PhD research she developed a simulation based optimization model for natural gas supply and demand systems to study pricing policies and their effect on energy supply security, reducing fossil fuel consumption, reducing CO_2 emission, and incentivizing supply.

Dr. Ali Elkamel is a Professor of Chemical Engineering. He holds a BSc in Chemical Engineering and BSc in Mathematics from Colorado School of Mines, MSc in Chemical Engineering from the University of Colorado-Boulder, and PhD in Chemical Engineering from Purdue University – West Lafayette, Indiana. His specific research interests are in computer-aided modelling, optimization and simulation with applications to energy production planning, carbon management, sustainable operations and product design. Professor Elkamel is currently focusing on research projects related to energy systems, integration of renewable energy in process operations and energy production systems, and the utilization of data analytics (Digitalization), machine learning, and Artificial Intelligence (AI) to improve process and enterprise-wide efficiency and profitability. Prof. Elkamel supervised over 90 graduate students (of which 35 are PhDs) and more than 30 post-doctoral fellows/research associates. Among his accomplishments are the Research Excellence Award, the Excellence in Graduate Supervision Award, the Outstanding Faculty Award, the Best teacher award, and the IEOM (Industrial engineering and Operations Management) Outstanding Service and Distinguished Educator Award. He has more than 280 journal articles, 141 proceedings, and 33 book chapters. He is also a co-author of four books; two recent books were published by Wiley and entitled Planning of Refinery and Petrochemical Operations and Environmentally Conscious Fossil Energy Production.Dr. Michael Fowler is a Professor and is cross-appointed to the Department of Mechanical and Mechatronics Engineering at the University of Waterloo. Professor Fowler's research focuses on electrochemical power sources in vehicles, specifically degradation analysis and control of batteries in hybrid and plug-in hybrid power trains. His interest takes him into the modelling of fuel cells and requires simulating the performance and reliability of fuel cells and batteries. Professor Fowler's research group is interested in performance evaluation, diagnostics, and forensics associated with fuel cell stacks, single cells and batteries. His study of fuel cell failure mode and reliability also encompasses the extensive development of polymers due to their function as the fuel cells' electrolyte, gas diffusion layer and blending of polymers for conductive bipolar plates.

Dr. Mohammad Reza Amin-Naseri is a professor of industrial and systems engineering at Tarbiat Modares University, Tehran, Iran. He is a member of the Institute for Operations Research and Management Sciences (INFORMS), and national Iranian Productivity Organization. His research focuses on Energy Planning and

Optimization including non-renewable and renewable energy considering environmental problems, energy markets, elimination of subsidies and its effects on various aspects of economical social and environmental aspects.