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# A System Dynamics Analysis of Investment, Technology and Policy that Affect Natural Gas Exploration and Exploitation in China

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**Abstract:** Natural gas has an increasing role in Chinese energy transformation. We present a system dynamics model of the natural gas industry in China. A new system dynamics model for natural gas companies based on reserve exploration and well construction as well as investment dynamics is proposed. The contribution of the paper is to analyze the influence of technology, investment and policy factors on the natural gas industry. We found that the dynamics of the main variables, including gas policy, cost of investment, accounting depreciation and exploitation technology, are sensitive to the sustainable development of resources. The simulations and results presented here will be helpful for government to reform policies, and for upstream companies to make decisions.

**Keywords:** natural gas industry; system dynamics modeling; exploitation and exploration; China

## 1. Introduction

As a coal-dominated energy-consumption structured economy, China has been suffering from serious pollution problems. Country Environmental Analysis of China has pointed out that, in 2012, seven of the world's ten most polluted cities are located in China. Among the largest 500 cities in China, less than 1% met the recommended air quality standards of World Health Organization [1]. In 2013, Beijing, and most of the eastern region in China, had experienced continued haze weather, which the public referred to as "haze China". Improving energy consumption structure and increasing the proportion of low carbon emission energy have become effective ways to solve China's current environmental pollution problems [2]. The Chinese government proposed the goal of $CO_2$ emission reduction in 2009, attaining a 40%–50% decrease of $CO_2$ emission per GDP by 2020 compared with that of 2005. Meanwhile, the 12th Five-Year Plan also set the goal of energy intensity control at a 3.7% decline every year. In 2014, the Sino–U.S. Joint Statement on Climate Change was signed, and the Chinese government proposed the plan for peaking the $CO_2$ emission by 2030 or earlier. At present, natural gas is already the main energy consumed in European countries. In the future, the proportion of natural gas and other renewable energy will be further increased [3,4]. China's current technology and market development of renewable energy is lagging, thus China is vigorously promoting the exploration and development of natural gas. Simultaneously, the government has put forward ambitious policies to promote the usage of natural gas [5]. Therefore, the government supports its strong determination to increase domestic production to guarantee energy security. Evidence of this decision includes the large-scale geological survey in potential domestic basins and strengthening the involvement of international natural gas market. According to Dai et al. (2015), conventional gas geological resources in China have risen from $(5.4 - 7) \times 10^{12}$ $m^3$ in the early 1980s to $63 \times 10^{12}$ $m^3$ in 2010, as have been assessed by various scholars and institutes over the past thirty years [6]. China reported $(39.0 - 39.2) \times 10^{12}$ $m^3$ recoverable reserves for conventional gas, which is among the greatest reserves in the world, and will provide a substantial foundation for the sustainable development of China's natural gas industry. However, large-gas reserve fields in China are mainly spread in the Midwest region, including Sichuan Basin, Ordos Basin and Tarim Basin. However, the "gold" buried depths of reserves are deeper than those abroad and with low pressure and low discovery rate, i.e., the reserves at buried depths of 3000–4500 m account for 46.11% of the total reserves, hence their exploration will be more difficult with higher costs and more complexity. As a result, the wellhead price of gas in China is equivalent to or higher than the border prices of Europe's imported gas. A number of studies have addressed the gas production and consumption patterns in China from a national perspective [7–9]. However, for a country as large as China in terms of market structure, competition and regulation reform, any analysis of natural gas market development needs to capture its industrial variations. Hence, it is very important to analyze corresponding measures and incentives, such as policy, technology, and regulation factors to reduce the production cost and improve investment efficiency.

Chinese upstream gas production has a long history characterized by oligopolies and monopolies with three dominating companies, i.e., China National Petroleum Corporation (CNPC), China Petroleum and Chemical Corporation (SINPEC) and China National Offshore Oil Corporation (CNOOC), which is unfavorable for technology progress, extraction cost reduction and market competition.

In recent years, China's natural gas industry has undergone major reforms. It consists of the following actions:

- The developing natural gas market has been in the process of transforming, consisting of improving investment efficiency and service quality through privatization. The desirability of expanding natural gas also calls for the strengthening of domestic and international exploration and exploitation. China has implemented various measures to better cope with supply–demand gap and significantly mitigate their effects, which means that the country seeks supplies from all possible sources, not only imports of liquefied natural gas (LNG) and pipeline gas but also from domestic gas production. The national oil companies (NOCs) have also increased their investment in exploration and development of upstream sector in order to meet increasing natural gas demands.
- Gas pricing is to be changed from a "production cost" regime to a "market net return" regime. Since domestic cost-plus regulated pricing for produced gas is low compared to alternative sources, there is less incentive for upstream producers to engage in exploration and production activity. Therefore, a transforming step toward launching a market-driven pricing regime will provide encouragement to upstream companies.
- Previously, the large corporations in the natural gas industry relied on command and control approaches. Since the mid-2000s, the Chinese government has hoped that NOCs will eventually rival the operation of major Western oil companies in the scope of their worldwide activities, which could promote the market evolution, leading to greater investment from private entrants. Thus, NOCs would become more profitable and market-oriented, thereby better able to increase their capital investment efficiency.
- Before 2010, the accounting method mainly applied in NOCs was full cost. In that approach, firms capitalized all operating expenses generated in prospecting for oil and gas reserves as well as in acquiring, exploring and proving oil and gas properties, regardless of the uncertainty and risk. Then, companies switched to the total successful efforts approach, in which only those acquisition, exploration and development costs related to the discovery of commercially viable reserves need

to be capitalized. Compared with Western companies, Chinese firms are less familiar with these accounting methods.

To be specific, it is important to have a perspective on the integrated systems in order to understand their behavior, and analyze those factors affecting the non-renewable resource exploration path and corresponding influence on investment behavior. In this paper, a new system dynamics model for natural gas companies based on reserve exploration and well construction as well as investment dynamics is proposed. The contribution of this paper is to analyze the influence of investment, technology and policy factors on the natural gas industry. The recommendations and simulations will be helpful for policy makers to formulate policies and to make decisions to create high returns for upstream companies.

The paper is organized as follows: in Section 2, the state of literature is reviewed. In Section 3, the subsystems are introduced through a step-by-step replication. Section 4 analyzes the results of the scenarios and Section 5 discusses the major conclusions and remarks.

## 2. State of Literature

As a tool for energy systems analysis, system dynamics (SD) has been used for more than 30 years [10]. The SD approach is suitable for modeling complex environments, such as ecosystems and human activities, on a muti-dimensional scope with time-dependent variables [11]. The SD modelling helps more clearly demonstrate the interactions of the environment and socio-economic variables, and also helps to identify the key factors that significantly alter a dynamic system. The original work that used system dynamics models in energy discussions traced back to Naill who modeled the process of natural gas discovery and production in the United States gas industry [12], originally advocated by Forrester [13]. Then, SD has a wide application in the energy field. After that, Naill developed the COAL1 and COAL2 models which eventually led to the FOSSIL1 model, which became the mainstream model for energy policy evaluation in the United states [14,15]. Following the same path, the use of SD methodology for the understanding of complex energy systems has increased significantly. Sterman was involved in the conversion of FOSSIL1 to FOSSIL2, a model that includes feedback from within the economy and energy system [16,17]. The SD modelling approach is very popular in literature on the energy sector and it has also been applied to many countries, such as the United States, UK, Argentine and so on [18–21]. Based on the life cycle of the petroleum resource, Davidsen et al. presented an SD model to show the interactions and feedback process of the petroleum industry in the United States [18]. Bodger showed that the SD model was also applicable to a small country where specific energy resources are available [20]. Chia et al. developed a system dynamics model to study the complex issues involving nuclear energy development in Singapore by evaluating four critical aspects, namely environmental, economic, political and social factors in various scenarios [21]. The SD modeling approach can be used to systematically model the oil and gas industry, and to conduct a scenario analysis and uncertainty analysis according to possible changes [22–24]. Chowdhurg et al. used the system dynamics model to study the long-term dynamic behavior of the oil and gas exploration and exploitation industry in India. The expected behavior of the model has been analyzed under different conditions [23]. Kiani and Amiri demonstrated a system dynamics model which analyzed the feedback between supply, demand and oil revenue of the energy system in Iran, simulating different sectors of the economy [24].

For the Chinese energy–environment system specifically, some SD models were newly developed during the 2000s. For example, some SD energy models were proposed to investigate the issues associated with resource development. Fan et al. analyzed the Chinese coal industry structure based on the SD model by regarding the coal production system as a huge system [25]. Li et al. developed a system dynamics model to forecast the future natural gas demand in China [7]. Feng, Chen and Zhang developed a similar model to study the energy consumption and $CO_2$ emission tendencies in Beijing city from 2005 to 2030 [26]. Xu et al. identify the main uncertainty factors that affect industry planning using a rough set approach, a dynamic system and multiple-objective-programming approaches [27].

Wu et al. (2015) built a system dynamics model to point out various trends of the Chinese shale gas sector under different scenarios, which shows that technology, policy and cost factors have combined effects on market competitiveness [5]. At last, the simulations reveal that the number of competitors in the Chinese SG industry will peak from 2019 to 2020.

As a review of the research on the dynamic model of the natural gas industry, the present paper develops a system dynamics model to analyze the factors influencing upstream behaviour. Our research has substantially developed a broader model to assess the effect of policy, technology, and capital cost factors on the revolution in the natural gas industry. The results and remarks will be useful for government to reform policies, and for gas producers to make investment decisions.

## 3. SD Model of Upstream Natural Gas Investment

As we are interested in general energy system behavior, the model presumes that the Chinese natural gas industry has one monopoly firm exploring and producing homogeneous natural gas. In reality, the upstream activities are conducted by nationally owned companies. This assumption is similar to the work by Naill [12] and Sterman et al. [17]. The upstreaming activities are modeled based on the total life-cycle which is comprised of exploration, development and production phases. The study takes the case of China Petroleum Chemical Corporation (CPCC) as an example. It is also the first time that an SD model is established that shows the exploration and production process of the upper part of natural gas in China. The system dynamics model involves a total of 56 variables, six flow-bit variables, 49 auxiliary variables, and one hidden variable. First, this paper gives bit variables initial convections: total resources for 2531.18 $\times$ $10^8$ $m^3$, sales of the initial value for 1.01 billion parties, and the capital cost ratio for 5.5%. Most of the other relationships between variables are established through fitting, regression, table functions and other forms. Based on the analysis of economic relations, regression relationships between variables are established by the least squares or partial least squares method. The determination of table function is more complex. Most of them are obtained mainly through the conclusions of literature, expertise and continuous simulation adjustment.

### *3.1. Establishment of the System Flow Diagrams*

Natural gas upstream activities, including investment, exploitation and production are handled by large state-owned companies in China. Exploration activities involve investment decisions to undertake resource survey and assessment. Exploitation activity involves extraction from a reservoir and development by drilling. Production activity involves the production process of gas using the optimal control technique.

In this paper, the established natural gas system dynamics model can clearly reveal all kinds of production process aspects of gas company exploration and development, and the relationship between production process input factors and output factors. The system dynamics model is a combination of qualitative and quantitative methods; the most prominent feature of this method is its ability to handle non-linear, high-level, multiple feedback, complex time-varying system problems. China's upstream gas companies often have insufficient data. In this situation, the system dynamics (SD) model can be used to carry out the calculation and research. In the exploration links, the investment includes direct investment and indirect investment. Direct investment includes investment in geophysical and exploratory wells and geophysical investment also includes two-dimensional and three-dimensional seismic earthquakes. All of these investments form the final output-proved reserves. Proved reserves have a direct impact on the development aspects of the inputs and outputs, and ultimately have a direct impact on sales. Therefore, all these critical nodes are mutually influential interactions.

The system is described diagrammatically in Figure 1. Then, we deconstruct the natural gas system into three subsystems.

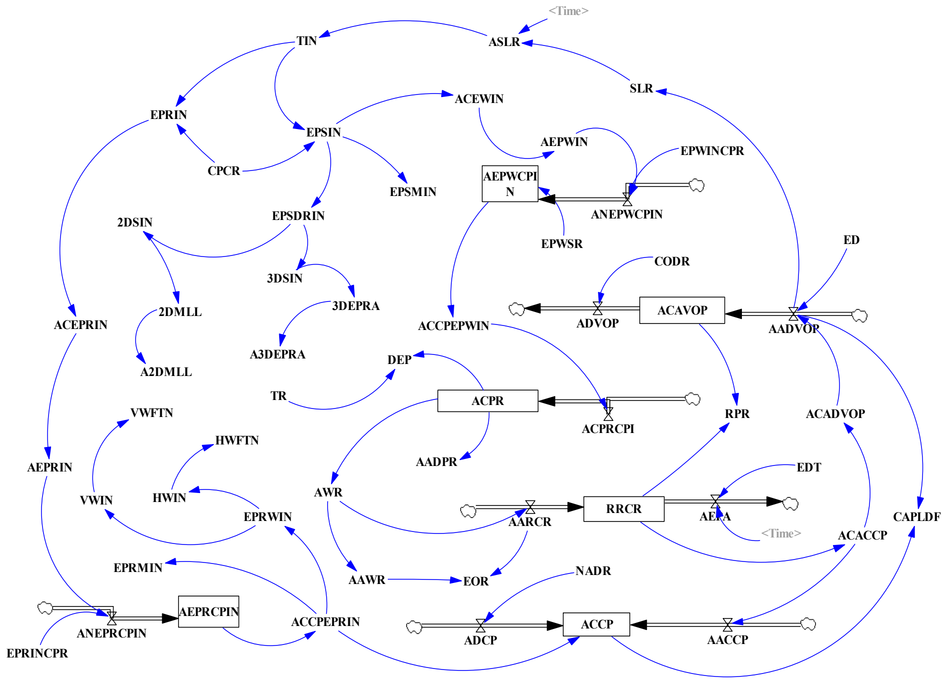


**Figure 1.** The System Dynamics model of natural gas exploitation and exploration.

## *3.2. Decomposition Analysis of SD Model*

The internal subsystems of natural gas exploitation and exploration are analyzed in detail to build up the natural gas SD model. The parameters and their connotations are explained in Table 1. The model constructed in this paper includes three subsystems: investment subsystem, exploration subsystem and production subsystem. The investment subsystem is the driving link for the exploration and production of the natural gas upstream sector. The exploration subsystem is the material basis for the sustainable development of upstream natural gas enterprises, and also the basis for raising production. The production subsystem is the product value-added system.

### 3.2.1. Investment Subsystem

When the model is first being created, it is assumed that the main symbol identifying the model structure was its capacity of production. Converting the stock-flow diagram into a casual loop diagram allows a better understanding of the nature of the interaction between installed capacity and investment and depreciation flows. Therefore, the model was identified as two stocks: the total assets value of the natural gas industry and the depreciation of the facilities over time [28]. Assets value is increased by the company's decision to order new capital and is decreased by its depreciation. Economic depreciation refers to the actual wearing out of the asset, as reflected in changes in the asset's value over time. Each of the stocks was linked with two flows: an inflow and an outflow.

Major feedback loops in the investment subsystem include: Total investment $\rightarrow +$ Accumulative investment $\rightarrow -$ Capital depreciation $\rightarrow +$ Capitalized exploitation/development investment.

Based on the above analysis, it is assumed that the capacity of natural gas assets is influenced by two factors: the amount of investment and the depreciation of the equipment over time. The total capacity increases if the investment flow increases. Thus, the interaction between the investment flow and the natural gas assets' depreciation forms a reinforcing loop that characterizes an exponentially growing systems structure. However, the larger the natural gas assets, the larger the depreciations.

The annual accounting depreciation method is estimated by deducting the salvage value of the end-of-life equipment (SV) from the capital cost base, i.e., the depreciable capital investment (DC), and dividing the value by the accounted years of depreciation (N) of the asset:

$$d_n = (DC - SV_N)/N \quad (1)$$

$d_n$ means the annual depreciation subtraction in year $n$. The main equations in this subsystem are:

$$\begin{gathered} TIN = EPSIN + EPRIN \\ EPSIN = (0.1632 \times TIN) \times (1 - CPCR) \\ EPRIN = (0.8368 \times TIN) \times (1 - CPCR) \end{gathered} \quad (2)$$

3.2.2. Exploration Subsystem

As reported, there are mainly three types of resources in Chinese official statistics. These are the prospective resources, geological resources and proved resources [9]. Prospective resources are undiscovered but are assumed to be technically and economically recovered through geological estimations. In the case that the prospective resources are proven via exploration drilling activities, they will be transferred to geological resources if they are technically recovered but uneconomic, and they can become undeveloped reserves immediately. Relying on fluctuations in gas price, some reserves may become uneconomic to develop, or some economic to develop. Although they are economically recoverable, undeveloped reserves are used for recovery only when they are ready for production within the construction of production wells, and then become proven resources. The production rate is devised as the percentage of annual demand for gas and developed reserves, with the assumption that there is no capacity restriction on the production process.

Major feedback loops in the exploration subsystem include:

- Exploration investment → + Two-dimensional seismic investment and Three-dimensional seismic investment → + Annual incremental proved reserve → + Annual incremental recoverable reserve → − Remaining recoverable reserve → + Annuity volume of production → + Total investment → + Exploration investment
- Exploration investment → + Annuity incremental successful exploration well investment → + Annual incremental proved reserve → + Accumulative workable reserve → + Annuity volume of production → + Total investment → + Exploration investment

The loop explains exploratory activity and reserves additions as a result of investment, which is activated by capital cost. The following formula shows that the construction and operating costs play a critical role in determining the mix of capacity that will serve future demand for natural gas.

$$PV = \frac{C}{(1+r)^t} \quad (3)$$

$PV$ is the present value of capital; $C$ is the capital stock amount in each period(Year); and $r$ is the discount rate, $t$ is the investment period.

The other equations are as follows:

$$\begin{gathered} AEPWCPIN = AEPWIN \times EPWINCPR \\ EPRIN = EPSDRIN + EPSMIN + EPSOIN \\ ED = ACPR \div TR \\ ANEPRCPIN = AEPRIN \times EPRINCPR \\ AEPA = RRCR \times RPP \\ RRCR = ACPR + AADPR - AVOR \\ AVOR = RRCR \times ED \\ ED = 50\% \end{gathered} \quad (4)$$

**Table 1.** Parameter list of the SD model.

| Variable Name | Description | Unit |
|---|---|---|
| TIN | Total investment | 10 thousand Yuan (RMB) |
| EPSIN | Exploration investment | 10 thousand Yuan (RMB) |
| EPRIN | Exploitation investment | 10 thousand Yuan (RMB) |
| CPCR | Capital cost ratio | Percentage % |
| AEPWIN | Annual newly-increased exploration well investment | 10 thousand Yuan (RMB) |
| ACEWIN | Accumulative exploration well investment | 10 thousand Yuan (RMB) |
| EPWINCPR | Ratio of exploration well investment capitalization | Percentage % |
| AEPWCPIN | Annual exploration capitalization investment | 10 thousand Yuan (RMB) |
| EPWSR | Success ratio of exploration well | Percentage % |
| ACCPEPWIN | Accumulative capitalization exploration well investment | 10 thousand Yuan (RMB) |
| EPSDRIN | Exploration directly investment | 10 thousand Yuan (RMB) |
| 2DSIN | Two-dimensional seismic investment | 10 thousand Yuan (RMB) |
| 3DSIN | Three-dimensional seismic investment | 10 thousand Yuan (RMB) |
| EPSMIN | Matched investment for Exploration | 10 thousand Yuan (RMB) |
| EPSOIN | Other investment for Exploration | 10 thousand Yuan (RMB) |
| AADPRCPIN | Annual newly-increased proved resource capitalization investment | 10 thousand Yuan (RMB) |
| AEPRIN | Annual exploitation investment | 10 thousand Yuan (RMB) |
| ACEPRIN | Accumulated exploitation investment | 10 thousand Yuan (RMB) |
| EPRINCPR | Ratio of exploitation investment capitalization | Percentage % |
| ANEPRCPIN | Annual newly-increased exploitation capitalization investment | 10 thousand Yuan (RMB) |
| AEPRCPIN | Annual exploitation capitalization investment | 10 thousand Yuan (RMB) |
| ACCPEPRIN | Accumulated capitalization exploitation investment | 10 thousand Yuan (RMB) |
| EPRWIN | Exploration well investment | 10 thousand Yuan (RMB) |
| HWIN | Horizontal well investment | 10 thousand Yuan (RMB) |
| VWIN | Vertical well investment | 10 thousand Yuan (RMB) |
| EPRMIN | Matched investment for exploration | 10 thousand Yuan (RMB) |
| SLR | Sale revenue | billion cubic meters (bcm) |
| ASLR | Accumulated sale revenue | billion cubic meters (bcm) |
| AADVOP | Annual newly-increased volume of production | billion cubic meters (bcm) |
| ACADVOP | Accumulated newly-increased volume of production | billion cubic meters (bcm) |
| ADVOP | Annual diminished volume of production | billion cubic meters (bcm) |
| ACCP | Accumulated capacity | billion cubic meters (bcm) |
| 2DMLL | 2-D measure line length | meter |
| 3DEPRA | 3-D exploration area | kilometer |
| A2DMLL | Annual 2-D measure line length | meter |
| A3DEPRA | Annual 3-D exploration area | kilometer |
| AVWDP | Average well depth | meter |
| ADCP | Annual diminished capacity | billion cubic meters (bcm) |
| ACCP | Accumulated production capacity | billion cubic meters (bcm) |
| AACCP | Annual newly-increased capacity | billion cubic meters (bcm) |

**Table 1.** *Cont.*

| Variable Name | Description | Unit |
| --- | --- | --- |
| ACACCP | Accumulated newly-increased capacity | billion cubic meters(bcm) |
| AEPA | Annual exploration production reserve | billion cubic meters (bcm) |
| RRCR | Remaining recoverable reserve | billion cubic meters(bcm) |
| AARCR | Annual newly-increased recoverable reserve | billion cubic meters (bcm) |
| AAWR | Annual newly-increased workable reserve | billion cubic meters (bcm) |
| AWR | Accumulated workable reserve | billion cubic meters (bcm) |
| UWR | Unworkable reserve | billion cubic meters (bcm) |
| AADPR | Annual newly-increased proved resource | billion cubic meters(bcm) |
| ACPR | Accumulated proved resource | billion cubic meters (bcm) |
| ACPRCPI | Accumulated proved resource capitalization investment | 10 thousand Yuan (RMB) |
| TR | Total reserves | billion cubic meters (bcm) |
| AVOP | Annual volume of production | billion cubic meters (bcm) |
| ACAVOP | Accumulated Annual volume of production | billion cubic meters (bcm) |
| CAPLDF | Capacity load factor | Percentage % |
| RPR | Reserve/production ratio | Percentage % |
| NADR | Nature diminished ratio | Percentage % |
| CODR | Composite diminished ratio | Percentage % |
| HWFTN | Horizontal well footage number | meter |
| HWN | Horizontal well number | No. |
| VWFTN | Vertical well footage number | No. |
| VWN | Vertical well number | No. |
| ED | Exploitation degree | Percentage % |
| EOR | Exploitation oil recovery | Percentage % |
| EDT | Exploitation degree table | meter |
| DEP | Degree of exploration proved | Percentage % |
| WN | Well number | No. |
| EPWFT | Exploration well footage | meter |
| EPWN | Exploration well number | No. |

3.2.3. Production Subsystem

Besides the aggregate investment-depreciation cycle and the investment-driven exploration diagram of the model, the input of construction investments for an exploration well will also lead to the formation of the production capacity.

The production capacity expands when new production wells are available, whilst it decreases when present wells are attenuated or old wells are scrapped. Its economic value is potentially influenced by specific intervention measures, such as regulations and certain policies.

The production capacity of natural gas requires drilling a higher number of wells due to the low recovery rate per-well in Orados basin. The allocation structure with wells enables the inclusion of the uncertainties issues in the model more explicitly. The objectives of this structure were exploration wells that result in an improved discovery rate and are beneficial in inducing effective production wells or stimulating the construction of new wells.

Similarly, major feedback loops in the production subsystem include: Exploitation investment → + Annual exploitation investment → + Exploitation well investment → + Well footage → + Annual production capacity → + Accumulative production capacity → + Annual production → + Sale → + Total investment

The production subsystem differs from others in terms of production techniques, demand signal and production technology, especially related to recovery degree. The main equations in this subsystem are:

$$\begin{gathered} ACAVOP = AADVOP - ADVOP \\ CODR = 16\% \\ ACCP = 2 \times 10^{-5} \times (ACCPEPRIN - AEPRCPIN) + AACCP - ADCP \\ AVOP = ACCP \times CAPLDF \\ CAPLDF = 0.9 \end{gathered} \tag{5}$$

## 4. Simulation Results and Analysis

### 4.1. Model Testing

This part is going to examine how the model explains the basic features of gas exploitation and exploration in China. In other words, it is necessary to check out whether the model dynamically reflects the reliability and is valid for the variables, and to what extent the model fits the actual data.

Three key variables—total investment, proved reserves and production capability—are taken as examples. The comparisons between simulated values and historical observations of the variables are listed in Tables 2–4. Obviously, the error between the simulation value (from 2006 to 2013) and historical data vary from 1% to 8%, indicating that the model could be used for analysis in the case of the natural gas system.

**Table 2.** Simulated errors of total investment (10 thousand RMB/Year).

| Year | Historical Value | Simulated Value | Errors (%) |
|---|---|---|---|
| 2006 | 214,446 | 213,218 | 0.57% |
| 2007 | 442,000 | 464,219 | −5.03% |
| 2008 | 564,769 | 581,278 | −2.92% |
| 2009 | 680,162 | 680,809 | −0.10% |
| 2010 | 855,112 | 883,749 | −3.35% |
| 2011 | 1,068,800 | 1,094,572 | −2.41% |
| 2012 | 1,324,860 | 1,405,523 | −6.09% |
| 2013 | 1,627,530 | 1,563,358 | 3.94% |

**Table 3.** Simulated errors of the accumulated proved resource (billion cubic meters).

| Year | Historical Value | Simulated Value | Errors (%) |
|---|---|---|---|
| 2006 | 123 | 112.71 | 8.37% |
| 2007 | 349 | 330.63 | 5.26% |
| 2008 | 579 | 540.48 | 6.65% |
| 2009 | 802 | 768.51 | 4.18% |
| 2010 | 1071 | 1066.31 | 0.44% |
| 2011 | 1439.01 | 1507.21 | −4.74% |
| 2012 | 1886.39 | 1835.25 | 2.71% |
| 2013 | 2428.33 | 2520.1 | −3.78% |

**Table 4.** Simulated errors of the annual production capability (billion cubic meters).

| Year | Historical Value | Simulated Value | Errors (%) |
|---|---|---|---|
| 2006 | 10.5 | 10.81 | −3.00% |
| 2007 | 14.5 | 14.13 | 2.56% |
| 2008 | 18.4 | 16.78 | 8.78% |
| 2009 | 19.6 | 18.79 | 4.13% |
| 2010 | 22.2 | 23.01 | −3.64% |
| 2011 | 26.5 | 27.02 | −1.96% |
| 2012 | 36.8 | 38.4 | −4.35% |
| 2013 | 45.1 | 47.2 | −4.66% |

### *4.2. Scenario Modeling*

The future natural gas policies in China will influence the process and path of China's natural gas reform, and inevitably lead to reactions from agents in the gas industry to the gas market. Thus, the depreciation policy, gas pricing, technical progress and enterprise capital structure are considered. Thus, we develop a variety of scenarios to examine the response of upstream sectors.

#### 4.2.1. Scenarios

- Gas pricing

China's natural gas pricing policy has long been using the cost-plus method. The pricing provided a natural gas subsidy to the macro economy but has insufficient incentives to upstream producers. In 2011, pricing reform which adapted a net-back approach based on imported oil price indexation, had been piloted by Chinese government and then expanded trials to other provinces [29]. The new pricing regime is in deep contrast to the cost-plus regime as it moves the pricing point in the downstream market from the wellhead to city gate. While, under the cost-plus system, prices are dependent on production costs, city-gate prices are linked to market-oriented oil-product prices that serve as a benchmark for each province. Thus, the city-gate price is linked to the prices of fuel oil and Liquefied Petroleum Gas (LPG), weighted at 60% and 40%, respectively. The price setting formula is:

$$P = K \times (\alpha \times P_0 \times \frac{H}{H_0} + \beta \times P_1 \times \frac{H}{H_1}) \times (1 + R)$$

where, $K$ the discount rate (0.9), $R$ the natural gas VAT rate, $H, H_0, H_1$ the heat content of natural gas, fuel oil and LPG, $\alpha, \beta$ the weighted percentage of fuel oil and LPG, $P_0, P_1$ the import price of fuel oil and LPG. Then, we have two scenarios:

Scenario A1: Cost-plus pricing; a pricing-regulated approach based on cost-plus for the production and pipeline tariffs. The cost-plus pricing method is the main pricing strategy of the Chinese natural gas industry, but it cannot meet the development demand for an integrated gas market.

Scenario A2: Net-back pricing; the natural gas price is linked with the price of imported fuel oil and LPG. From 2013, China began to pilot the net return value method in Guangdong and Guangxi, which is an important stage in China's natural gas pricing reform process.

- Cost of Investment

The model shows the long-term investment efficiency of the natural gas upstream industry in China, therefore it is necessary to consider the time value, investment, and discount of investment [30].

We adjusted firm's net operating profit after tax (NOPAT) and capital each year by adding an estimation of the increase in the net present value (NPV) of the firm's investment in exploration and exploitation, and also to the capital flow that was carried into the next year. More specifically, we estimated the net present value by regarding the year-to-year change in the reserve value and added investment based on different levels of capital cost rate. A discount formula is:

$$PI = \frac{I}{(1+r)^t}$$

where, $PI$ is the present value of investment; $I$ is the investment volume of each period; and $r$ is the capital cost rate, $t$ is the investment period. Then, we have the following three scenarios:

Scenario B1: capital cost rate = 5.5%. In 2009, State-owned Assets Supervision and Administration Commission (SASAC) and National Development and Reform Commission (NDRC) decided to set the capital cost ratio at 5.5% on the basis of the bank loan interest rate.

Scenario B2: capital cost rate = 8%. This is the possible capital cost rate level that China's upstream natural gas enterprises can reach in the future.

Scenario B3: capital cost rate = 12%. This is the average capital cost rate level of the industrial sector, or internal return rate (IRR) [31].

- Accounting Depreciation

Depreciation is the asset depleting over time and is properly recognized as a cost of business operation. Depreciation may bear some skepticism but it should be pointed out that accounting depreciation is a policy tool that may be used to encourage or discourage certain types of investment, especially in emerged energy fields. In China, depreciation is calculated on a straight-line basis and is subject to certain minimum depreciation periods. Under the same circumstances, accelerated depreciation should apply to enterprises engaged in oil and gas exploration activities.

Scenario C1: Straight-line depreciation for an 8-year depreciation settlement.

Scenario C2: Depreciation with the accelerated declining method combined with a switch to straight-line depreciation; 150% declining method for the former 4-year depreciation settlement, straight-line depreciation for the rest 4-year depreciation settlement.

- Discovery Rate for Exploratory Wells

Exploratory wells obviously continue to have a high risk of failure. However, the technology process has reduced the possibility of dry holes. Hence, the discovery rate is an important factor representing the exploitation technology.

Scenario D1: discovery rate for wildcat wells = 0.51. This is the current technological level of the discovery rate that is currently used by China's upstream natural gas enterprises.

Scenario D2: discovery rate for wildcat wells = 0.6. It is a high technological level when the exploration and development of upstream enterprises achieve some technological progresses. Scenario D3: discovery rate for wildcat wells = 0.7. This is a higher technological level when the upstream enterprises achieve important technological progresses.

#### 4.2.2. Simulation Results

In this section, we will show some simulation results from each scenario.

- Gas pricing scenario

Figures 2 and 3 show the results of different gas pricing policy scenarios and the net-back method has a remarkable positive effect on both sales and investment. After using the net-back method, sales of natural gas improved by nearly 17%, and investment also had a 16% increase in the model. Due to the impact of the international economic crisis, the movement has a certain irregular fluctuation during 2007 and 2009. However, the overall trend of the natural market is reasonable. Natural gas sales increase in line with the upstream gas companies' targets of maximizing the benefits. The evolution of natural gas pricing strategies has not only led to an increase in sales, but has also contributed to an increase in annual investment in upstream exploration activities, which is conducive to the positive cycle of the upstream natural gas business.

Figure 4 shows that annual proved reserves improved from $488.06 \times 10^8$ $m^3$ to $549.57 \times 10^8$ $m^3$ when the net-back method is applied. The amount of growth before 2015 is larger than that after 2015. The annual added proved reserves rose rapidly in 2006–2008. However, they drop sharply in 2009, which was mainly due to the global financial crisis sweeping the world in 2008. The exploration and development of the upstream natural gas industry is often lagging behind, and the impact of the financial crisis was fully apparent in 2009. However, after that, the exploration and development of the Chinese upstream natural gas industry began to rise steadily. This effect is more apparent when the net return pricing method is adopted.

Figures 5 and 6 show that the proportion of exploitation investment and exploration investment is essentially unchanged in different sceneries. Different natural gas price making policy scenarios have little influence on the investment proportion of upstream sectors. In the process of increasing total investment, the company needs to maintain the increase in exploitation investment. However, the proportion of exploration investment declined after 2010; the proportion of investment in development changes is relatively small. The possible reason for the decline in the proportion of exploration investment is that the upstream enterprises are less active in exploration. This is not a positive signal. Because natural gas is still very limited in China's total energy consumption, increasing natural gas exploration is the basis for ensuring China's natural gas energy supply.

Much research has shown the negative effects of cost-plus pricing in developing the national natural gas market. Our simulations also indicate that the competitive pricing of natural gas based on alternative fuels really provides a stimulus to producers.

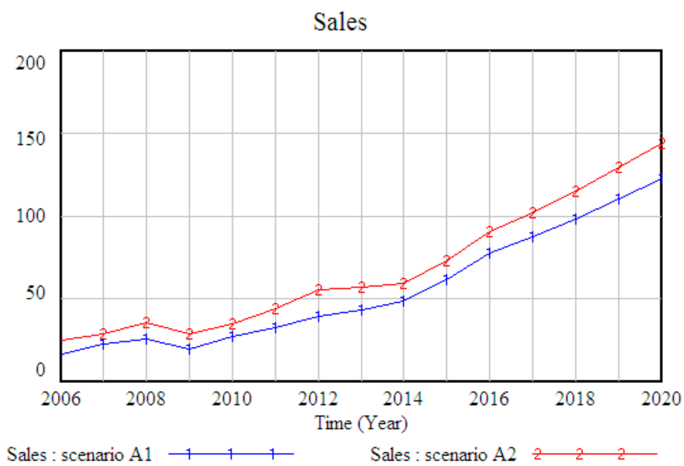


**Figure 2.** Sales of natural gas (billion cubic meters).

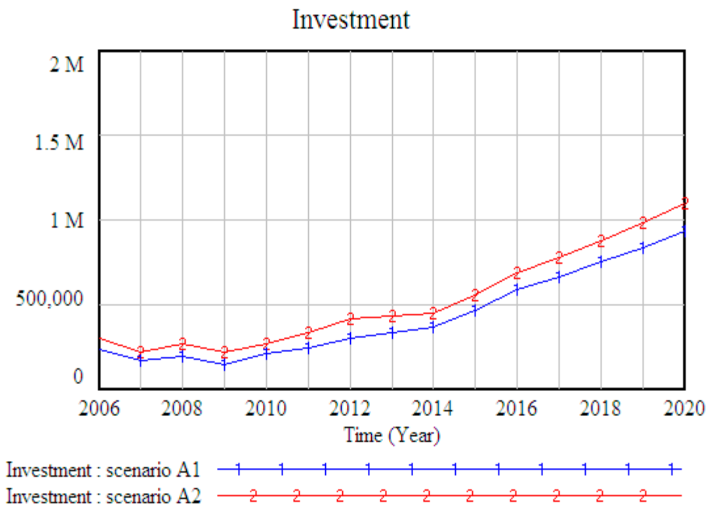


**Figure 3.** Annual investment (ten thousand Yuan).

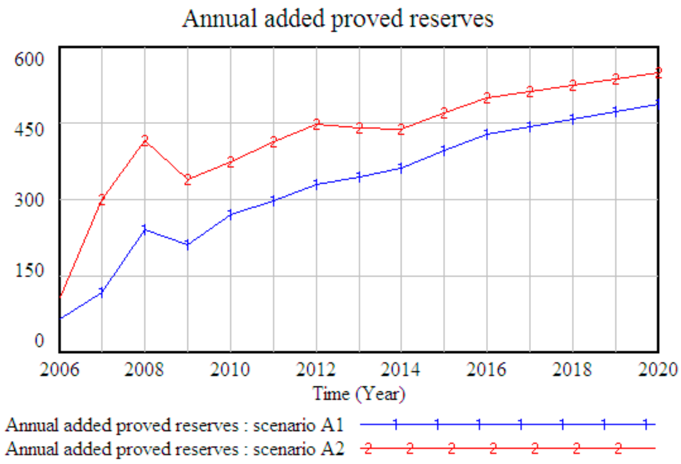


**Figure 4.** Annual added proved reserves (billion cubic meters).

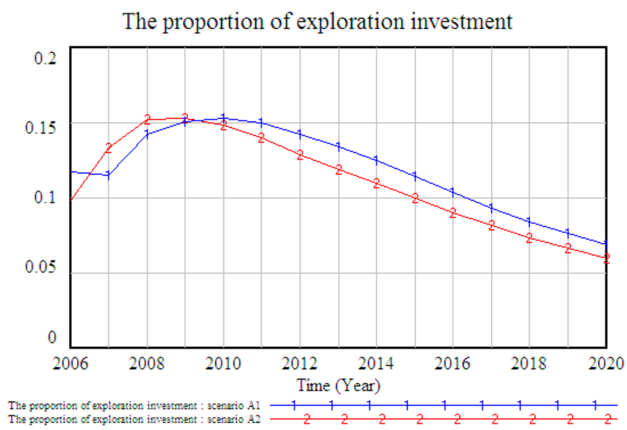


**Figure 5.** The proportion of exploration investment.

- Investment Cost Scenario

An excessive capital cost rate will affect the increase in annual added proven reserves and annual production. Simulations show that investment sufficiency did not receive enough attention. Figure 7 shows that the higher capital cost rate has some effect on the basic trend of annual proved reserves. In scenario B2, annual proved reserves are essentially unchanged. However, in scenario B2, annual proved reserves decrease obviously. Figure 8 shows that the capital cost rate is a negative factor to annual production. The possible capital cost rate level in the future leads to a 2% decrease and the industry average level is 16%. Therefore, governments and upstream gas companies need to be careful when setting the capital cost rate, which is more important for the exploration and production of upstream enterprises.

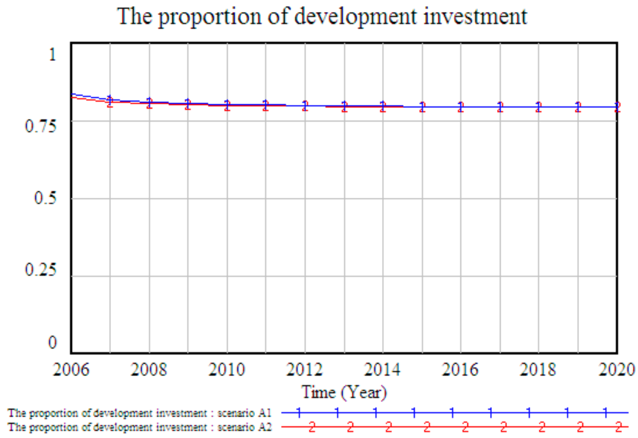


**Figure 6.** The proportion of development investment.

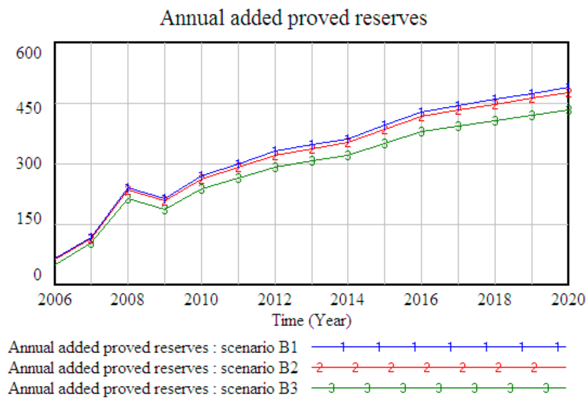


**Figure 7.** Annual added proved reserves (billion cubic meters).

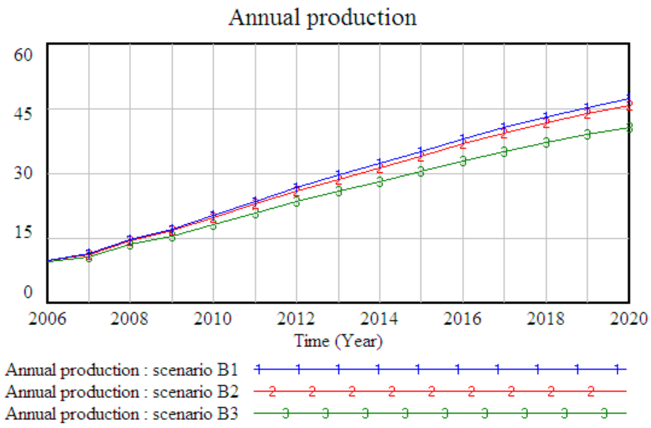


**Figure 8.** Annual production (billion cubic meters).

- Accounting Depreciation Scenario

General taxation policies have the strongest impact on industrial avenues. Since depreciation settlement has a direct influence on the industry's returns, we assess the different depreciation methods (or scenarios) for Natural Gas Company.

We evaluate the impact of different depreciation settlements. Figures 9 and 10 show that accelerated depreciation has an obvious impact on both annual proved reserves and annual production. The use of the double declining balance method can obviously increase both annual proved reserves and annual production.

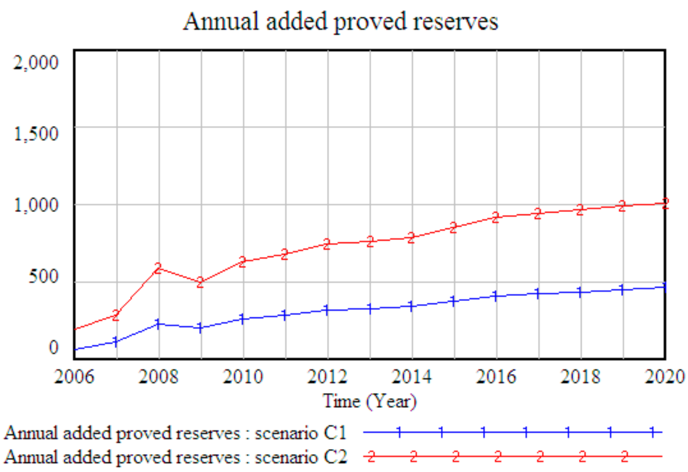


**Figure 9.** Annual added proved reserves (billion cubic meters).

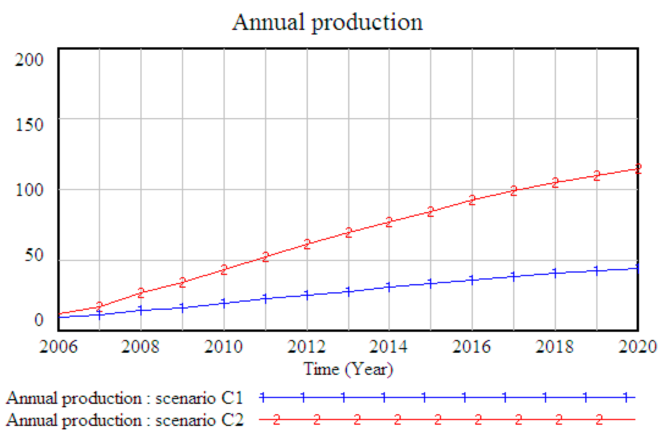


**Figure 10.** Annual production capability (billion cubic meters).

Obviously, the high IRR is accompanied with relatively short depreciation periods of eight years, while the technical duration would be more like 40 to 60 years. This has the potential to increase the tangible cost even further. The depreciation period for energy assets is set too low by the accounting rules in China. If, as part of its investment policy, China decides to maintain the short depreciation period for tax balance and energy security purposes, it should reflect the real economic life of the upstream assets, otherwise, accelerated depreciation would create incentives for investment.

- Exploratory Technology Scenario

In general, technological progress encourages the discovery of exploration well, that is the success ratio of exploration well. Figures 11 and 12 show that the effect of the technology factor on both annual proved reserves and annual production is both positive and effective. The higher the technical progress, the more annual proved reserves and annual production increase. The simulated results show that annual proved reserves of higher technology in 2020 have a 10% increase compared to annual proved reserves of current advanced technology, and annual production has an almost 19% increase. Therefore, the upstream enterprises need to increase investment in scientific research to promote technological progress. In addition, purchasing advanced equipment and implementing an advanced enterprise management model are also important for the enterprise to maintain indispensable sustained progress.

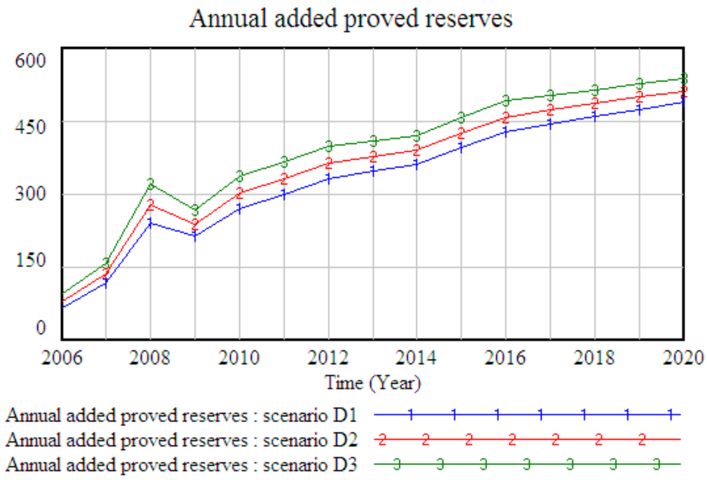


**Figure 11.** Annual added proved reserves (billion cubic meters).

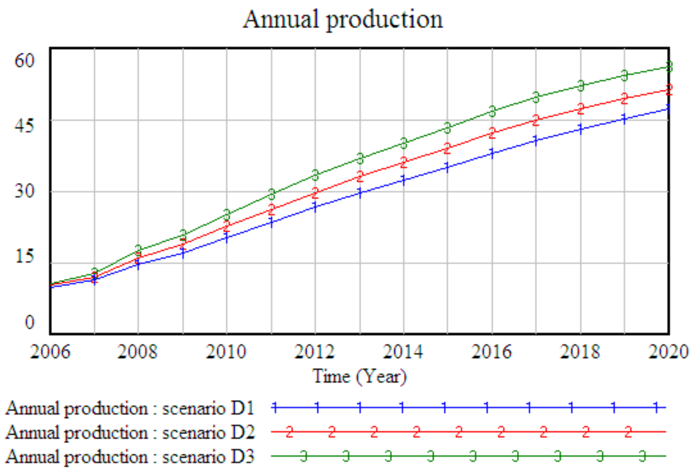


**Figure 12.** Annual production (billion cubic meters).

- Overall Scenarios Comparison

High-revenue expectation in exploration and production between 2006 and 2013 results in natural gas production rising. In the model, it is assumed that investments in exploration and development are supported by the cumulative profit obtained from the sales. Figure 13 shows that the reserve/production ratio does not change due to the different scenarios, and the basic trend is clear. At the beginning, it gradually decreases, but after 2015 it keeps constant and stays at about the level of 20. This finding has shown that the model is not able to provide investment levels that are sufficient to obtain a considerable production level, because low reserve/production rates result in low revenues and also low investments.

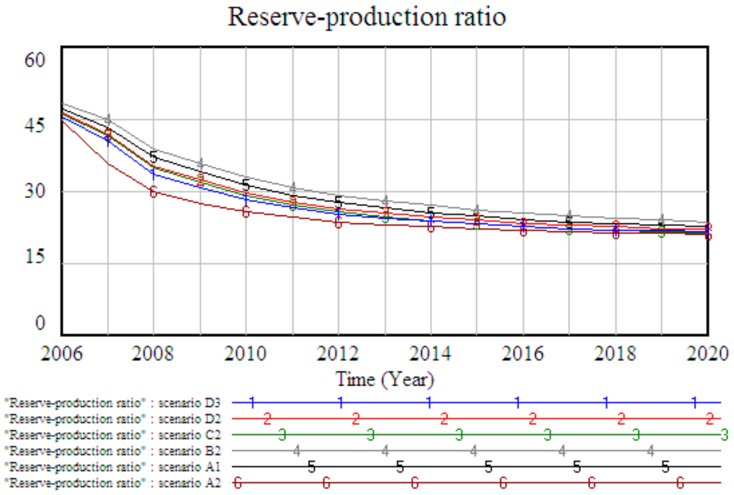


**Figure 13.** Reserve/production ratio.

Overall, Figure 14 shows that different scenarios have different effects on annual proved reserves, but the basic trend does not change due to the different scenarios. Gas pricing and the discovery rate for exploratory wells are the most effective factors among the variables that we chose.

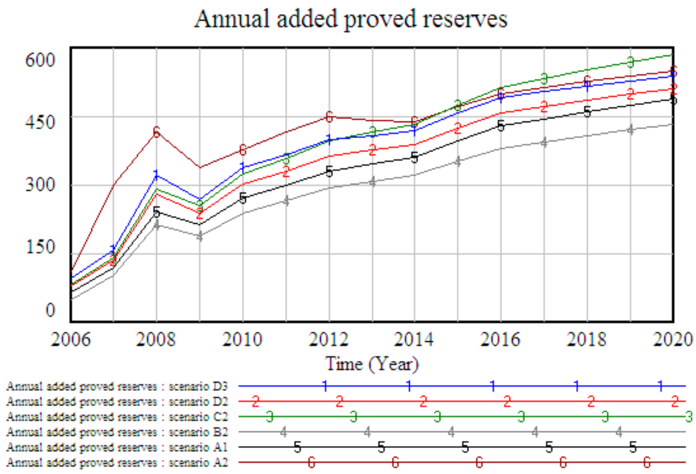


**Figure 14.** Annual added proved reserves (billion cubic meters).

## 5. Conclusions

The presented model in this paper is the first large system dynamics model in Chinese natural gas industry and its approach is to analyze how the complicated factors, including price, policy, technology and cost, influence the whole natural gas system.

This model examines how the different factors affect the dynamic system and by simulating the results, the government can potentially make complementary policies for an upstream company. The model shows that reform of the gas pricing policy can create an intrinsic motivation for upstream sectors of natural gas to increase investment and annual production. This requires a fundamental reform of the gas pricing regime, by adopting a broader net-back approach based on the market-determined measure of gas compared with alternative fuels. If the government wants upstream enterprises to encourage the exploration and development of natural gas, it is necessary to implement the market-oriented pricing to fully mobilize the upstream gas production enterprise initiative. The net-back pricing method is only the first step, the final objective is establishing market-based natural gas pricing system in China. In addition, Chinese upstream gas companies need to accelerate the construction of natural gas infrastructure and improve the small cities and rural areas of the pipe network construction. The government also needs to enact policies and regulations, and actively guide the residents of green energy consumption.

The key challenge is to recognize that the gas industry needs to reconcile the required investment amount with the need to improve investment efficiency. More generally, the strategic objective of the gas industry is to ensure long-term efficiency. Therefore, the upstream natural gas enterprises need to increase R&D investment to continuously improve the production efficiency. In addition, due to the current low level of production and management of natural gas enterprises, improving the production and management level is also an important method to ensure higher production efficiency in upstream fields.

Obviously, the adjustment of depreciation can enhance the annual natural gas production of upstream sectors effectively, which shows that being inherently profit-driven can significantly increase gas production capacity. In this regards, the other elements of the tax and accounting regime should be propitious to foster re-investment into the expansion of upstream exploration and exploitation. This could call for accelerated depreciation providing incentives for re-investing earnings into the gas industry.

Technological improvement is an important factor for natural gas exploration and development; the enhancement of wildcat wells' success rate can improve the annual proved reserves and annual production effectively. Gas recovery techniques can significantly extend proved reserves and hence support the sustainable development of the gas industry. In terms of upstream natural gas enterprises, it is necessary to strengthen the research of engineering technology and adopt advanced technology, such as horizontal well technology and multi-layer fracturing technology, so as to improve the success rate of exploration wells and ultimately improve enterprise efficiency. As China's economic development went into the "new normal" stage, the natural gas demand growth has gradually slowed down. However, the development of the natural gas industry is in line with China's energy-saving emission reduction strategy. Therefore, the government has the responsibility to increase the R&D support for upstream natural gas enterprises to promote their rapid development.

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