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Highlights

- A natural gas supply and demand system is modeled using system dynamics.
- The optimal consumption share of each demand sector is determined through differential pricing.
- Environmental and economic objective functions are investigated.
- The residential sector has a much smaller share and export and transportation a much larger share of the recommended consumption mix in 2040.
- Appropriate policies will result in up to 11% reduction in CO_2 emission on the demand side.

A System Dynamics Model for Optimal Allocation of Natural Gas to Various Demand Sectors

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Abstract

Natural gas is the most promising fossil fuel in the transition to a low-carbon energy future, and many countries have long term plans to increase its share in their energy supply mix through pricing regulations. While these policies encourage substitution of natural gas with more polluting fossil fuels, its over consumption and inefficient use can lead to misallocation of resources and CO_2 emission increase. This paper develops a supply-demand model to optimally allocate natural gas to various demand sectors through determining a price path for each sector. The dynamic effects of price on demand, and income on supply are modeled using system dynamics. The model is applied to a case study on the optimal consumption share of each demand sector according to economic and environmental criteria. The results show that the residential sector should have a much smaller and export much larger share of the recommended consumption mix in 2040.

Keywords: Energy Policy, CO_2 Emission Cost, System Dynamics, Energy Systems Planning, Pricing, Natural Gas

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1. Introduction

Natural gas (NG) is the most promising fossil fuel in the transition to a low-carbon energy future, since its combustion produces less CO_2 in units of generated energy, compared to oil and coal (Holz et al., 2013). NG will be a more important fuel in the world's energy supply mix by 2040, with a steeper growth rate than any other fossil fuel over the next three decades (Exxon Mobil, 2017), and an average 1.9% yearly increase in its global demand between 2012 and 2035 (IEA 2014, 2017). NG trade over long distances has increased rapidly in the last few decades and many countries now have long term plans to increase its share in their energy supply mix. Several models have been developed to forecast future NG demand for countries in which NG currently is or will be one of their main energy resources according to these plans (Hartono et al., 2017; Shaikh and Ji 2016; Azadeh et al., 2010; Melikoglu 2013; Honore 2014; Taspinar et al., 2013; Boran, 2015), and a number of them studied the technical issues of NG development like network expansion problems (Da Silva et al., 2016; Zavala, 2014; Isom et al., 2018; Odetayo et al., 2018). Subsidizing or keeping NG prices low are among those plans that can encourage NG usage as a replacement to more polluting fossil fuels. Such plans result in higher NG share in the countries' energy supply mix, but simultaneously, can lead to over consumption, wastage of energy, and inefficient allocation of energy resources, especially in NG producing countries with access to low-cost hydrocarbons (Fattouh and El-Katiri 2013; Schneider and Saunders, 2000). In these cases, while the unit consumption of NG is less polluting than other fossil fuels, its overconsumption will contribute to environmental damages and real economic costs, and depletes nonrenewable NG reservoirs.

Energy pricing is one of the major instruments in the overall energy policy in any country, used to satisfy various and usually contradictory objectives (Bhattacharyya, 2011). This is a kind of governments' interventions in energy markets which is quite widespread (Bhattacharyya, 2011) and distorts the optimal allocation of resources (Bacon et al. 2010). Energy prices play an important role in controlling demand

and also providing enough incentives and financial capital for energy supply. In this paper, we study the effect of prices in an NG supply and demand system using a dynamic model. Since energy use can be intermediate or final, prices should distinguish between consumers (Bhattacharyya, 2011). Therefore, we examine different prices for each demand sector and investigate their effect on that sector's demand including the residential, power plants, industrial, and transportation as the biggest possible consumers of NG in a country. On the supply side, prices have a direct effect on providing financial resources and future investments. Adjustments in various sector's NG demand and supply due to price changes lead to a different consumption share for each demand sector. The optimal price in each year, i.e. price path, for each demand sector from 2015 to 2040 is determined. The solution offers the optimal way NG should be allocated to various demand sectors.

2. Literature Review

In this paper, we study NG allocation to demand sectors through pricing policies. Accordingly, the reviewed papers in this section are divided into two groups. The first is focused on studies with the aim of determining NG allocating priorities and the second includes papers investigating domestic NG prices.

Hutagalung (2014) analyzed the problem of NG allocation priority to domestic sectors in Indonesia using a Computable General Equilibrium (CGE) model. In his model, the impacts of NG shortages on macroeconomic variables were investigated in various scenarios. His analysis determines that the priorities in allocating NG to the domestic sectors should be industry, the petrochemical sector, crude oil production, and electricity. John Rowse (1986) presented a nonlinear optimization model for allocating Canada's NG to domestic and export markets using optimal depletion concept. The consequences of allocation based on wrong assumptions were investigated in pessimistic and optimistic scenarios for Canada's gas export market. More recently, Maroufmashat and Sattari (2016) developed a linear mathematical model to study the replacement of oil products with NG and to allocate NG to demand sectors in Iran. The model has supply and demand constraints for each sector and has been implemented in three scenarios that differ in their supply and demand limits. Alikhani and Azar (2015) proposed a Fuzzy Goal Programming model for allocating NG to various sectors and to deal with vague input data and decision maker's uncertainties in defining the preferences of the goals and weights of objectives. They concluded that NG injection, export, and transportation should be prioritized over other options.

The other group of studies investigates how domestic NG prices affect energy and economy variables. Energy price is one of the main variables directly influencing energy demand and supply, and indirectly affecting micro and macro-economic variables. These studies vary from calculating the NG price elasticity of different demand sectors (Wang and Lin, 2014; Dagher, 2012), to determining the price effects on macroeconomic variables (Shahbaz et al., 2014). Orlov (2015) studied the Russian government's plan to eliminate domestic NG price regulation. He developed a static multi sector CGE model to find the optimal domestic NG price, and to investigate the impacts of its increase on the whole economy. His findings suggested that the domestic NG price should be 55% of the export netback price to result in increased government revenue, reduced total CO_2 emission, and a shift in the economy from energy-intensive industries to non-energy intensive ones. In another paper, he studied the effect of domestic NG price increases on households and the electricity sector in Russia, using a dynamic multi-sector multi-region CGE model. He examined how a government revenue increase due to higher domestic NG prices could be used to reduce greenhouse gas emission through investment in energy efficiency programs (Orlov, 2017). Zhang et al. (2017) developed a CGE model to analyze the effect of domestic NG price increase on the overall Chinese economy indexes like GDP, imports, household income, and government and enterprises income. This investigation is based on the NG price reform plan in China to help grow NG supply (Paltsev and Zhang, 2015). They concluded that the chemical industry will be most influenced by any NG price increase. Zhu et al. (2016) used an input output model to analyze the NG price effects on the industrial and residential sectors. They concluded that the Chinese nationwide NG pricing reform will have a relatively small effect on general price levels and the country's total economic output.

In this paper, a long-term planning model is developed to optimize the allocation of NG to various demand sectors through specific price path for each sector in view of economic and environmental criteria and supply sustainability. The domestic demand sectors studied are the residential and commercial, power plant, industrial, transportation, injection to oil fields for enhanced recovery, and export. The price paths for the first four sectors and the amount of NG allocated to export and injection are determined leading to an optimum NG consumption mix for 2040. The dynamic effects of each sector's price on its demand and on NG income and NG supply, and the effects of each sector's NG price on NG substitute usage and CO_2 emissions are modeled. System dynamics method is used to simulate the mentioned dynamics, then using simulation optimization approaches, the optimal values of prices are determined. In our previous research, (Daneshzand et al. 2018), we developed a system dynamics model to study the sustainability of domestic NG supply by modelling the effect of NG income on providing financial capital in NG industry. In that work, all domestic demand sectors were modeled aggregated, and allocation to various domestic sectors was not modeled. According to Table 1, which summarizes the papers most related to the present work, to the best of our knowledge, none of the previous studies have planned NG allocation to demand sectors through pricing policy tools and modelling the aforementioned dynamics and interrelationships. The model hereafter is called Dynamic Model for optimal Allocation of NG through Differential Pricing, "DMADiP".

Table 1- Comparison of related studies in literature

Paper	**Modelling**		**Purpose of the model**					Environmental Measures	Case Study
	Method	Dynamic	Domestic NG Development	Consumption Priorities			Effect of NG Price on Economic Variables		
				Optimal Allocation	Different Domestic Demand Sectors	Using Price Tools in Allocation			
Rowse, 1986	NLP[1]	✓	✓	✓					Canada
Dayo, Adegbulugbe 1988	LP[2] (MESSAGE[3])	✓	✓					✓	Nigeria
Boucher, Smeers, 1996	NLP[1]	✓	✓						Indonesia
Hutagalung, 2014	CGE[4]	✓	✓		✓		✓	✓	Indonesia
Orlov, 2015	CGE[4]			✓			✓	✓	Russia
Alikhani, Azar, 2015	FGP[5]				✓			✓	Iran
Maroufmashat, Sattari 2016	LP[2]			✓	✓				Iran
Zhu et al. 2016	Input-output						✓		China
Orlov, 2017	CGE[4]	✓					✓	✓	Russia
Zhang et al. 2017	CGE[4]						✓		China
Daneshzand et al. 2018	SD[6]	✓	✓			✓			Iran
DMADiP	SD[6]	✓		✓	✓	✓		✓	Iran

[1]NLP stands for nonlinear programming, [2]LP: Linear Programming, [3]MESSAGE: Model for Energy Supply System Alternatives and their General Environmental impact, [4]CGE: Computational General Equilibrium, [5]FGP: Fuzzy Goal Programming, [6]SD: System Dynamics

3. Modelling

This section first introduces system dynamics method briefly, then explains the important variables and sub-systems of the problem and their counter-effects that shape the dynamics of the model. In the remaining subsections, we explain how the system’s subsystems are modeled by providing the causal loop diagram, stock and flow diagram, and important equations of the quantitative model.

3.1 System Dynamics Method

System dynamics is a modelling technique grounded in control and nonlinear dynamics theory first introduced by Jay Forrester in 1961. System dynamics focuses on modelling systems with various dynamics feedbacks using computer simulation. It models complex interactions among many factors in a system to study how nonlinear interactions influence the behaviour of the system over time. This approach is an aspect of systems theory enabling the modeler to understand the nonlinearities of a system through modelling its structure including circular feedbacks or time delayed relationships between the system’s elements. System dynamics models are used to predict the behaviour of systems and to develop and analyze structural policies and the efficiency of decision makings (Li et al. 2016). The model enables the modeler to find solutions to change the behavior of the system, by considering different dynamics and side effects (Sterman, 2000).

Qudrat-Ullah et al. (2018) describe how a system dynamics model with structure-behavior graphs and stock and flow perspectives can address energy problems as complex, dynamic, and long-term ones with many interactions with the economy, environment, etc. System dynamics technique has been used for developing models for different types of energy like oil and gas (Kiani and Pourfakhraei, 2010; Hosseini and Shakouri 2016; Li et al. 2016), electricity (Qudrat-Ullah et al., 2018; Pereira and Saraiva, 2011) and renewable energies (Aslani et al., 2014; Robalino-Lopez et al., 2014; Mohammadia et al., 2016).

Yeo et al. (2013) divide modelling with SYSTEM DYNAMICS into three phases. Logical modelling phase consisting of problem definition, developing the *Causal Loop Diagram*, and conceptual design of the model. This phase tries to qualitatively reveal the structure of the system. The next phase is model quantification in which the system is qualitatively modeled using *Stock and Flow Diagram*, data are collected and the model is validated. The last phase is the model application in which the validated model is used for various purposes such as forecasting the future behaviour of the system, examining various policy options and analyzing the results of decisions over time.

A causal loop diagram includes a set of nodes that represent the variables, and arrows that represent the relationship between the two variables. The positive (negative) sign at the end of the arrow indicates that the increase in the first variable causes an increase (decrease) in the other. If the relationships between variables generate a feedback loop that reinforces the original change, it is a positive or reinforcing loop; if it opposes the original change, it is a negative or balancing loop. The stock and flow diagram transforms descriptive relationships into a quantitative one through differential equations. A stock variable is represented as a rectangular box and a flow variable as an arrow pointing into or out of a stock variable. The stocks are representatives of the accumulation of inflows and outflows over time that characterize the state of the system (Figure 1).

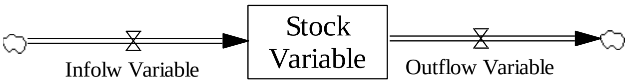


Figure 1. Stock and flow variables

$$Stock_t = \int_{t_0}^{t} (Inflow_t - Outflow_t)dt + Stock(t_0)$$

3.2 Subsystems and their Interactions

The presented work models a supply and demand system to optimize the allocation of NG to various demand sectors through different price paths for each sector, i.e. differential pricing. In DMANDiP, six NG consumption sectors including the residential, power plants, industrial, transportation, injection to oil fields and export are studied. The dynamic effects of price on the consumption of the first four sectors and the effect of income made by the allocation of NG to all sectors on supply are modeled. Figure 2 gives an overview of the developed model. The main variables and their interactions are depicted inside the gray box and exogenous variables are outside. Decision variables are NG price for the first four domestic sectors, NG allocated to export and NG allocated to injection, and the evaluation criteria are NG income, CO_2 emission costs, and underground reserves' value. The NG price for the first domestic sector affects NG demand and also NG substitute's demand in that sector. The demand in each domestic sector plus NG production decides the amount of NG that can be allocated to that sector. NG and NG substitute consumption in each sector determine CO_2 emission. It is assumed that produced NG is first consumed in the domestic sectors because of their higher priority. Injection to oil fields, which aims to enhance oil recovery in future years, and export have less priority in NG allocation. Thus, NG production and NG allocation to domestic sectors affect NG allocation to export and injection. The NG allocated to domestic sectors, NG allocated to export, and NG price for each sector determine NG income, which in turn influences NG production through providing financial resources. NG injected to oil fields increases oil recovery and oil resources' value at the end of the simulation period. Moreover, the production and consumption of NG in the various sectors, apart from the injection, reduce underground NG resources and their value. Modelling all these yearly dynamics, the optimum NG allocation to the six demand sectors are determined.

With a holistic view of the main variables and their relationships now established (Figure 2), the different parts of the model need to be explained in more detail, using the causal loop and stock and flow diagrams. The next three sub-sections explain the model's important formulations that represent demand and supply sub-systems and their interactions.

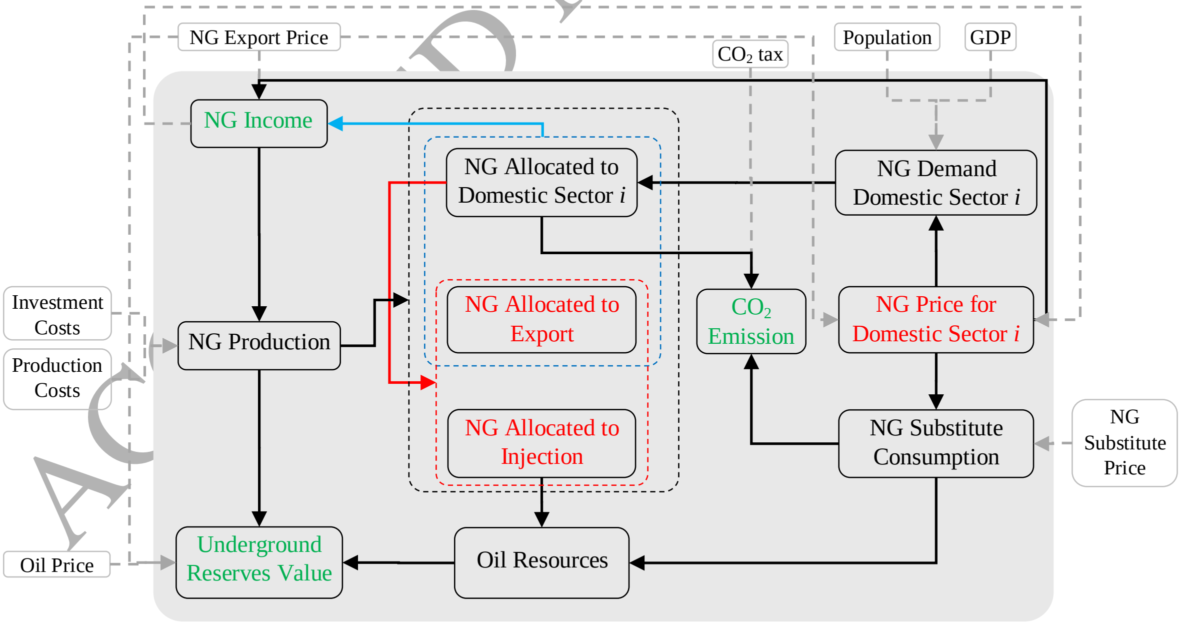


Figure 2. Overview of the presented model

i = 1 to 4, 1: residential, 2: power plant, 3: industrial, and 4: transportation sector

3.2.1 Reinforcing Loops of Supply and Income

There is a reinforcing loop between supply and income. Many decisions about investing in the development of proven reserves in the supply side, which will be explained in the following sub-sections, are related to *Cumulative Income*. The inflow rate to *Cumulative Income* is *NG income*, which is determined by the level of export and NG consumption in each domestic sector on the demand side. The reinforcing loops between the level of consumption in each sector and the effect on cumulative income, and finally on the production rate, are shown in Figure 3 and represent the interactions between supply and demand. Throughout the paper, these loops are called income-supply reinforcing loops.

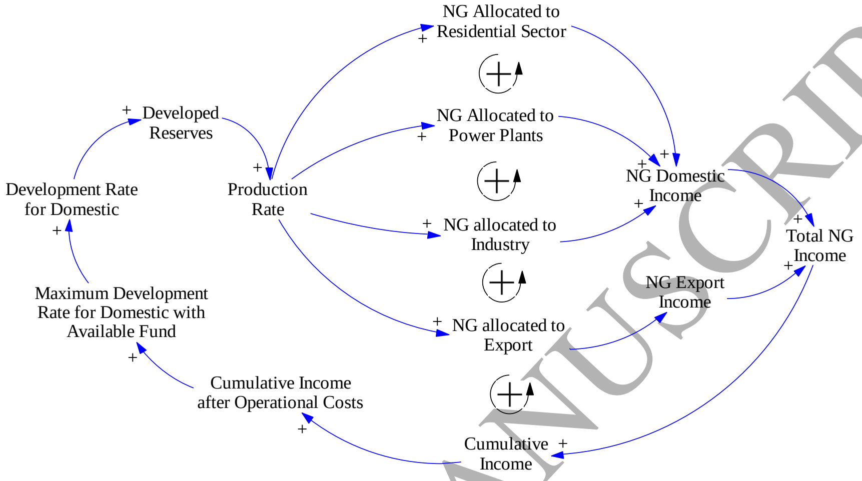


Figure 3. Reinforcing loops between supply and income

3.2.2 Demand Sub-system

As mentioned, six demand groups are modeled in DMANDiP. Since domestic NG prices affect NG demand in the first four sectors including the residential, power plants, industrial, and transportation, these sector's prices are modeled as a stock variable which is determined by annual price change as shown in Figure 4. *NG Export Price* affects *Domestic Sector*$_i$ *Price Change* because it is assumed that domestic prices cannot be more than export prices.

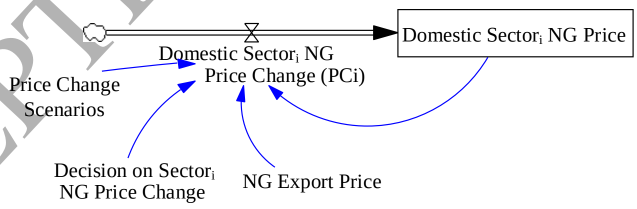


Figure 4. NG price model for each domestic sector

Energy demand in each sector and also NG share for supplying that demand is estimated using a log-linear regression function based on explanatory variables, x_1, x_2, ..., as formulated in Eqn. 1 (Bhattacharyya, 2011). Figures 5.a and 5.b represent the variables affecting the energy demand and NG share for two domestic sectors. For instance, residential energy demand is estimated based on urban percentage, income, and population. Then, the residential NG share is determined by the NG and NG substitute's price and NG pipeline length, which represents NG development in regions of a country. Other sectors' energy demands and NG shares are also determined by similar variables. CO_2 generated by energy consumption, and income made by selling NG to each sector is measured according to the level of NG consumption in each sector.

$$Y = \exp(\alpha_0 + \alpha_1 \ln(x_1) + \alpha_2 \ln(x_2) + \cdots) \tag{1}$$

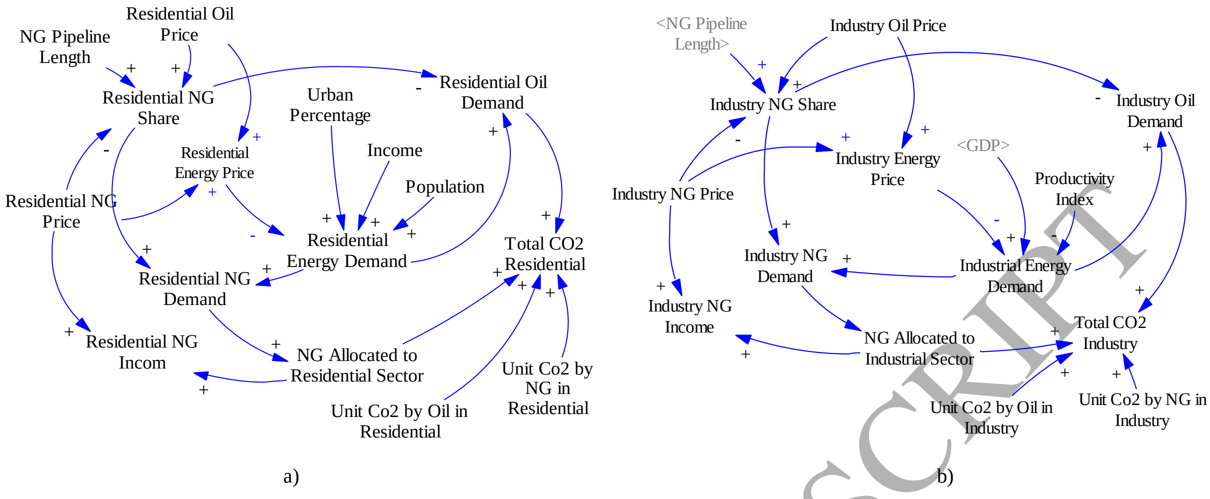


Figure 5.a) Residential NG demand model, b) Industrial NG demand model

Injection, as depicted in Figure 6 is not affected by NG prices. Injection upper limit is the maximum injection technically required, based on the state of oil fields (Thomas, 2008) and is an exogenous variable in our model. The model decides about NG allocated to injection, but this allocation is constrained by total NG production and the NG allocated to other domestic sectors that have higher priorities to avoid shortages between supply and demand. It is assumed that the NG used for oil fields' recovery enhancement is reserved and can be extracted in the future (Pashakolaie et al., 2015); therefore, all NG allocated to injection is accumulated in a stock variable and increases NG reserves' value at the end of the planning horizon. Moreover, NG injection enhances oil recovery and increases oil reserves' value.

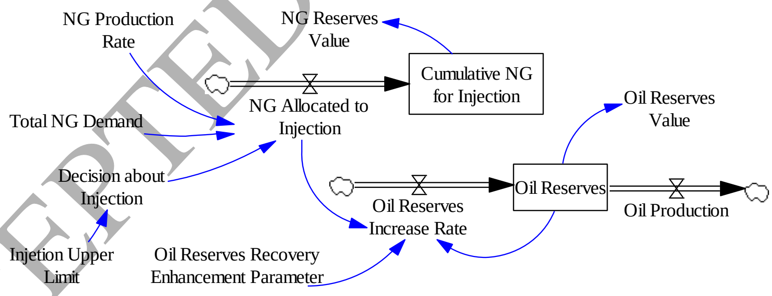


Figure 6. Modelling NG for Injection

3.2.3 Supply Sub-system

The stock and flow diagram of supply, income, and investment in NG development is presented in Figures 7 and 8. Developed reserves and proven reserves are modeled as two stock variables which determine the NG ready for production whenever needed, and deterministic underground NG reserves respectively. Proven reserves are converted to developed reserves after investment and development. Developed reserves are increased by development rate and decreased by production rate (Eqn.2). Production rate is determined according to the NG production profile, the volume of developed reserves divided by the reservoir's lifecycle, and cannot be more than NG demand (Eqn.3).

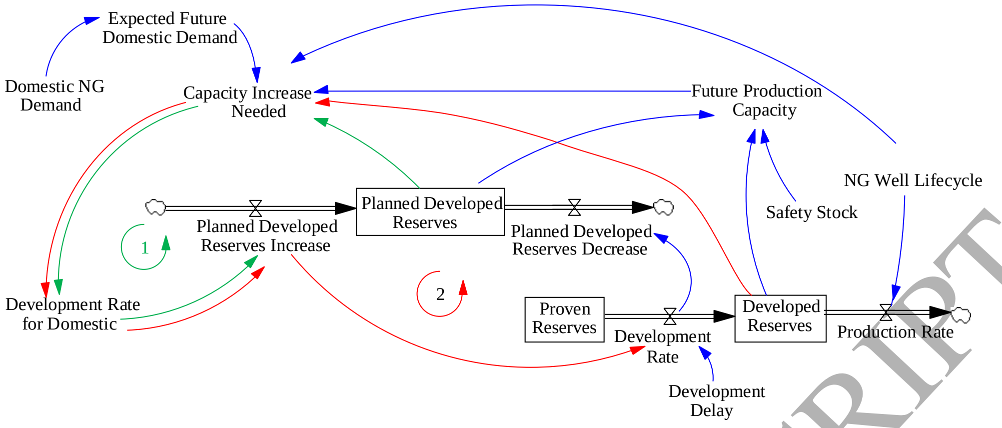


Figure 7. Modelling production rate in the supply side

In each period, the decision about investment in NG development for domestic usage depends on the state of available and planned developed reserves, which determine the production capacity of future years, and the estimates of planners about future domestic NG demand. The *Expected future Domestic Demand* is determined according to recent domestic demand trends. Eqn. 4 indicates that the past three year trend of domestic demand provides an estimation for the future. For deciding about investment in NG development for domestic usages, estimated demand should be compared with *Future Production Capacity*. Since there is a delay between the decision about investment in NG development and development, production capacity in period $t + DDl + SS$ should be greater than or equal to demand estimates for this period. DDl is the development delay and SS is the safety stock as defined in the Appendix. Safety stock is considered to reduce the risk of any possible shortages. Therefore, Eqn. 5 measures the future production capacity which is the current and planned developed reserves minus domestic demand in the delay and safety stock period divided by NG reserve's lifecycle. *Capacity Increase Needed* determines that if future production capacity is less than expected domestic demand, an investment in NG development equal to the opposite of future production capacity multiplied by NG lifecycle is needed (Eqn. 6). Since the feasible development rate is limited to available financial resources, it cannot be more than the *Maximum Development Rate for Domestic with Available Funds*, and the available fund for investment in the domestic sector is the total cumulative income when operational costs are deducted (Eqns. 7-9). After the decision is made about development rate for domestic usage, it is stacked in a stock variable named *Planned Developed Reserves*, which decreases after a time delay in which all operational development tasks take place (Eqns. 10-14). Balancing Loops 1 and 2 in Figure 6 indicate that less capacity increase is needed when there are enough *Developed Reserves* plus *Planned Developed Reserves*.

All money made by NG sales to domestic and export markets plus other financial resources allocated to the NG industry are accumulated under *Cumulative Income*. *Operational Costs*, *Investment Cost for Export*, and *Investment Costs for Domestic*, the latter calculated based on the *Development Rate*, decrease the *Cumulative Income* (Eqns. 15-17). Withdrawals from the cumulative income to meet operational costs are assumed to have the highest priority, as, if not met, domestic NG demand cannot be supplied. Thus, the *Maximum Development Rate for Domestic with Available Funds* is calculated by the *Cumulative Income*, after the *Operational Costs* is deducted (Eqn. 7). Loop 4 explains the relevant balancing loop. When production rate increases, more money for the operational cost is needed and will reduce the available cumulative income that can be used for investment in infrastructure. Thus, the maximum development rate for the domestic sector with available funds decreases, and less NG investment for the domestic sector is possible.

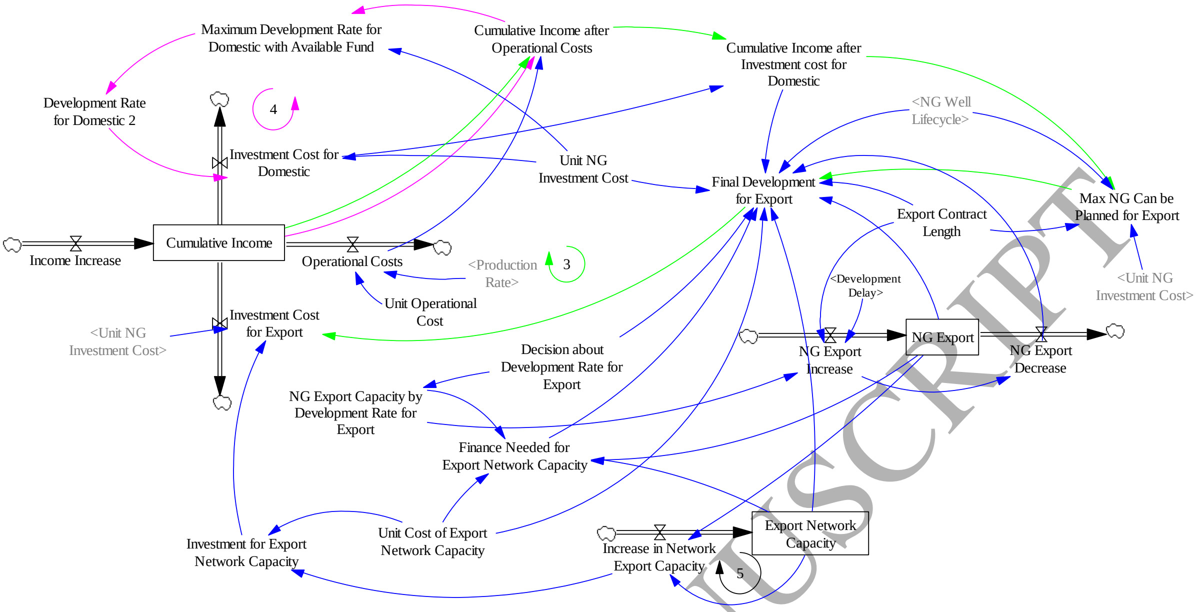


Figure 8. Modelling income and investment

$$DR = \int (D_{Rt} - P_{Rt})dt + DR(t_0) \tag{2}$$

$$PR = Min(\frac{DR}{LC}, D) \tag{3}$$

$$EFDD = DD \times (1 + Trend(DD, 3, 0)) \tag{4}$$

$$FPC = ((DR + PDR) - (EFDD \times (DDl + SS)))/LC \tag{5}$$

$$CIN = If\ then\ else\ (\ FPC < EFDD, EFDD \times (DDl + SS) - DR - PDR, 0) \tag{6}$$

$$MD_{Rt}DF = CIOC/UCC \tag{7}$$

$$CIOC = CI - OC \tag{8}$$

$$D_{Rt}D = If\ then\ else(CIN > MD_{Rt}DF, MD_{Rt}DF, CIN) \tag{9}$$

$$PDRI_{Rt} = D_{Rt}D \tag{10}$$

$$PDRD_{Rt} = D_{Rt} \tag{11}$$

$$PDR = \int (PDRI_{Rt} - PDRD_{Rt})dt + PDR(t_0) \tag{12}$$

$$D_{Rt} = delay\ fixed(PDRI_{Rt}, DDl, 0) \tag{13}$$

$$PR = \int -D_{Rt}dt + PR(t_0) \tag{14}$$

$$CI = \int (II_{Rt} - OC - ICD - ICE)dt + CI(t_0) \tag{15}$$

$$ICD = D_{Rt}D \times UIC \tag{16}$$

$$OC = P_{Rt} \times UOC \tag{17}$$

After decisions are made about investment for domestic consumption, decision makers can consider using the remaining financial resources for NG development for export. Therefore, *Max NG Can be Planned for Export* is determined by *Cumulative Income* after *Investment Cost for Domestic* is deducted (Loop 3, Eqn.18). Eqn.19 determines the NG amount that can be exported yearly if all remaining cumulative income is used for investment for NG development for equal to *CIID*/*UCC*. It is assumed that based on the amount of developed reserves for export, contracts for NG export with *Export Contract Length* are made. Therefore, in order to be able to export a specified volume till the end of the export contract, export volume at period *t+ECL* should be equal to development rate minus export till the last period which is export volume multiplied by *ECL*−1:

$E_t = E_{t+1} = \ldots = E_{t+ECL} = E, E_{t+ECL} = DR_{t+ECL}/LC = (DR_t - E \times (ECL-1))/LC = E \rightarrow E = DR_t / (ECL+LC-1)$

Eqn.20 like Eqn.19 determines the NG amount that can be exported yearly if the development rate for export is equal to the *Decision about Development Rate for Export*. Then checking will determine whether this amount of export added to the previous export amounts can be supported by the current export network, or whether an investment in the export network development should be made. Eqn.21 calculates the *Finance Needed for Export Network Capacity*.

Eqn. 22 calculates the final feasible development rate for export purposes. The first “if clause” indicates that, if the financial resources needed for export network capacity increase (*FENC*) and the investment costs for NG development for export are more than the available funds after investment in NG for domestic consumption (*CIICD*), the development rate for export can be the same as the amount decision makers had decided on. Otherwise, it is not possible to plan for that rate of NG development for export with the available financial resources. In this case, investment should be limited to the maximum development rate that can be funded by available financial resources (*MPE*). Thus, if the annual NG export under the maximum feasible investment in development rate for export plus current export will be less than the current export network’s capacity, all available funds can be used for NG development for export purposes; otherwise the development rate should be less, because a portion of that available fund should be used for increasing export network capacity. *Export Network Capacity* is a stock variable that increases with export network capacity increase rate (Eqn.23). Eqn.24 measures the increase in network export capacity if the export is more than current network capacity. As depicted in Figure 7, NG Export is modeled as a stock variable which increases with export increase rate, EI_{Rt} and decreases with ED_{Rt}. The increase rate happens after a delay assumed for development (Eqn.25). Eqn.26 indicates that export decreases after the export contract length. *NG Export* is the integral of export net change (Eqn.27). Equations 28 and 29 measure the cost of investment for export and export network capacity.

$$CIICD = CIOC - ICD \tag{18}$$

$$MPE = (\frac{CIIDD}{UCC})/(LC + ECL - 1) \tag{19}$$

$$CDRtE = DcDRtE/(LC + ECL - 1) \tag{20}$$

$$FENC = if\ then\ else(CDRtE + E \leq ENC, 0, CDRtE + E - ENC) \times UCENC \tag{21}$$

$$FDE = if\ then\ else(FENC + DcDRtE \times UIC < CIICD, DcDRtE, if\ then\ else(MPE + E - ED_{Rt} < ENC, \frac{CIICD}{UIC}, ((CIICD - (ENC + EDD - E) \times UCENC)/(UIC + UCENC/(\mathrm{LC+ECL-1}))) \tag{22}$$

$$ENC = \int NEC_{Rt} dt + ENC(t_0) \tag{23}$$

$$NEC_{Rt} = if\ then\ else(E > ENC, E - EC, 0) \tag{24}$$

$$EI_{Rt} = delay\ fixed((\frac{FDE}{LC + ECL - 1}), DDl, 0) \tag{25}$$

$$ED_{Rt} = delay\ fixed(EI_{Rt}, ECL, 0) \tag{26}$$

$$E = \int EI_{Rt} - ED_{Rt} dt + E(t_0) \tag{27}$$

$$INEC = NEC_{Rt} \times UCENC \tag{28}$$

$$ICE = INEC + FDE \times UIC \tag{29}$$

3.3 Developing Scenarios

Due to uncertainties in exogenous variables, three scenarios are developed based on different values for the oil export price, GDP annual growth, the annual increase in family income, productivity index of industries, and inflation rate. Of these scenarios, scenario 1 (Sc1) has the highest carbon tax, and lowest international crude oil and NG prices, whereas Sc3 has the lowest carbon tax, and highest NG and oil prices of the three scenarios. The values of carbon tax, NG and oil prices in Sc2 are between those of Sc1 and Sc2. Table 2 shows the values of GDP annual growth, per family income annual increase, productivity index for industries, and the inflation rate in the three scenarios, and Figure 9 depicts the unit carbon tax, oil and NG price from 2015 to 2040. These prices are developed based on the IEA's 2017 world energy outlook (IEA, 2017).

Table 2. Various parameters in the scenarios

Scenarios	**Sc1**	**Sc2**	**Sc3**
GDP Annual Growth	1%	3%	5%
Per Family Income Annual Increase ($)	100	150	180
Productivity Index for Industry (Million ton oil equivalent)	54.4	75	95
Inflation Rate	2%	3%	4%

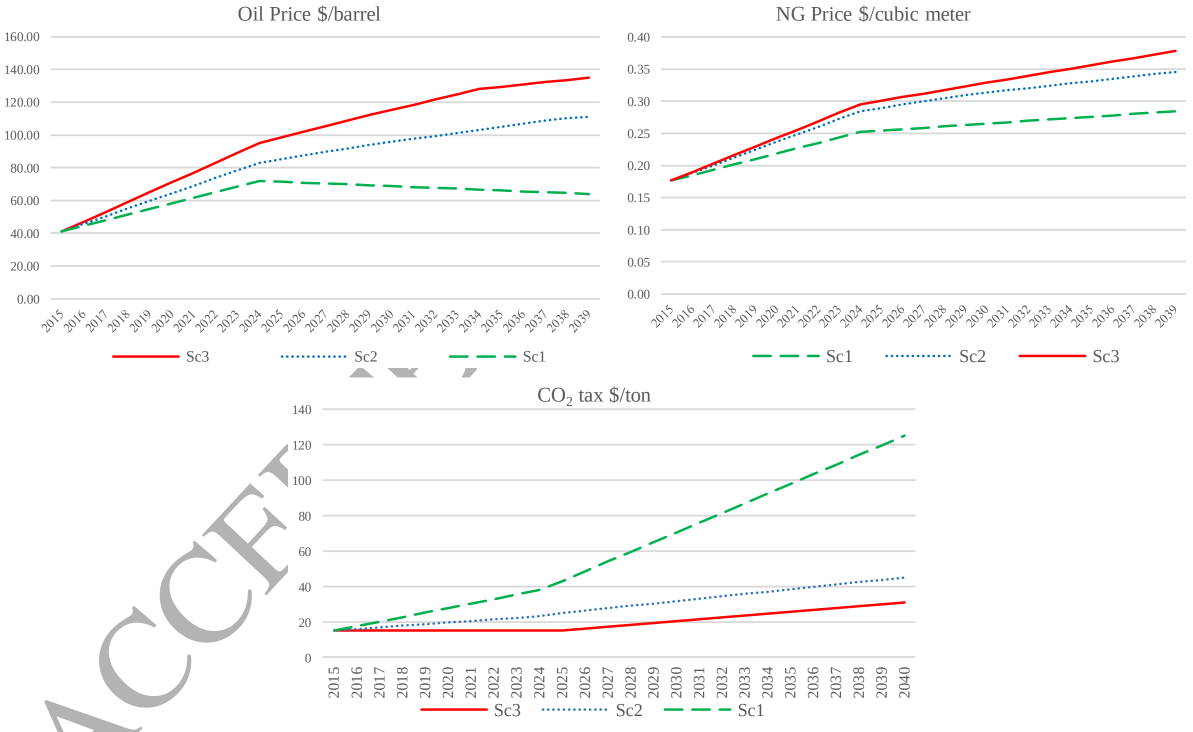


Figure 9. Oil, NG price and CO_2 tax in the scenarios

4. Simulation and Results

The developed model, DMANDiP, is simulated using *Vensim*, which is a system dynamics software and provides a platform for visualizing and formulizing system dynamics models. The problem is modeled from 1985 to 2035 using data of the case study. Some of the historical data required for running the model such as population and urban percentage are taken from the World Bank, and other domestic energy data such as oil and NG production and consumption in each sector are taken from annual energy balance sheets from 1995 to 2013). The model is then validated and used to examine various pricing and allocation policies in the developed NG supply and demand model.

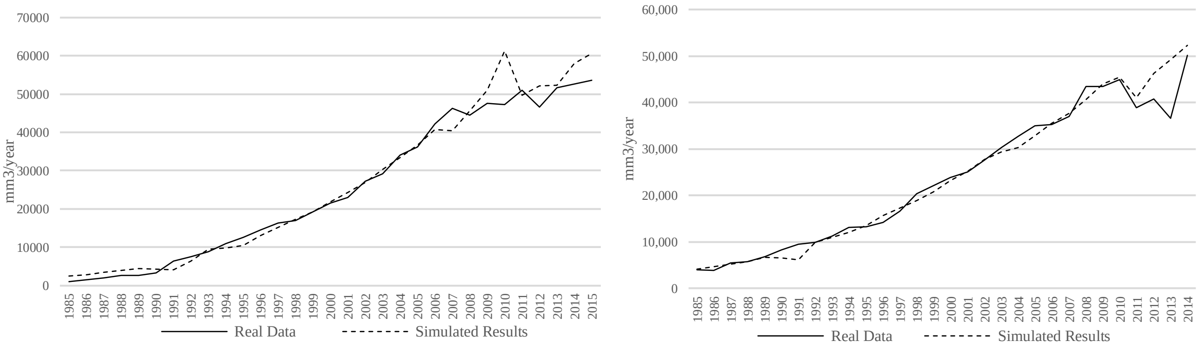
4.1 Case Study Background

NG supplies about 60% of the primary energy in Iran; therefore, the country's energy supply is heavily dependent on NG (Energy Balance Sheet, 2015). About 30 years ago, oil products were the main domestic energy resource in Iran. Due to the predicted growth in population and domestic energy consumption, policy makers decided to supply the increasing domestic energy demands of different sectors with NG, and save crude oil for export. Therefore, they increased NG production and developed the related infrastructure. Accordingly, domestic NG consumption has increased steeply, whereas oil product consumption has grown very slowly. In spite of the increase in NG production, the income made from NG is minimal due to low domestic NG prices and the very tiny share of export. Currently, almost all NG produced is consumed domestically, and despite Iran being the third biggest producer of NG (BP, 2017), it exports only 4% of this NG (Energy Balance Sheet, 2015). Therefore, crude oil export income, arising from the substitution of domestic oil products with NG, has provided financial resources for vast investments in NG development.

The distribution of NG consumption throughout various sectors is the result of government policies as well as the NG prices set for each sector. Currently, the residential, industrial, power plant, and injection to oil fields are bigger consumers of NG, and the smallest NG consumption share goes to export and transportation (Energy Balance Sheet, 2015). Using the model, the optimum distribution of NG consumption in the demand sectors is determined through the optimum price path for the residential, power plant, industrial, and transportation sectors and the optimum amount of NG allocated to injection and export. This analysis examines economic and carbon mitigation criteria, and assume that the entire domestic NG demand should be supplied by domestic NG production.

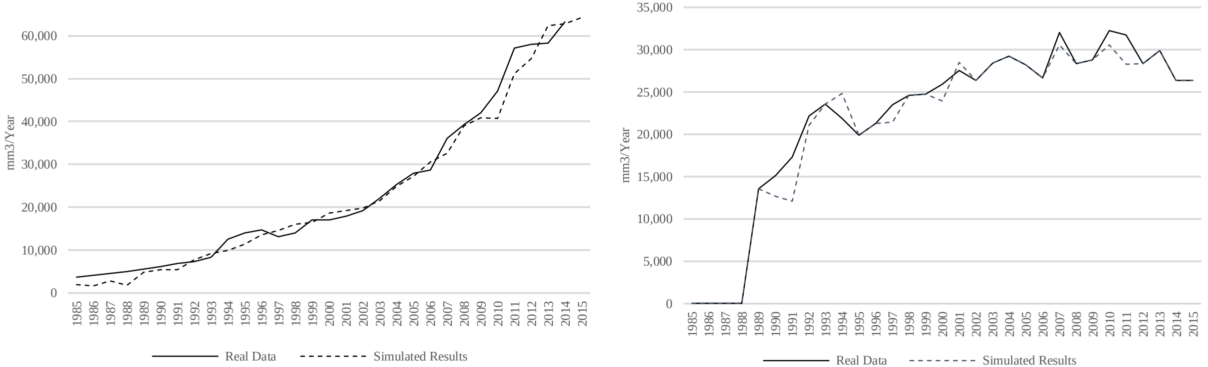
4.2 Model Validation

A system dynamics model should be validated to make sure that it truly simulates the structure of the real system and is a useful representation of the problem at hand (Saleh et al., 2010). Sterman proposes some methods for validating a system dynamics model (Kwon et al., 2016). Extreme conditions, dimensional consistency and behavior reproduction are among the most popular. To ensure the validity of the model, its dimensional consistency has been checked. Moreover, the model has been tested to confirm its validity in extreme conditions. This test evaluates the model's robustness against extreme conditions, i.e. very large or very small values of inputs or parameters. The model should behave realistically and appropriately at these extreme values. For example, NG demand cannot be less than zero regardless of values of input parameters determining NG demand, or when NG demand is zero investment in NG development should reach zero as well. Another validity test is behaviour reproduction test that compares simulation results with real data. Since system dynamics models the structure a system, it is expected that the simulated values of variables are compatible with the real historical data, if the model works appropriately. Figures 10-12 represent this comparison and demonstrate the conformity of simulation results with real historical data.



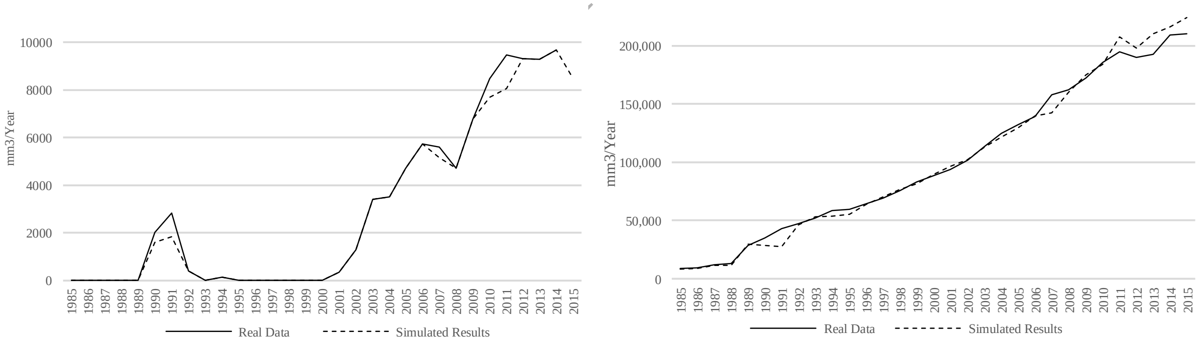
a) b)

Figure 10.a) NG allocated to residential sector, b) NG allocated to power plants, real data versus simulated results



a) b)

Figure 11. a) NG allocated to industry, real data versus simulated results, b) NG allocated to injection, real data versus simulated results



a) b)

Figure 12. a) NG allocated to export, real data versus simulated results, b) Production rate, real date versus simulated results

4.3 Results

After validation, the model can be used for studying the system's future behaviour under various policies. This section will first forecast NG supply and demand if current trends continue and no corrective policies emerge in the three scenarios. Then, each sector's optimum NG allocation through domestic NG pricing and export and injection policies will be discussed in view of economic and environmental objectives.

4.3.1 Business as Usual Case

A Business as Usual (BAU) is a case in which all variables continue their previous trends and no corrective policies are explored. In the BAU, the results of the model are explored if NG consumption in all sectors continues the existing trends. Therefore, the NG price growth of each sector is considered to be the same as the past 30 year’s average, and NG export and NG injection to oil fields are the same as 2015 value for future years. Figure 13 shows that in all scenarios there will be a gap between production and demand.

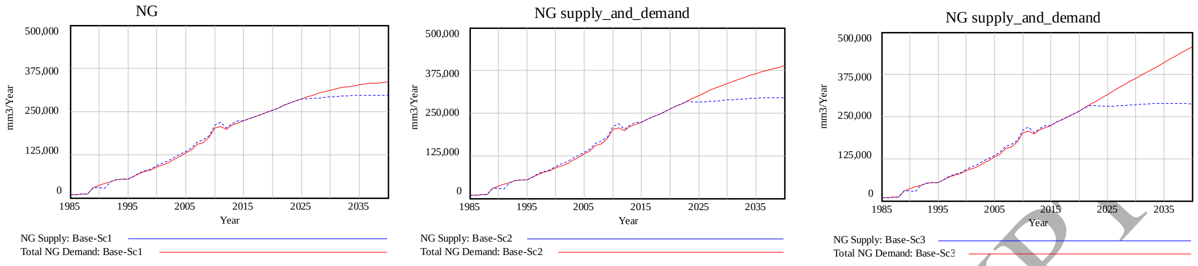


Figure 13. The gap between supply and demand in business as usual case

4.3.2 Policy Optimization

System dynamics models can evaluate various scenarios or policy options and study their effect on various criteria. Finding the best policy options in a system dynamics model requires various scenario analysis, changing the value of different parameters, and trial and error simulation (Morecroft, 1988) which can be a hard task when the number of valid options is not limited. For finding the best combination of policy variables, automatic optimization methods can be used to traverse the policy space in a simulation model based on simulation optimization methods (Romagnoli et al. 2014, Sterman 2000).

The evaluation criteria of the model are to omit any shortage between supply and demand that causes shortage costs (Eqn. 30), maximize the net present value of net annual income (Eqns. 31-33), minimize the net present value of CO_2 costs (Eqn. 34), and maximize the net present value of underground resources at the end of planning horizon (Eqns. 35-37). The policy variables affecting these criteria are NG allocated to export, annual injection to oil fields, plus NG price change for the residential, power plant, industrial, and transportation sectors. Table 3 represents various cases which differ in decision variables and evaluation criteria. The objectives of an NG provider are to maximize the net present value of net income in all years and the net present value of underground resources at the end of planning horizon considering all explained policy variables. The combination of these decision variables and evaluation criteria represents Case4 in Table 3. Case3 differs from Case4 in CO_2 emission objective. This case is examined to see how the NG provider objective function may contrast the government’s objective which aims in reducing CO_2 emission. Case1 is developed according to the Base Scenario results that forecast a supply and demand gap in the near future. Therefore Case1 is developed to investigate how the prices should change if it is just intended to be able to supply the increasing domestic demand completely, and avoid supply demand gap.

Table 3. The Optimization Processes

Case #		Case1	Case2	Case3	Case4
Evaluation Criteria	1.Maximization of Net Income			✓	✓
	2.Maximization of Underground Resources’ Value			✓	✓
	3.Minimization of Domestic Price Increase	✓	✓		
	4.Minimization of CO_2 Cost		✓	✓	
Policy (Decision) Variables	1.Each Sector Domestic Price growth	✓	✓	✓	✓
	2.NG Allocation to Export			✓	✓
	3.NG Allocation to Injection			✓	✓

$$ShC = \sum_{t=t_1}^{T} \frac{(S - D) \times EP}{(1 + \frac{i}{100})^{(t-t_1)}} \qquad (30)$$

$$NAI = \sum_{t=t_1}^{T} \frac{(AI - AC)}{(1+i)^{(t-t_1)}} \tag{31}$$

$$AI = NGI + II \tag{32}$$
$$NGI = DI + EI$$

$$AC = OC + ICD + ICE \tag{33}$$

$$CO2C = \sum_{t=t_1}^{T} \frac{(CO2 \times CO2T)}{(1+\frac{i}{100})^{(t-t_1)}} \tag{34}$$

$$UV = OV_T + NGV_T \tag{35}$$

$$OV_T = O_T \times OEP_T \tag{36}$$

$$NGV_T = DR_T \times (EP_T - UOC_T) + PR_T \times (EP_T - UIC_T - UOC_T) \tag{37}$$

Case1 intends to eliminate shortages between supply and demand with minimum increase in domestic NG prices, by deciding on the increase in each sector's price for each year. To eliminate the shortage, the supply should be increased and the demand should be decreased. NG price growth in each sector increases the total income, and consequently the NG supply, due to the income-supply reinforcing loops (Figure 3). At the same time, NG price growth decreases that sector's demand due to negative demand elasticity to price. Figure 14 shows that, in all scenarios, the transportation sector has the lowest annual price growth, a result that contrasts with the previous policies in the case study, in which the transportation sector's NG price had the maximum growth. Of all the domestic sectors, the transportation sector's demand has the maximum elasticity to price, making the transportation sector the best option to have the highest price growth. Because with a certain amount of the transportation sector's price growth, its demand will decrease the most due to its elasticity, and the most demand reduction with a tiny price growth is in alignment with the objective function in Case1. However, the transportation sector has only a tiny share in the total domestic demand, and so its price increase does not decrease the total NG demand and does not increase the total NG income to a great extent. In scenarios 1 and 2, the industrial sector's NG price experiences the highest growth. The industrial sector's NG demand has the greatest price elasticity after the transportation sector. Moreover, NG industries' demand is about 27% of the whole NG demand and so any changes in this sector's consumption h a greater impact on the total NG demand and NG income.

Comparing the results of the three scenarios indicates that scenario 2 shows more price increase than scenario 1, and scenario 3 has more price increase than scenario 2 due to greater domestic energy demands and greater need for energy supply. The higher need for energy supply requires more NG development, necessitating financial resources obtained through price growth. The indicated price paths save 468, 820 and 1208 billion cubic meters of NG in scenario 1, 2, and 3 respectively to make supplying the total NG demand possible.

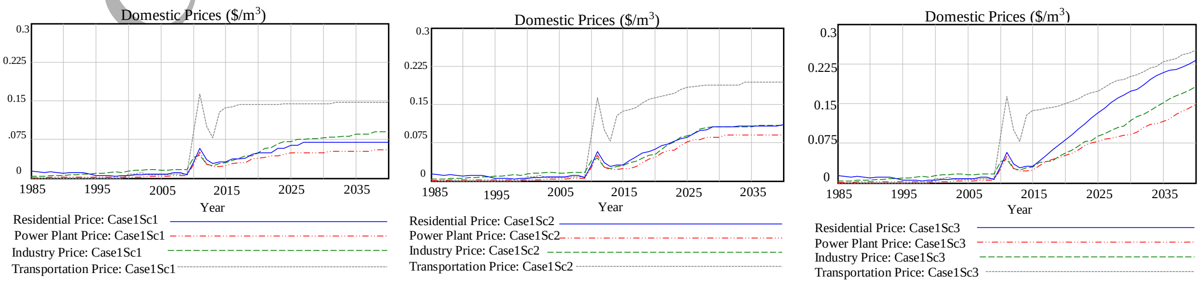


Figure 14. Price increase in each sector in Case1

Case2 examines another objective function, CO_2 cost minimization, with the same decision variables. In this case, there will be more increase in residential price to compensate for less increase in other sector's prices (Figure 15). To eliminate shortages with the minimum price increase, the sector with the highest elasticity is an appropriate target for the price increase. Meanwhile, to minimize CO_2, the increase in the NG price of the sector with less cross elasticity leads to a higher NG share in that sector, which is more favorable and leads to less consumption of NG substitute, (i.e. oil products in the case study) that causes more pollution. In this challenge for choosing which sector's price to increase, the residential sector's NG price increase improves the overall objective functions. Because of the higher demand in scenario 2, the power plant's price should also increase. In scenario 3, with the highest domestic energy demand, the prices for the residential and power plant sectors increase to the maximum limit in all simulation years, and the transportation and industrial sector's prices increase a bit less than in the base scenario between 2015 and 2040.

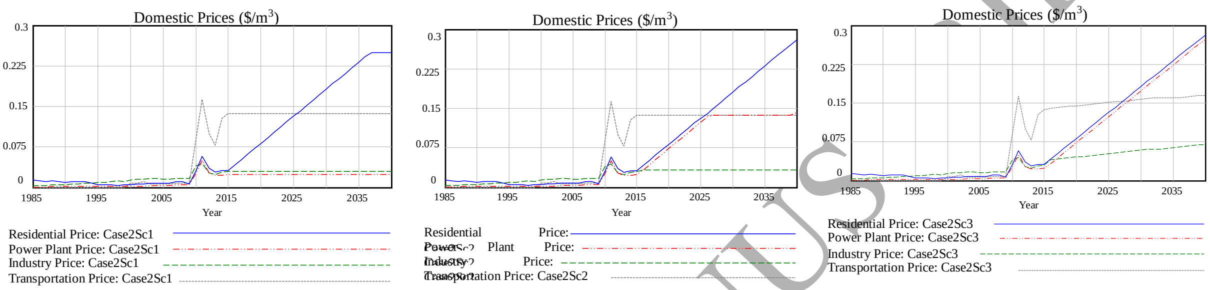


Figure 15. Price increase in each sector in Case2

In Case3, as shown in Table 3, NG allocation to export and injection are added to the decision variables, and the objectives are to maximize the net present value of the net annual income (annual income minus annual cost) and underground resources' value, and to minimize the net present value of CO_2 costs. Figure 16 shows the results of Case3 in Scenario 2 when the objective functions have the same coefficient. As can be seen, there is no shortage between supply and demand. To the year 2029, injection to oil fields cannot happen at the maximum level needed, but after that, NG is allocated to injection at the maximum value, and NG export also starts increasing.

Price and consumption volume are two determinants of income. Price growth decreases demand and consumption and increases the price. But since the absolute elasticity of demand to price is less than one, price growth has a more significant effect on income increase than consumption quantity. Thus, to meet the first objective, i.e., the net present value of net income, it is better that the price is increased to the upper limit defined in the optimization. The price increase is also in line with the underground resource value objective. Price growth leads to lower demand, and lower demand lowers production. Therefore less underground reserves are extracted and consumed, leaving more reserves available underground. On the other hand, very steep price growth is not suitable for CO_2 emission's reduction. High NG prices raise consumption of NG substitutes, which are more polluting. Thus, the optimum price path for each sector is a tradeoff between environmental and economic objectives.

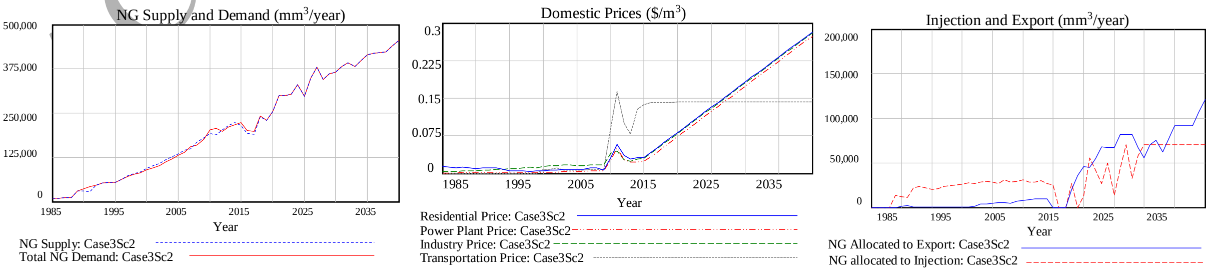
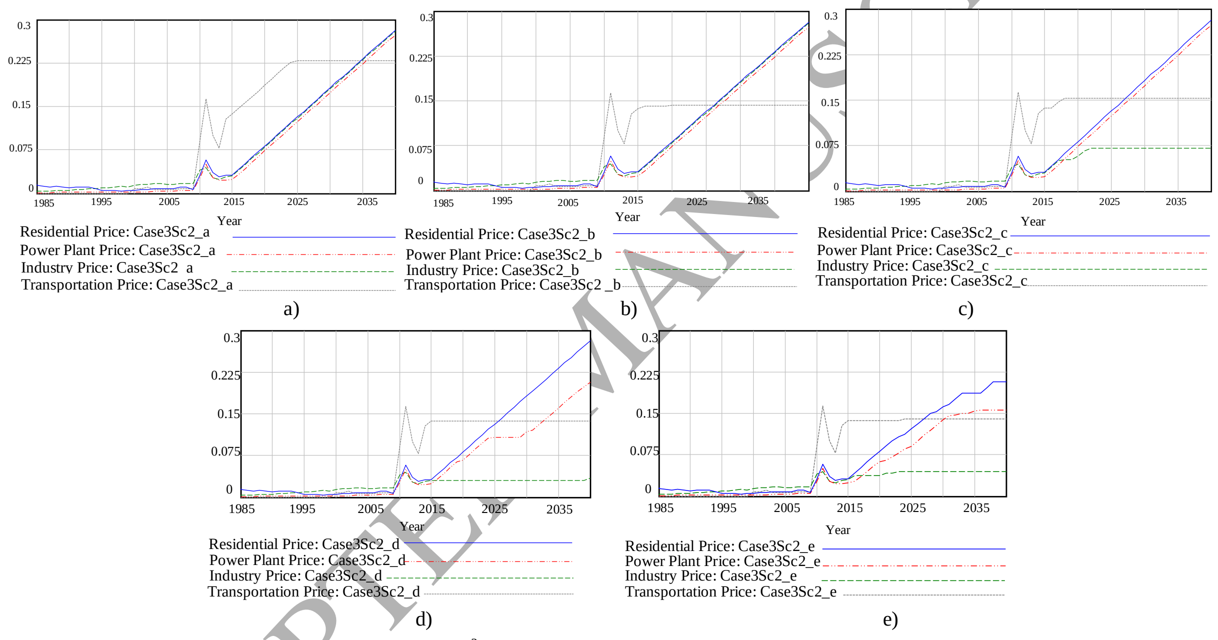


Figure 16. The results of the model in Case3Sc2

CO_2 emission in Case3Sc2 is compared to that in Case4Sc2 in which all decision variables and objective functions are the same as Case3Sc2 except that CO_2 minimization is not an objective function in Case4Sc2. The results show that the net present value of CO_2 cost in Case3Sc2 is only 0.5% less than that in Opt4Sc2, with no CO_2 reduction objective. This result indicates that when CO_2 reduction has the same coefficient as economic objectives, economic objectives are dominant and determine the value of decision variables. Following this result, changes in decision variables and objective functions are examined through an increase in the relative coefficient of CO_2 reduction in the objective functions. Figure 17 demonstrates the related changes in price paths. Figure 17.a is the case in which CO_2 objectives and economic objectives have the same coefficients. In this case, CO_2 minimization is not the determinant of price paths, and all sectors' prices increase to their upper limit. When the relative coefficient of the CO_2 objective to the economic objective functions increases, transportation is the first sector that reacts to this change, followed by the industrial, power plant and finally residential sectors. Therefore, in Figure 17.b transportation price does not increase at all; in Figure 17.c, industry price levels off; in Figure 17.d, power plants NG prices, and finally; in Figure 17.e, residential NG prices also level off.



a) b) c)

d) e)

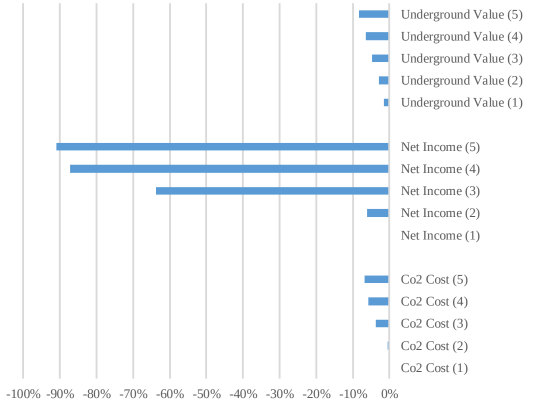
Figure 17. Change in Prices ($\$/m^3$) path with an increase in the relative coefficient of CO_2 objective

The results indicate a quick reaction to the transportation sector's NG prices after an increase in the relative importance of the CO_2 emission objective. This reaction results in lower transportation sector's NG prices and more attraction of consumers in using NG in competition with gasoline. Industries form the second sector that reacts to the CO_2 emission objective, because the sector's NG price growth and NG share drop have significant negative effects on CO_2 objective. The residential sector's price growth is higher than that of other sectors, and almost at the highest level even in Figure 17.e, in which the CO_2 objective coefficient is the highest. While the residential sector is currently the biggest NG consumer in the case study, the results indicate that its consumption should be curbed to a great extent.

Figure 18 illustrates the percentage of change in each objective function in Case3Sc2 compared to Case4Sc2. This Figure shows that the size of the objective function's change with the increase in the relative coefficient of CO_2 cost objective function is different. With this change, the percentage of reduction in the CO_2 cost objective is much slower and smaller than the percentage of reduction in the net annual income.

Moreover, it is very interesting to note that the same weights of economic and environmental objectives will not reduce CO_2 emissions, as that requires more incentives.

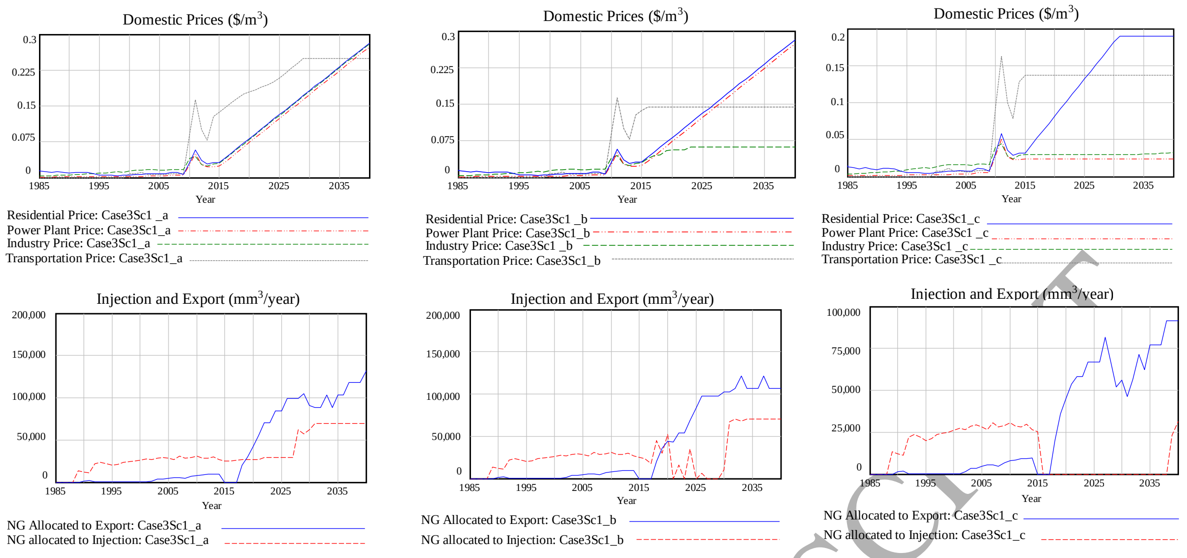
Thus far, this paper has discussed the optimum NG volume that should be allocated to each sector by determining NG prices for each domestic sector. NG allocation to injection and export-discussed next- is based on a tradeoff between annual income and costs, and the value of underground resources at the end of the planning horizon. As stated, the produced NG is first allocated to domestic sectors other than injection; afterwards, the decision is made to use the extra NG in injection or the extra amount of financial resources in NG development for export. Allocation to export increases net annual income, which activates the income-supply reinforcing loop (Figure 3), while allocation to injection increases the oil reserves' value and consequently the underground resource's value.



Case #/ Objective Function	Percentage of change in objective functions		
	CO_2 cost	Net annual income	Underground value
Case3Sc2 (1)	− 0.05%	− 0.21%	− 1.55%
Case3Sc2 (2)	− 0.5%	− 6.13%	− 2.81%
Case3Sc2 (3)	− 3.7%	− 63.79%	− 4.82%
Case3Sc2 (4)	− 5.72%	− 87.24%	− 6.46%
Case3Sc2 (5)	− 6.78%	− 90.91%	− 8.33%

Figure 18. Percentage of change in Case3Sc2 objective functions compared to Case4Sc2's, with an increase in the relative coefficient of CO_2 objective. The increase in the numbers in parentheses represents the increase in the relative coefficient of CO_2 objectives.

Figure 19 depicts how the allocation of NG to injection and export changes when the relative coefficient of CO_2 objective is increased. When the domestic prices are increased to satisfy economic objectives, more NG production will be available, and the remaining NG after allocation to the residential, power plant, industrial and transportation sectors can be allocated to injection or export. However, when the relative importance of CO_2 objective increases, the NG price growth of domestic sectors starts leveling off, and less NG production becomes available. In this case, the remaining NG will be less than upper limits of injection and export, and the model should decide on allocating a part of remaining NG to injection or export, according to the objective functions. In Figure 19.a, there is a steep price growth in all domestic sectors; therefore, NG injection reaches its upper limit in 2028 and in the previous years, export is prioritized over injection. In Figure 19.b, industries' NG prices also level off, delaying maximum NG injection to oil fields until 2031. In Figure 19.c in which power plant prices also level off, there is almost no injection, and the amount of export also decreases. Although the amount of injection and export, and the year in which price growth levels off, differ in the other two scenarios, the general trends are similar. With Case3, CO_2 emission can be reduced to 6.6%, 11.5% and 7.7% in scenario1, 2 and 3, respectively, depending on the relative coefficient of carbon objectives to economic objectives.



a) b) c)

Figure 19. NG allocation to injection and export in Case3

As mentioned, NG price paths of the residential, power plant, industrial and transportation sectors affect each sector's NG demand, which will be met by domestic NG production by the model's constraints. Therefore, each sector's demand equals its NG consumption. These values plus the decision about the amount of injection and export determine the optimal NG allocation to all demand sectors from 2015 to 2040. NG allocated to each sector for the first and last year of simulation is given in Table 4 for the three scenarios and the trend of NG allocation to each sector from the first to the last simulation year is depicted in Figure 20. For simplicity in following the results, each sector's NG consumption is averaged for every 5 years. The first and the last 5-year average are depicted on pie charts and show how NG should be distributed between demand sectors from 2015 to 2040 in the three scenarios.

Table 4. Average data on NG allocation to demand sectors

Year/Sector	Domestic	Residents	Power Plants	Industry	Transportation	Injection	Export	Total
Scenario1								
2009-14	188,121	54,265	46,525	52,329	6,179	28,824	8,627	196,748
2036-40	351,072	78,984	96,954	90,042	15,093	70,000	100,569	451,641
Consumption Growth	87%	46%	108%	72%	144%	143%	1066%	130%
Change in Share		**-22%**	**12%**	**-8%**	**31%**	**30%**	**524%**	
Scenario2								
2009-14	188,118	54,263	46,524	52,328	6,179	28,823	8,626	188,118
2031-35	368,276	80,470	108,440	94,385	14,981	70,000	103,510	368,276
Consumption Growth	**96%**	**48%**	**133%**	**80%**	**142%**	**143%**	**1100%**	**140%**
Change in Share		**-24%**	**19%**	**-8%**	**24%**	**24%**	**513%**	
Scenario3								
2009-14	188,118	54,263	46,524	52,328	6,179	28,823	8,626	196,744
2036-40	390,481	81,287	121,032	103,546	14,616	70,000	74,767	465,248
Consumption Growth	**108%**	**50%**	**160%**	**98%**	**137%**	**143%**	**767%**	**136%**
Change in Share		**-37%**	**10%**	**-16%**	**0.03%**	**2.7%**	**267%**	

The residential, industrial, power plant, transportation, export, and injection sectors had 27%, 24%, 27%, 3.14%, 4% and 15% share of the total NG consumption in 2015, respectively. According to the results, in all scenarios, the residential sector's share should decrease from 27% in 2015 to 17-18% in 2040 as shown in Table 5. The residential sector's price growth in Case2 also demonstrates the idea of curbing the sector's NG consumption. Table 4 also shows that the increase in the residential sector's NG allocation should be much less than the average domestic NG consumption growth in all scenarios. Although domestic NG consumption grows by 87%, 96% and 108% in scenario 1, 2 and 3, respectively, the NG allocation to the residential sector should have only 46%, 48% and 50% growth in the three scenarios, which is almost half of average domestic NG growth. Therefore, NG allocation to the residential sector should have the least growth in 2040. On the other hand, NG allocation to the transportation sector, injection to oil fields and power plants should increase the most. Even though Figure 20 does not represent any significant increase in the transportation sector's consumption share in 2040, Table 4 shows about 140% increase in allocating NG to this sector, which is much more than the average domestic NG growth in Sc1. The small increase in transportation share in 2040 despite its huge consumption growth is because of very high increases in NG export. The transportation consumption growth is in compliance with Case1 and Case2, in which transportation's price should not increase so as to motivate NG consumption compared to gasoline, in this sector.

Table 5- NG share in each sector in 2015 and 2040

Sector	Residential	Power Plants	Industrial	Transportation	Export	Injection
NG Share-2015	27%	24%	27%	3.14%	4%	15%
NG Share-2040	17-18%	21-26%	20-22%	3.14-3.34%	16-22%	15-16%

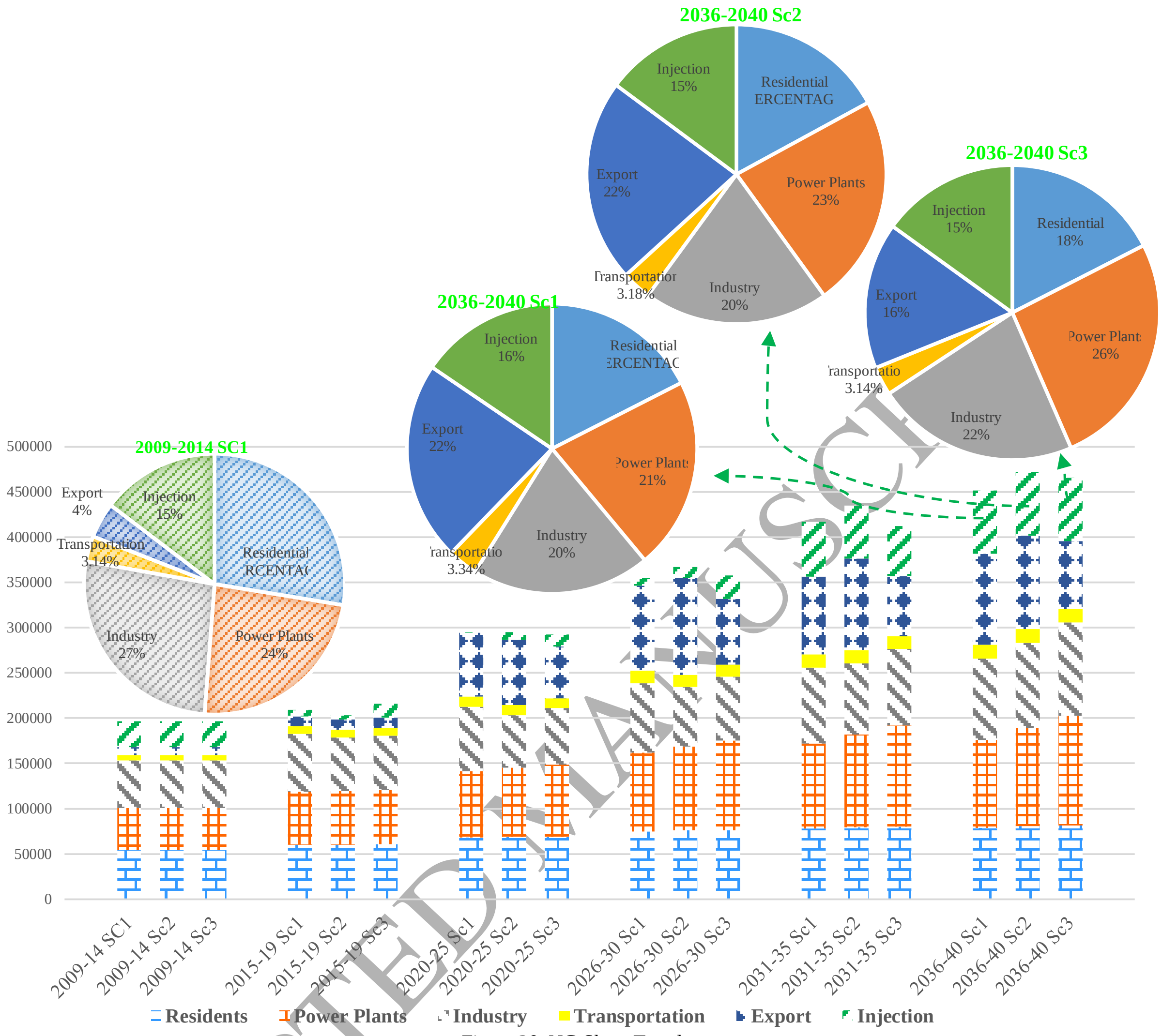


Figure 20. NG Share Trend

Comparing all sectors' NG consumption growth in Table 4, export has the highest growth rate. It is also clear in Figure 20 that the NG export share increases drastically from 4% in 2015 to 16-22% in 2040 in the three scenarios. NG export and injection shares are lower in scenario 3 than in scenarios 1 and 2, because an increase in domestic NG demand means less NG remaining for injection or export after the domestic consumption. The growth in NG allocated to injection is also greater than the average domestic consumption growth, but much less than export growth. As demonstrated in previous sections, when the choice is between injection and export, the model selects export over injection to activate the income-supply loop and provide annual financial resources.

4.4 Conclusions and Policy Implications

NG share in many countries' energy supply mix is increasing. NG can be consumed in various demand sectors, such as residential, commercial, electricity generation, industrial, and transportation. Since NG consumption in each sector has different economic and environmental effects, it is important to study the optimum distribution of NG consumption in these demand sectors. This paper presents a model for an NG supply and demand system to study the optimum NG volume that should be allocated to each demand sector through differential pricing. The problem is studied using system dynamics by modelling the dynamic effects of price on demand, and NG income on supply. Economic and environmental objectives including maximization of net income and underground resources' value, and minimization of CO_2 costs are examined to explore the optimal policies in three scenarios. The optimal NG price paths determined for the residential, power plant, industrial and transportation sectors affect each sector's NG demand, which will be met by domestic NG production through the model's constraints. Therefore, each sector's demand equals its optimum NG allocation. Each sector's optimal price path and optimal allocation of NG to injection and export determine the optimal NG allocation to all demand sectors from 2015 to 2040.

The model is applied to a case study of Iran and it is concluded that continuing current trends will result in a gap between supply and demand. Different objective functions and decision variables have been examined in the model to study how various factors affect the optimal price paths and each sector's NG consumption share. The results show that the allocation of NG to the residential sector and its share should decrease a lot in the three scenarios. On the other hand, the highest percentage of increase in consumption share and also the highest growth rate goes to export. Selling NG for export at international prices activates the income-supply reinforcing loop and increases the net annual income value. In the years with lower financial resource values, in which the maximum level of injection and NG allocation to export cannot be met, export has a higher priority over injection, i.e., injection is decreased to make NG available for export and activate the supply-income loop.

Comparison of price paths in the scenarios and different types of optimization examined in the model indicate that the price growth rate in the transportation sector should be the least among domestic sectors, a finding that contrasts with previous trends from 2000 to 2015 in which the sector's price growth has been the highest. The NG allocation to the industrial sector should decrease a lot. This reduction does not mean that the industrial sector's NG demand should not be met, rather, that its consumption should be curbed through pricing policies, because of the sector's higher demand elasticity to price and higher potential for energy conservation.

Another important observation in the study is the dominance of economic objectives over environmental ones. The results indicate that the same weights of economic and environmental objectives prioritize economic criteria over environmental ones, but appropriate policies will result in up to 11.5% reduction in CO_2 emission on the demand side. Comparing the values of economic and environmental objective functions indicates that even the highest CO_2 taxes in the IEA's scenarios for 2040 do not provide enough motivation for reducing CO_2 emission in countries with the same NG or other fossil fuels' production costs or industry structure. An increase in the relative coefficient of carbon mitigation objective was examined to investigate how CO_2 emission decreases accordingly. The results demonstrate that giving higher coefficients to CO_2 emission objective affects the value of objective functions differently; that is, the absolute value of economic objective reduction is more than that of CO_2 emission objective. This result confirms the necessity of regulations and economic incentives for achieving carbon mitigation objectives, and that the incentives should be more attractive in regions with access to lower-cost fossil fuels.

Although this model is calibrated for Iran's case study, it can be used for other regions and countries to investigate their optimal allocation of NG or other energy resources to various demand sectors through revising their energy prices. The model provides a framework for modelling a country's energy income and its sufficiency for long term investment in energy infrastructure development according to future energy demand. It argues how energy consumption mix in various demand sectors produces different economic and environmental revenues. The model can be extended to study a broader effect of energy consumption in various sectors through their effect on the country's overall GDP.

5. References

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Appendix

Symbol	**Description**	**Symbol**	**Description**
DR	Developed Reserves	*CDRtE*	NG Export Capacity by Development Rate for Export
D_{Rt}	Development Rate	*DcDRtE*	Decision about Development Rate for Export
P_{Rt}	Production Rate	*FENC*	Finance Needed for Export Network Capacity
LC	NG Well Life Cycle	*E*	NG Export
D	NG Demand	*ENC*	Export Network Capacity
EFDD	Expected Future Domestic Demand	*UCENC*	Unit Cost of Export Network Capacity
DD	Domestic NG Demand	*FDE*	Final Development for Export
FPC	Future Production Capacity	NEC_{Rt}	Increase in Network Export Capacity
PDR	Planned Developed Reserves	*INEC*	Investment for Export Network Capacity
DDl	Development Delay	EI_{Rt}	NG Export Increase
SS	Safety Stock	ED_{Rt}	NG Export Decrease
CIN	Capacity Increase Needed	*ShC*	NG Shortage Cost
$MD_{Rt}DF$	Maximum Development Rate for Domestic with Available Fund	*S*	NG Supply
CIOC	Cumulative Income after Operational Costs	*EP*	NG Export Price
UCC	Unit Capex Costs	*i*	Inflation
CI	Cumulative Income	*NAI*	NG Net Annual Income
OC	Operational Costs	*AI*	Total Annual Income
$D_{Rt}D$	Development Rate for Domestic	*AC*	Total Annual Cost
$PDRI_{Rt}$	Planned Developed Reserves Increase	*NGI*	Total NG Income
$PDRD_{Rt}$	Planned Developed Reserves Decrease	*II*	Indirect Income
PDR	Planned Developed Reserves	*DI*	NG Domestic Income
PR	Proven Reserves	*EI*	NG Export Income
II_{Rt}	Income Increase Rate	*CO2C*	CO_2 Cost
ICD	Investment Cost for Domestic	*CO2*	Total Domestic CO_2
ICE	Investment Cost for Export	*CO2T*	Carbon Tax
UIC	Unit NG Investment Cost	*UV*	Underground Value
UOC	Unit NG Operational Cost	*OV*	Oil Value
MPE	Max NG Can be Planned for Export	*NGV*	NG Value
CIICD	Cumulative Income after Investment Cost for Domestic	*O*	Oil Reserves
ECL	Export Contract Length	*OEP*	Oil Export Price

Rate variables are represented by subscript “Rt”

Graphical abstract