The Future of Natural Gas in China: Effects of Pricing Reform and Climate Policy

by

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Submitted to the Institute for Data, Systems, and Society
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Abstract

China has a goal of reducing carbon emissions. At the same time, China is currently targeting an increase in natural gas consumption as a part of broader national strategies to reduce the environmental (air pollution) impacts of the nation's energy system, which at present is still heavily reliant on coal. Natural gas is also being promoted in residential sector as a way to improve living standards.

Chinese policy makers have recently launched nationwide gas pricing reform that links the natural gas price to oil prices to address natural gas supply shortages. My analysis of the pricing reform shows that it leads to a better predictability and transparency than the previous pricing regime. The reform also increased natural gas price that incentivized gas suppliers to produce and import more gas. However, there are also some limitations of the reform. First, it creates biased incentives that favor suppliers. Second, natural gas and oil have different supply and demand patterns and linking natural gas price to oil price may create distortions for natural gas use. The Chinese government should support a market-based natural gas pricing system because it will establish a better resource allocation system and improve welfare of China.

To assess natural gas scenarios up to 2050, I use the EPPA model, which is a global energy-economic model where China is represented as a separate region. Based on my updates to the EPPA model to represent China's energy system and cost of technologies, three main policy scenarios are explored: the reference scenario, the cap-and-trade policy scenario, and the integrated policy scenario that coordinates the natural gas subsidy with economy-wide emission constraints.

The results show that a cap-and-trade policy will reduce natural gas consumption while enabling China to achieve its climate goals. The integrated policy uses a part of the carbon revenue obtained from the cap-and-trade system and promotes natural gas consumption. The integrated policy results in a further reduction in coal use relative to the cap-and-trade policy case. Both the climate objective and the natural gas promotion objective can be achieved with the integrated policy. The integrated policy has a very moderate welfare cost while leading to a reduction in air pollution. The results are tested for their sensitivity to excluding the household sector from the cap-and-trade scheme, the cost of natural gas-based power generation, the substitutability of fuels in final consumption, and the level of nuclear power generation in China.

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Table of Contents

Chapter 1 Introduction

1.1 Research Questions

China's energy supply has long been dominated by coal. Over the past three decades, about two-thirds of China's primary energy consumption has come from coal, causing significant local, regional and global environmental pollution. At present, natural gas accounts for approximately 6% of China's primary energy supply, which is substantially below the global average of 23.7% (BP, 2014). Further, natural gas use generates much less pollution than coal and thus natural gas is often regarded as a cleaner energy. China has already become the world largest CO_2 emitter and suffers the most from air pollution. The substitution of natural gas for coal has been listed as an important part of China's sustainable energy system transformation strategy by the Chinese government. Natural gas use is widely encouraged in Chinese cities as an important option to address the deteriorated air pollution and improve living standards. According to China's national energy strategy action plan, the share of natural gas in primary energy supply should reach 10% by 2020 (State Council, 2014). In this regard, natural gas has a great potential for expansion in China's future energy market. In reality, however, there are still significant economic and institutional barriers to expansion of natural gas consumption. The natural gas future in China is quite uncertain without innovative approaches to address these barriers.

The literature on China's transition to a low carbon energy system has been increasing in volume, and most of these studies have also demonstrated an increased contribution of natural gas in China's future energy supply. But there is a limited research on the specific mechanisms and institutional arrangements relevant to the claimed increase of natural gas contribution. The future of natural gas development has many determinants. The natural gas pricing mechanism is the most important one. Natural gas prices in China have long been determined by government agencies, predominately by National Development and Reform Commission (NDRC), with less flexibility, predictability, and transparency. Since the early 2010s NDRC has launched a natural gas pricing reform initiative. Regarding this objective, I will address the following questions. What are the strengths and deficiencies of the current natural gas pricing reform initiative? How does it affect China's natural gas market players? What should be the directions for future natural gas pricing?

There is also a significant research literature that finds that public interventions will be needed to enable China's transition to a low carbon energy economy (Chai and Zhang, 2010; Zhou et al., 2014; Wang and Cheng, 2015; Zhang et al., 2015). Of the proposed public policies for China's mitigating climate change, carbon tax and/or carbon dioxide emission cap-and-trade scheme have been mostly considered as a cost effective approach in mitigation (Paltsev et al., 2012; Zhang et al., 2015). China has recently announced its plans to build a national carbon emission cap-and-trade system to harness its soaring CO_2 emission (The White House, 2015). In its intended nationally determined contribution (INDC) submitted to the United Nations for the meeting in Paris in December 2015 (NDRC, 2015a), China has also pledged to peak its CO_2 emission around 2030 by introducing a number of policy measures with the national cap-and-trade system being highlighted. There have been studies which analyze the level of the carbon price needed for China to honor its climate pledge (Zhang et al, 2015). As natural gas contains carbon, the natural gas use could be penalized by the carbon price. The existing studies does not address the issue to what extent such a carbon price will affect the achievement of China's natural gas consumption goal. Such investigation, however, is important as climate policy might lead to substantial deviation from the natural gas promotion objective. I will address the following related questions. Will there be an innovative approach with which both China's climate mitigation objective and the natural gas promotion objective could be achieved simultaneously at the least cost to the economy? How sensitive are the results to the costs of natural gas power technology? How much additional air pollution emission reduction can be achieved with promoting natural gas?

In order to address the research questions and fill in the literature gaps mentioned above, it is critical to find an appropriate analytical tool. Some researchers have applied a number of bottom-up engineering-based approaches, such as MARKAL (Jiang et al., 2008), Fourier functions model (Jiao et al., 2002), self-organizing data mining approach (Gao and Dong, 2008) to project and quantify China's future energy consumption. However, those methods fail to fully take into account the economic impacts. To address the shortcomings, Li et al (Li et al., 2011) applied a system dynamics model which was originally established by Forrester (Forrester, 1956) to quantify the trend of natural gas substitution for coal. Even with Li's improvement, his engineering-based model lacks the capability to model impacts from global trading, interactions among sectors, and economic-based policies. In this thesis, I will use a global energy-economic model that tracks all economic activities and allow studying interactions between different sectors, regions and policies.

1.2 Contributions and Organization

The contributions of my thesis include: 1) conducting an integrated assessment of China's natural gas pricing reform initiative; 2) investigating the appropriateness of the oil-linked natural gas pricing scheme which is proposed under the current pricing reform for China's natural gas development in long-term; 3) examining the consistency of climate policy with the natural gas promotion objective; and 4) identifying an integrated policy approach which combines the natural gas subsidy scheme with the cap-and-trade policy, and can simultaneously enable the achievement of the climate mitigation objective and natural gas promotion objective at less cost to the economy.

The assessment of China's recent natural gas pricing reform initiative is focused on the impacts on different players in China's natural gas market, covering suppliers, distributors, and consumers. The projections of natural gas use in different scenarios are based on the energy-economic model developed at the MIT Joint Program on the Science and Policy of Global Change, the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev et al., 2005; Chen et al., 2015). An advantage of this modeling framework is that both the commodities' quantities and prices are endogenously determined. I choose the EPPA model to simulate the natural gas price trajectories under an oil-linked pricing scheme and a completely market-determined one to examine the difference between the two pricing mechanisms. For this task, I enhance the EPPA model with a representation of the latest China's policy objectives and updating the technology costs in China's power generation sector.

I also employed the EPPA model to investigate to what extent the climate policy could lead to a deviation from the natural gas promotion objective. Natural gas price is much higher than coal price in China, and the large scale substitution of natural gas for coal will need a large amount of subsidy. To afford this subsidy, Chinese government may need new income sources. The proceeds from a cap-and-trade scheme can be used for such a new source of government revenue. In this context, there is a possibility of achieving both the climate mitigation objective and natural gas promotion objective if we integrate the climate policy with the natural gas promotion policy. The critical part of the work is to determine the subsidy level and estimate the cost to the economy. The EPPA model has strengths to implement such analysis.

My thesis is organized as follows. Chapter 1 above introduced the motivation and research questions of this study. Chapter 2 provides an overview of the natural gas market and the policies which might affect natural gas use in China. Chapter 3 conducts an integrated assessment of China's recent natural gas pricing reform in terms of predictability and transparency, analyzes its impacts on natural gas producers, distribution companies and end users, and discusses the major limitations of the current reform. Chapter 4 introduces the analytical tool used in this study, namely the EPPA model. It also presents major assumptions, data, modifications made for the China region of the model, and compares the modeling results on the oil-linked pricing scheme and the completely market-determined pricing mechanism. Chapter 5 conducts a projection of the natural gas use in several scenarios: the reference scenario, the cap-and-trade policy scenario, and the integrated policy scenario. It also compares the CO_2 emission, coal consumption, and the air pollutant emissions under different scenarios, and estimates the costs of implementing the climate and natural gas promotion policy. Chapter 6 concludes.

Chapter 2 China's Natural Gas Market and Policies: An Overview

2.1 Gas Supply

The government of China considers the expansion of natural gas use as a critical component of shifting away from coal-dominated energy structure, necessitated by interest in tackling air pollution problems and reducing carbon emissions[1]. China's natural gas consumption climbed from 46.4 billion cubic meters (bcm) in 2005 to 167.6 bcm in 2013 with an average annual growth rate of 17.4% (CNPC, 2014). As shown in **Figure 2.1**, the natural gas share in China's primary energy supply increased from 2.4% in 2005 to 5.3% in 2013 (NBS, 2015) . The natural gas contribution to China's energy supply is well below coal and oil, which were approximately 67% and 17%, respectively, in 2013 (also depicted in **Figure 2.1**). It is also lower than the global average of 23.7% in 2013 (BP, 2014).

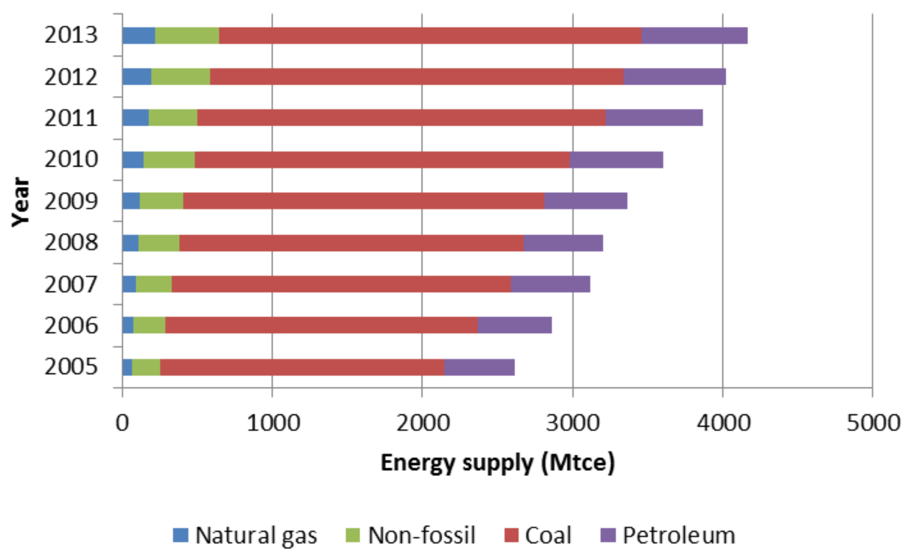


Figure 2.1 Natural gas in China's total energy supply (Mtce). Data source: NBS (2015).

Prior to 2006, China's natural gas supply had come from domestic production sources (**Figure 2.2**). Since then, imports have grown rapidly, especially since 2010, when the Central Asia – China pipeline started operations. By 2013 approximately 31% of annual natural gas consumption came from imports (CNPC, 2014). The Myanmar - China pipeline and the

[1] The material in Sections 2.1-2.3 is based on my contribution to Paltsev and Zhang (2015a).

liquefied natural gas (LNG) receiving terminals in Guangdong, Hebei, and Tianjin started operation in 2013, significantly expanding China's gas import capacity. In 2013, 54% of China's gas imports were delivered through the Central Asia and Myanmar pipelines, with the rest coming from LNG (CNPC, 2014).

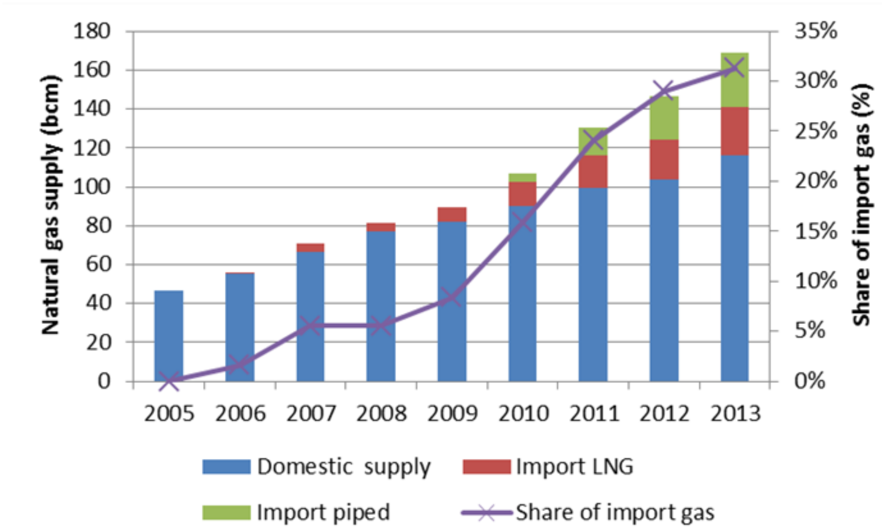
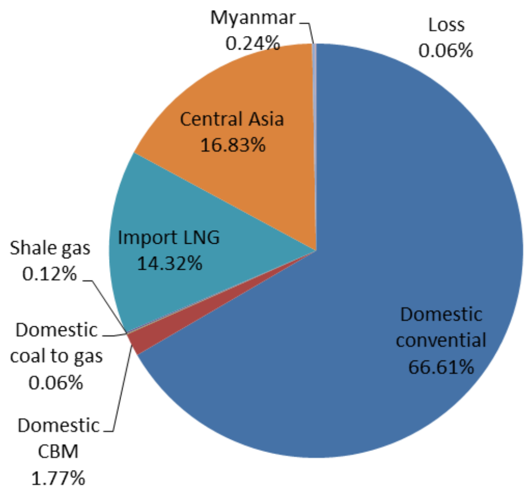


Figure 2.2 Supply structure of natural gas in China in 2013 (bcm). Data source: domestic supply data (NBS, 2015), imports by source (CNPC, 2014).

In 2013 China's domestic gas production contributed 115 bcm, or approximately 69% of the total gas supply (**Figure 2.3**). Conventional gas production accounts for about 97% of domestic production. The three top gas basins – Tarim, Ordos, and Sichuan—currently play a dominant role in China's domestic gas supply, accounting for over 90% of China's total domestic gas production. China's current unconventional gas production capacity is rather limited. The total unconventional gas production was 3.3 bcm or 1.95% of China's domestic gas supply in 2013, of which coal bed methane (CBM), shale gas, and coal to gas constituted 1.77%, 0.06% and 0.12%, respectively.



	2013
Domestic:	
Convential	111.6
CBM	3.0
Shale gas	0.2
Coal to gas	0.1
Import:	
LNG	24
Central Asia	28.2
Myanmar	0.4
Loss	0.1
Total	167.6
	bcm

Figure 2.3 Supply structure of natural gas in China in 2013. Data source: BP (2014) and personal communications with industry experts.

2.2 Import Capacity

The 2014 import pipeline capacity was 30 bcm for the combined two lines of the Central Asia – China pipeline and 12 bcm for the Myanmar - China pipeline. Construction of a third line of the Central Asia – China pipeline was mostly completed and a capacity of 55 bcm for the combined three lines is expected to be operational in 2016. A fourth line (with a capacity of 30 bcm) of the Central Asia – China pipeline is under construction with an expected completion by 2020.

China has also signed an agreement with Russia to supply 38 bcm by 2018 from the Power of Siberia pipeline. An advantage of this project is that it will cross China's border in the North-East side with a close proximity to industrial centers rather than supplying gas through the China's West-East pipeline. Another pipeline (called Altai or The Power of Siberia II, with 30 bcm capacity) from Russia is under consideration. The Altai pipeline is expected to be connected to the Russian fields that currently supply Europe. In China it would be linked to the West-East pipeline. As for another import option, LNG, in 2014 China had 12 regasification terminals with a combined capacity of about 50 bcm, or 35 million tonnes (Mt) of LNG (Interfax, 2015).

It is expected that by 2020 China will have an estimated pipeline import capacity of 165 bcm (85 bcm from Cenral Asia, 12 bcm from Myanmar, and 68 bcm from Russia). It is also expected that by 2020 LNG import capacity would reach 88 bcm. Another 58 bcm of LNG capacity has been proposed, but these projects can be postponed or cancelled depending on natural gas demand development (BMI Research, 2013; Du and Paltsev, 2014). In total, by 2020 China's import capacity (both pipeline and LNG) will be 223 bcm considering existing capacity and the projects under construction. Another 88 bcm is possible if both the Russia's Altai pipeline and additional LNG projects move forward.

2.3 Gas Consumption

China's natural gas consumption by sector from 2005 to 2013 is presented in **Figure 2.4**. According to the figure, in 2005 most of consumption occurred in three sectors: as a fuel in industry (36%), as feedstock in chemical production (30%), and residential use (17%). Consumption in the power and heating sector and the transport sector was very limited in 2005, but increased rapidly from 2008 and so that by 2013 these two sectors accounted for 30% of gas consumption.

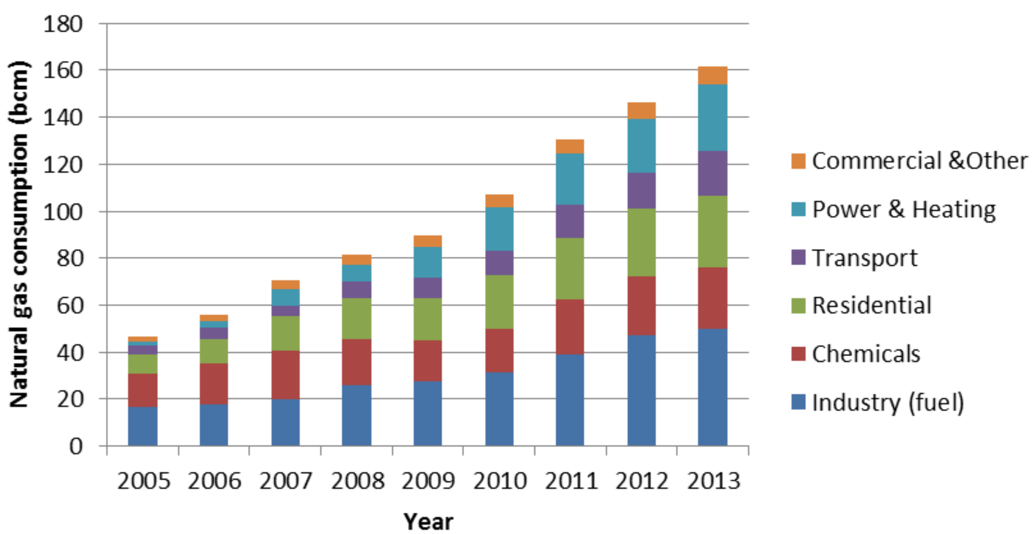


Figure 2.4 Gas demand by sector 2005-2013. Data Source: 2005-2012 data (NBS 2014); 2013 data (personal communication with industry experts).

As of 2013, industry was still the largest natural gas user in China. It consumed approximately 50 bcm of gas and accounted for 31% of the total gas consumption. The residential sector consumed 30 bcm and accounted for 19% of the total consumption. The power & heating sector became the third largest gas user in China and accounted for 18% of China's total natural gas consumption, followed by chemicals (16%) and transport (12%). Gas use increased substantially in all sectors except for chemicals, hence most of the increased gas consumption has been used as fuel by substituting for coal rather than as a feedstock for the production of chemical products. This largely reflects China's natural gas policy that discourages use of gas as a feedstock in the chemical sector, while encourages fuel switching from coal to gas to tackle air pollution and mitigate CO_2 emissions (NDRC, 2012a).

Over the past decade, China has increased its efforts in constructing the natural gas pipeline distribution systems. As a consequence, around 32% of medium and large sized cities in China (with a total population of approximately 240 million) have access to gas pipelines (CNPC, 2014). Figure 5 shows the picture of China's gas consumption by regions. As denoted by blue-shaded areas in Figure 5, natural gas consumption is mainly concentrated in four regions: Southwest (Sichuan, Chongqing), Bohai Bay Area (Liaoning, Beijing, Tianjing, Shandong, Hebei), Yangtze River Delta (Shanghai, Jiangsu, Zhejiang), and the Southeast Coastal Area (Fujian, Guangdong). These four regions together contributed to more than 60% of China's gas consumption in 2012 (NBS, 2014). Large consumption of gas in the Southwest (Sichuan and Chongqing) and Xinjiang is because they are located in the major natural gas production areas of China. The major gas consumers in the eastern coastal area of China such as Beijing, Tianjin, Shanghai, Jiangsu, and Guangzhou are among China's most developed provinces. The rapid growth of natural gas consumption in these rich areas is largely attributed to their efforts to promote the substitution of gas for coal to reduce the frequent smog incidence which has recently caused unprecedented health concerns in these areas.

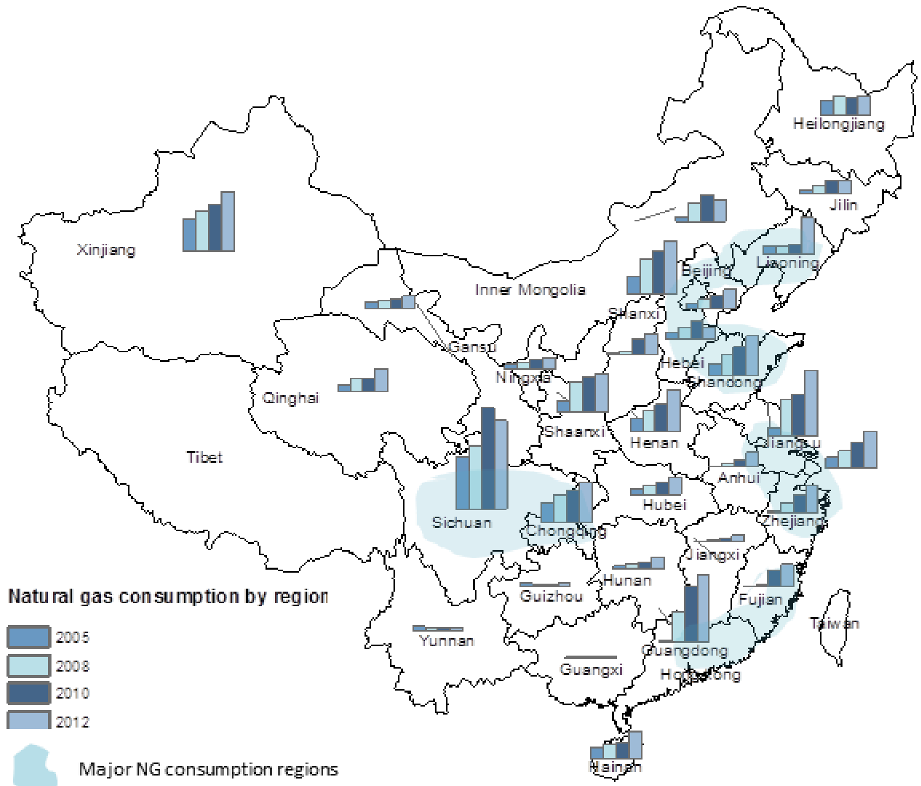


Figure 2.5 Gas consumption (in bcm) by region during 2005-2012. The vertical bars for each province are provided for illustrative purposes. They can be compared to the represented 2012 consumption of 15 bcm in Sichuan and 10 bcm in Xinjiang. Data Source: NBS (2014).

Relative to these consumption centers depicted in **Figure 2.5**, major domestic producing areas are Tarim in Xinjiang, Ordos (located in part in Shaanxi, Shanxi, Gansu, Ningxia), and Sichuan. As for the points of entry for imports, the pipeline from Central Asia enters China in Xinjiang. The pipeline from Myanmar goes to Yunnan, Guizhou, and Guangxi. The Power of Siberia pipeline from Russia will enter in Heilongjiang with a potential to reach Jilin, Liaoning, and Beijing. LNG terminals are located in coastal provinces.

2.4 Policies Affecting Natural Gas Supply and Use

Government policies that affect the future of China's natural gas development can be divided into three categories: the pricing policy, other natural gas promotion policy except for the pricing policy, and the climate policy. China's major natural gas pricing policy is a result of China's natural gas pricing reform, which will be discussed and analyzed in details in Chapter 3. Below I provide a review of China's key climate and natural gas promotion policies.

2.4.1 Natural Gas Pricing Policy

Natural gas pricing reform has played a vital role in promoting natural gas supply from both domestic and overseas sources. China's natural gas pricing used to favor consumers. The highly regulated pricing regime resulted in a low gas price and failed to provide enough incentives for natural gas suppliers. A new gas pricing reform was firstly put into trial in Guangdong and Guangxi provinces in December 2011, and was introduced nationwide in July 2013. The pricing reform aims to create a more market-based pricing mechanism to encourage natural gas supply. To minimize potential political opposition during the new regime implementation, the government adopted a two-tier pricing approach for the period of transition. During the transitional process, the pricing for the incremental volume of natural gas supply was linked to the international oil products prices while the prices for the existing volume was gradually increased to the level of incremental volume. . The transitional process lasted until April 2015. Now China's wholesale natural gas price is connected to a weighted price of international fuel oil and liquid petroleum gas (LPG) prices. A positive aspect of the oil-linked pricing regime is that it has a better predictability and transparency compared to the highly-regulated pricing system where prices were established more arbitrary and without indication how they would be changing.

2.4.2 Other Natural Gas Promotion Policy

In addition to the pricing reform, the Chinese government implements a set of natural gas promotion policies. The primary objective of China's natural gas promotion policy is to facilitate the substitution of natural gas for coal to address the air pollutions and improve the household quality of life in Chinese cities. Approximately 66% of China's energy consumption currently comes from by coal (NBS, 2015). Burning coal emits air pollutants such as SO_2, NOx, black carbon and fine particles such as PM2.5 and others. China's air pollution is largely attributed to the massive use of coal and a lack of clean coal technologies. Natural gas is regarded as a cleaner than coal fossil fuel because it emits less air pollution than coal during the combustion process. In this regard the Chinese central government and local governments often attach a great importance to an increase in a share of natural gas in the energy supply mix.

China’s natural gas promotion policies range from national and urban targets for natural gas use, regulations on natural gas utilizations, and natural gas pricing to subsidies, tax relief and feed-in tariff for nature gas fired electricity generations. **Table 2.1** gives an overview of China’s natural gas policy development. China’s *National Energy Development Strategy Action Plan* (2014-2020) sets the target for natural gas development and utilization by 2020 (State Council, 2014). The *Action Plan* emphasizes on the role of natural gas in China’s sustainable energy system transformation. According to the target for China’s energy system transformation, the share of natural gas in China’s primary energy supply should exceed 10% by 2020. Chinese government has also set clear guidelines for restrictions in natural gas use. According to the *Revised Natural Gas Utilization Policy* (NDRC, 2012b), it is encouraged that natural gas is used as fuel in residential, manufacturing, electricity and transportation sector, but natural gas is discouraged as a feedstock in producing chemicals.

The market-based energy policy instruments create dynamic incentives for energy producers or consumers as they provide the best value for the resource. In China, one policy instrument for promoting natural gas use is the import value-added tax refund to encourage natural gas imports (MOF, 2011). Others include the feed-in tariffs for gas-fired power plants to encourage substitution of natural gas for coal in electricity sector (NDRC, 2014b). Since 2007 coal-bed methane producers in China receive a subsidy of 0.2 yuan per cubic meter if the gas is delivered to residential and industrial users (MOF, 2007). These instruments promote natural gas use but they can create economic distortions. In my modeling exercise described later, a general subsidy is used as a proxy for these policy instruments.

2.4.3 Climate-Related Policy

The Chinese government submitted to the United Nations its climate action plan, namely “Intended Nationally Determined Contribution” (INDC) on June 30, 2015 (NDRC, 2015a). The INDC is regarded as an international commitment to address climate change for the post-2020 period. China’s INDC gives the most updated information on China’s enhanced actions to address climate change which include China’s major climate policy.

According to China's INDC, China is pledged to peak its CO_2 emission around 2030 and decrease carbon intensity (CO_2 emissions per unit of GDP) by 60-65% below 2005 levels by the same year. The new carbon intensity target builds on China's existing target – the commitment which was made at the Copenhagen climate talks in 2009 — to reduce its CO_2 intensity by 40-45% in 2020, relative to 2005 levels (NRDC, 2015). As a major policy instrument to honor the pledges listed in its INDC, China has recently decided to establish a nationwide carbon dioxide emissions cap-and-trade system or emission trading scheme (ETS). Chinese President Xi Jinping officially announced (The White House, 2015) that a nationwide ETS will be launched in 2017.

Table 2.1 Key gas-related policies

Date	Policy	Object	Remarks
Dec 2005	Ex-plant gas price reform[1]	Gas pricing	First effort to liberalize gas market by increasing ex-plant gas price
Apr 2007	Subsidization for Coal-bed Methane Production and Utilization[2]	Gas produce	A 0.2 yuan/m^3 subsidy has been introduced for the CBM used in residential and industrial sector.
Sep 2007	Gas Utilization Policy[3]	Gas use	Outlines for where natural gas use are encouraged or restricted. Residential and public services sectors are more encouraged than power sector.
Nov 2007	Adjustment of ex-plant gas price[4]	Gas pricing	Ex-plant gas price for industrial gas users has been raised by 0.4 yuan/m^3.
May 2010	Adjustment of ex-plant gas price[5]	Gas pricing	An increase of 0.23 yuan/m^3 in ex-plant gas price for all sectors. City gate gas price for NGVs will move in line with market prices of gasoline and diesel.
Aug 2011	Adjustment of the import value-added tax on Imported Natural Gas[6]	Import gas	Gas importers will receive a Value-added tax (VAT) refund.
Oct 2011	Guidance on Developing Natural Gas for Distributed Generation[7]	Gas use	Promoting gas use in Combined Cooling, Heat, and Power (CCHP) systems. Installed capacity of distributed natural gas projects will reach 50 GW by 2020.
Dec 2011	Trial of Gas Price Reform in Guangdong and Guangxi[8]	Gas pricing	A combined ceiling city gate price linking to imported LPG/FO for pipeline gas.
Dec 2011	12th Five-Year plan for CBM Development[9]	Gas produce	CBM will reach 30 bcm by 2015.
Mar 2012	12th Five-Year plan for Shale Gas Development[10]	Gas produce	Annual production of shale gas will reach 60-100 bcm in 2020.
Jul 2012	12th Five-Year plan for city gas Development[11]	Gas use	Natural gas will account for 67.3% of total city gas supply by 2015

Oct 2012	12th Five-Year Plan for Natural Gas[12]	All	In 2015, domestic gas production will reach 176 bcm. Total gas demand will increase to 230 bcm. 18% of total population will have access to gas.
Oct 2012	Revised Gas Utilization Policy[13]	Gas use	Gas use as fuel in power sector (peaking shaving) and industrial sector (interruptible contracts) are more encouraged.
Jul 2013	Nationwide Gas Grice Reform[14]	Gas pricing	Introducing nationwide two-tier pricing system. City gate price for incremental volume has been oil-indexed and linked to imported fuel oil and LPG prices..
Sep 2013	Air Pollution Prevention and Control Action Plan[15]	Environment/ Gas use	Setting targets for air pollutants reduction by 2017, focusing on Bohai Bay, Yangtzi River Delta and Pearl River Delta. Promoting coal switching to gas in residential, industrial and power sectors in cities. Restricting gas use in chemical manufacturing as feedstock.
Sep 2013	Adjustment of Feed-in Tariff for Gas-fired Power Plants[16]	Gas use	Requiring Shanghai, Beijing, Tianjin, Jiangsu, Zhejiang, Guangdong, Hainan, Henan, Hubei, Ningxia to raise the level of on-gird tariff for gas-fired power plants
Nov 2013	Adjustment of Preferential Policies for Tax on Imported Natural Gas[17]	Import gas	More imported pipeline gas and LNG projects are receiving VAT refund.
Aug 2014	Nationwide Gas Price Reform[18]	Gas pricing	City gate price for existing volume has been raised by up to 0.4 yuan/m^3 across the country. A step for promoting the convergence of the existing gas price with the incremental gas price.
Feb 2015	Nationwide Gas Price Reform[19]	Gas pricing	The two-tier pricing is merged by cutting incremental gas price and raising existing gas price. The city gate price in China has been connected to international fuel oil and liquid petroleum gas prices.

Source:
[1]NDRC, 2005; [2]MOF, 2007; [3]NDRC, 2007a; [4]NDRC, 2007b; [5]NDRC, 2010; [6]MOF, 2011; [7]NDRC, 2011b; [8]NDRC, 2011a; [9]NEA, 2011; [10]NDRC, 2012c; [11]MOHURD, 2012; [12]NDRC, 2012a; [13]NDRC, 2012b; [14]NDRC, 2013a; [15]State Council, 2013; [16]NDRC, 2013b; [17]MOF, 2013; [18]NDRC, 2014a; [19]NDRC, 2015b

Chapter 3 Natural Gas Pricing in China

3.1 Evolution of China's Natural Gas Pricing Approach

Before the new pricing regime was introduced nationwide in July 2013, China's pricing approach was characterized as costs plus profit margin[2]. **Figure 3.1** presents the institutional framework of the old pricing regime. The key players in the old approach included National Development and Reform Commission (NDRC), the central government pricing authority, provincial/local government pricing agencies, gas producers/importers, transmission operators, and gas users.

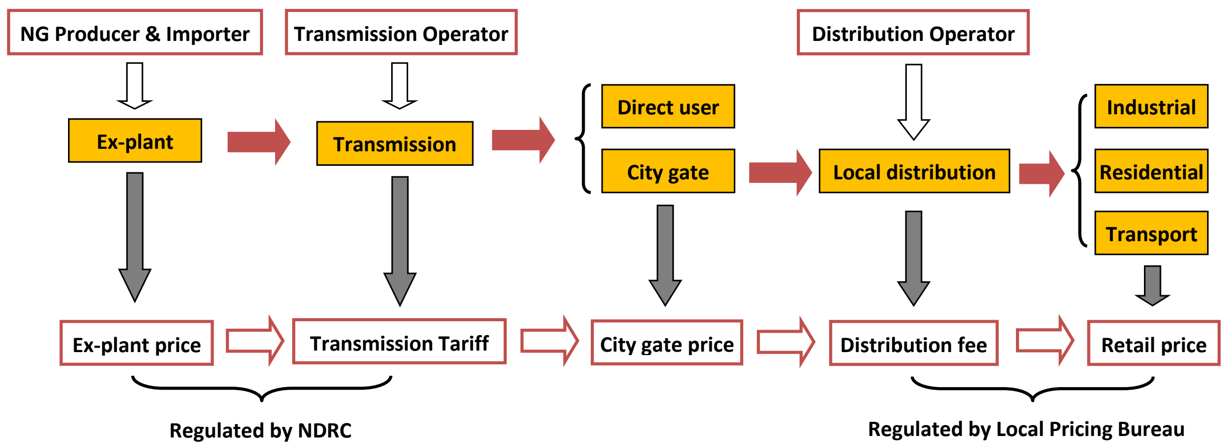


Figure 3.1. The institutional framework of the old natural gas pricing regime in China.
Source: Adopted from Zhao (2011).

The natural gas price formulation process involved ex-plant price, transmission tariff, city gate price, distribution fee, and end user price. These components are discussed below.

Ex-plant prices were determined by NDRC. The ex-plant prices were also differentiated by users. For example, the ex-plant prices were different for large users (some industrial users and fertilizer manufactures, denoted as "Direct user" in **Figure 3.1**), smaller industrial, transport and residential gas users (that face "Retail prices" in **Figure 3.1**). Ex-plant prices were formulated based on a costs-plus-appropriate margin pricing approach that includes wellhead cost, purification fee, and applicable taxes and margins. Producers and buyers were able negotiate up

[2] The material in Chapter 3 is based on my contribution to Paltsev and Zhang (2015a).

to 10% price increase or decrease based on the ex-plant prices set by the NDRC.

The transmission tariff was also determined by NDRC. It was based on the tariff proposals by gas transmission pipeline operators. The pipeline operators and gas producers are often the same companies in China. The transmission tariff is largely determined by a formula that includes coverage of construction cost, operation cost, taxes and margins, and additional terms based on a distance from the gas source to a user.

City gate prices are the wholesale prices that local gas distributors pay to the pipeline operators to purchase gas. Under the old pricing approach, the city gate prices are in principle the sum of the ex-plant price and transmission tariff. Since the ex-plant prices are differentiated by user, the city gate prices are also different for the four categories of users mentioned above.

The distribution fee is determined by the provincial/local pricing authority, which is often a department of the provincial development and reform commission, based on the fee proposals by local distribution operators. The distribution fee calculation is similar to the transmission tariff calculation as it includes coverage of construction and operation costs and appropriate margins and taxes.

End user prices are the retail prices that gas consumers pay to local distributors. The retail prices are proposed by the local distributors reflecting the level of the city gate price and the distribution fee and they are set by the local pricing agency after a check of the cost report prepared by the distributor. Since city gate price varies, retail prices for different gas users are also different.

The old pricing regime was established when natural gas was supplied domestically and as such it was based on the cost of domestic production. After 2010, with a substantial increase of natural gas imports by LNG and a pipeline from Turkmenistan, in many situations the city gate prices set by the old pricing approach were much lower than the contract prices for imported natural gas. Natural gas importers incurred significant losses, which discouraged natural gas imports. In addition, being tied to the cost of supply only, the old pricing approach did not reflect the fast growth in natural gas demand. As a result, many cities experienced severe shortages of natural gas (IEA, 2012a).

3.2 Highlights of the New Pricing Reform

Given the problems that had emerged in gas markets, China launched a national natural gas pricing reform program in the early 2010s. I provide a summary of the key points of the reform based on key policy documents (NDRC, 2010; NDRC, 2011a). The basic reform was to enable the market to play a more important role in a city gate price formulation, by linking gas price with prices of imported fuels. The reform was tested in two provinces, Guangdong and Guangxi, in 2011 before being implemented nationwide in 2013. Two new concepts have been introduced: an existing volume, defined as the amount of natural gas consumption in 2012, and an incremental volume that is the amount added in 2013, 2014, and 2015 beyond that in 2012. The new pricing approach was applicable only to the incremental volumes of the pipelined natural gas. Pricing of imported LNG and unconventional gas are based on negotiations between producers and users, while the prices for household use are unchanged from the levels determined by old pricing regime.

A three-step transition process was introduced: 1) in 2013 the nationwide city gate prices for the incremental volumes of natural gases were formulated by the new pricing approach; 2) in 2014 the cite gate prices for the existing volumes were increased and the city gate prices for the incremental volumes were adjusted by the new pricing approach; 3) in 2015 the city gate prices for the existing volumes were increased to the level of the incremental volumes and the city gate prices for the incremental volumes were adjusted again by the new pricing approach. As a result, a new single natural gas price for the existing and incremental volumes was formulated.

Energy pricing reform is politically sensitive and it involves several conflicts of interests. As China's natural gas was underpriced for a long time because of government control, natural gas prices were expected to increase as a result of the reform. To minimize the political risks associated with the rise in natural gas prices, the Chinese government decided to include the division of the natural gas consumption into the existing volume and incremental volume and adopt a differentiated pricing approach.

The primary rationale for the new pricing is that the value of natural gas can be largely represented by the value of its two substitutes in terms of providing energy services – fuel oil used in the industrial sector and liquefied petroleum gas (LPG) used in the residential sector. Based on this rationale, a new natural gas price basis was created. New formula represents a weighted composite of the imported fuel oil price and the imported LPG price. The new natural gas price basis is termed as $P_{CGPIN@SH}$ (City Gate Price for Incremental Volume in Shanghai). The ex-plant prices and retail prices are based on this price. The formula for calculation is set by NDRC as follows (NDRC2011a; NDRC 2013).

$$P_{CGPIN@SH} = K \times [w_{FO} \times P_{FO} \times \frac{H_{NG}}{H_{FO}} + w_{LPG} \times P_{LPG} \times \frac{H_{NG}}{H_{LPG}}] \times (1 + R) \qquad (1)$$

The terms in the formula are: $P_{CGPIN@SH}$ is the city gate price for the incremental volume in Shanghai; *K* is a constant discount rate to promote gas use and it is currently set at 85% by the NDRC; w_{FO} and w_{LPG} are the weights for fuel oil and LPG respectively, representing their relative contribution to China's energy supply; P_{FO} and P_{LPG} are the average imported fuel oil and LPG prices; H_{NG}, H_{FO}, and H_{LPG} are the heating value of natural gas, fuel oil and LPG respectively; and *R* is the value added tax (VAT) rate for natural gas.

Under the new pricing regime, Shanghai is chosen as a starting point for the calculation of natural gas prices because Shanghai is not only a large natural gas consumer but also an important energy trade center in China. Shanghai's city gate price is set by $P_{CGPIN@SH}$. **Figure 3.2** depicts how other natural prices are determined by the institutional framework of the new pricing paradigm. The major difference between the new pricing approach and the old one lies in a formulation of the ex-plant prices. While under the old approach the ex-plant price of natural gas was largely based on the production cost, now it is a result of the $P_{CGPIN@SH}$ (or Shanghai's city gate price) minus the transmission tariff for a distance from Shanghai to where the natural gas is produced. The calculation of the transmission tariffs and the retail prices under the new regime, however, is almost the same as under the old approach.

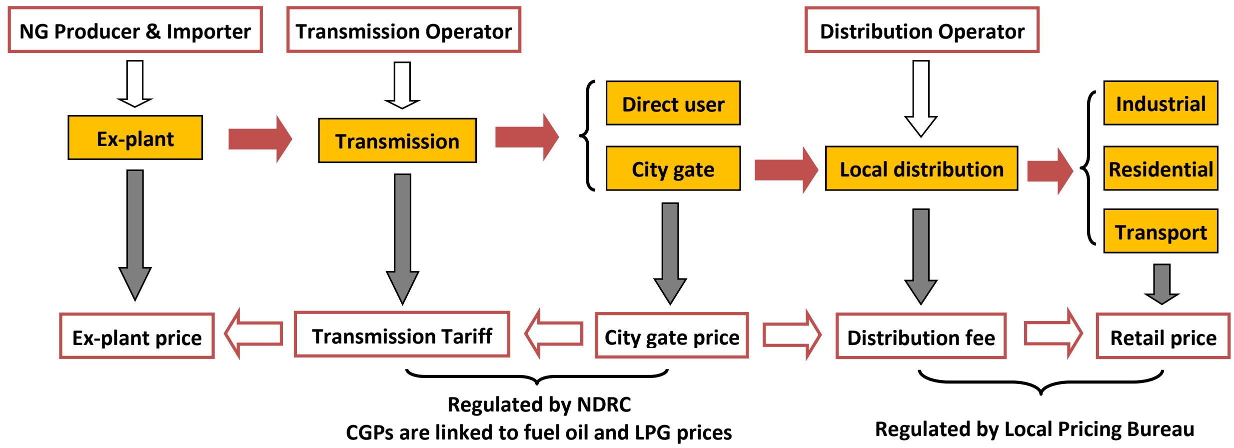


Figure 3.2 The institutional framework of the new natural gas pricing regime in China. Source: Adopted from Zhao (2011) and modified based on NDRC (2013).

3.3 Natural Gas Price Adjustment Exercises

The pricing reform program has been implemented largely through the three NDRC directives on city gate price adjustments released in 2013, 2014, and 2015, respectively. The directives specified the starting dates when new pricing is planned to be implemented, but they did not specify for how long these prices will stay in place and when they will be revised next time. **Figure 3.3** presents the changes in city gate price by region set by NDRC under the three directives for three periods of time. The first period was governed by the first NDRC directive on city gate price adjustment (NDRC, 2013a) and lasted for 417 days from July 10, 2013 to August 31, 2014. As can be seen in **Figure 3.3**, the incremental volume price was significantly higher than the existing volume price (which represented natural price levels before the reform). The pricing reform created incentives for natural gas companies to increase natural gas supply because they were able to sell additional gas at higher prices.

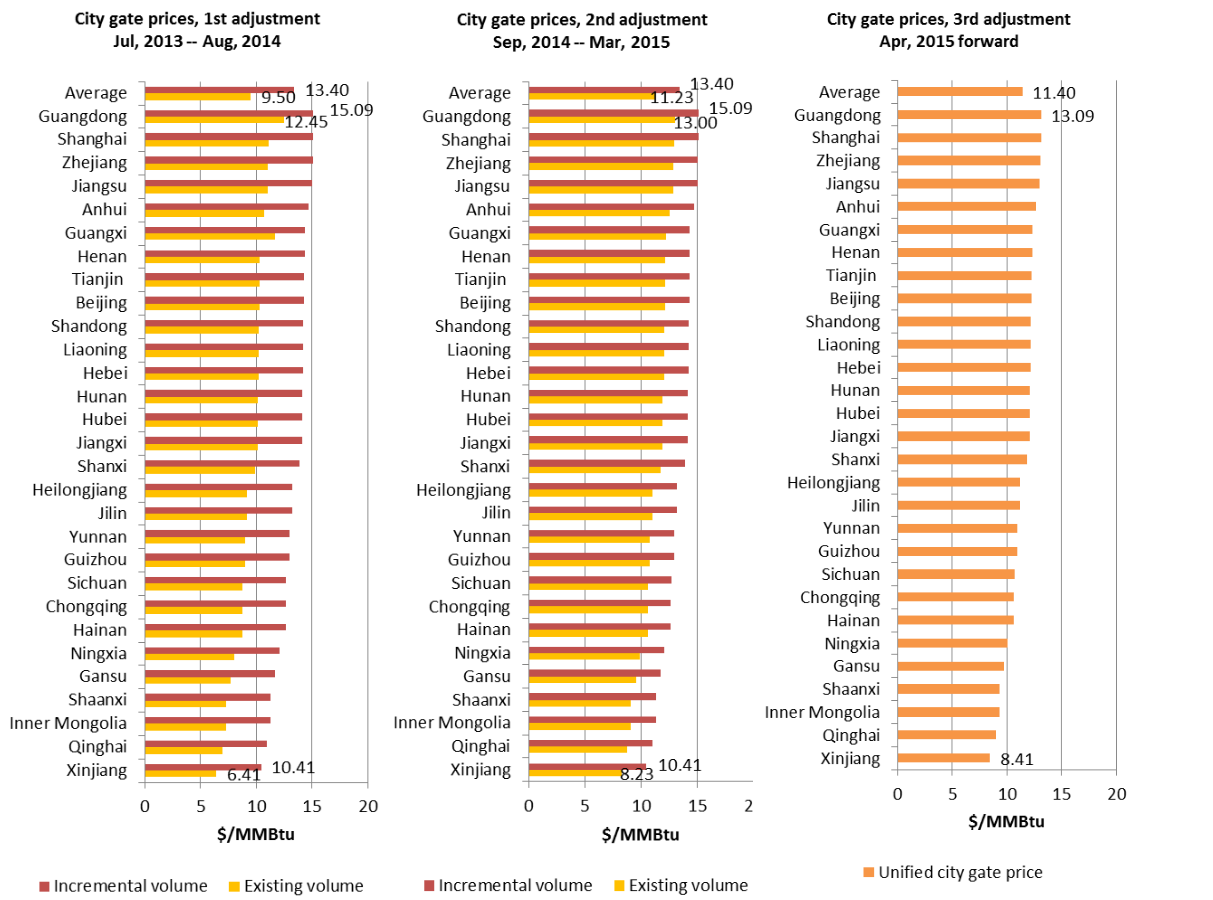


Figure 3.3 City gate prices by region in China, 2013-2015. Data Source: city gate prices after first adjustment (NDRC, 2013a); city gate prices after second adjustment (NDRC, 2014a); city gate price after third adjustment (NDRC, 2015b). Prices reported by NDRC are converted into $/MMbtu using the following conversion factors: 1000 m^3 of natural gas = 35.7 MMBtu (BP, 2014), 1$ = 6.16 yuan (average exchange rate for 2014 from USForex, 2015).

NDRC issued its second directive on price adjustment on August 10, 2014 as a second step of natural gas pricing reform (NDRC, 2014a). According to the second directive, the existing volume price was increased by 0.55 $/MMBtu (0.12 yuan/m3) in Guangdong and Guangxi, and was increased by 1.82 $/MMBtu (0.40 yuan/m3) in the other provinces. The incremental volume price was left unchanged. As demonstrated in the middle panel of **Figure 3.3**, the price gap between the existing volume and the incremental volume has been significantly narrowed. This pricing period started from September 1, 2014, and will last until March 31, 2015. This pricing period has 212 days, which is shorter than the first pricing period. The end of the second pricing period was determined by NDRC's third directive on natural gas price adjustment released in February 28, 2015 (NDRC, 2015b).

In the third directive, NDRC increased the city gate gas price for the existing volume once more but decreased the city gate price for the incremental volume to a large extent (as shown in the right panel of **Figure 3.3**). Since the international price of fuel oil and LPG was lower, the price for the incremental volume fell. With the third price adjustment, the prices for the existing volume of natural gas and for the incremental volume of natural gas reached the same level, indicating the end of the two-tier pricing. The new pricing approach is applied to the pipelined natural gas pricing after April 1, 2015.

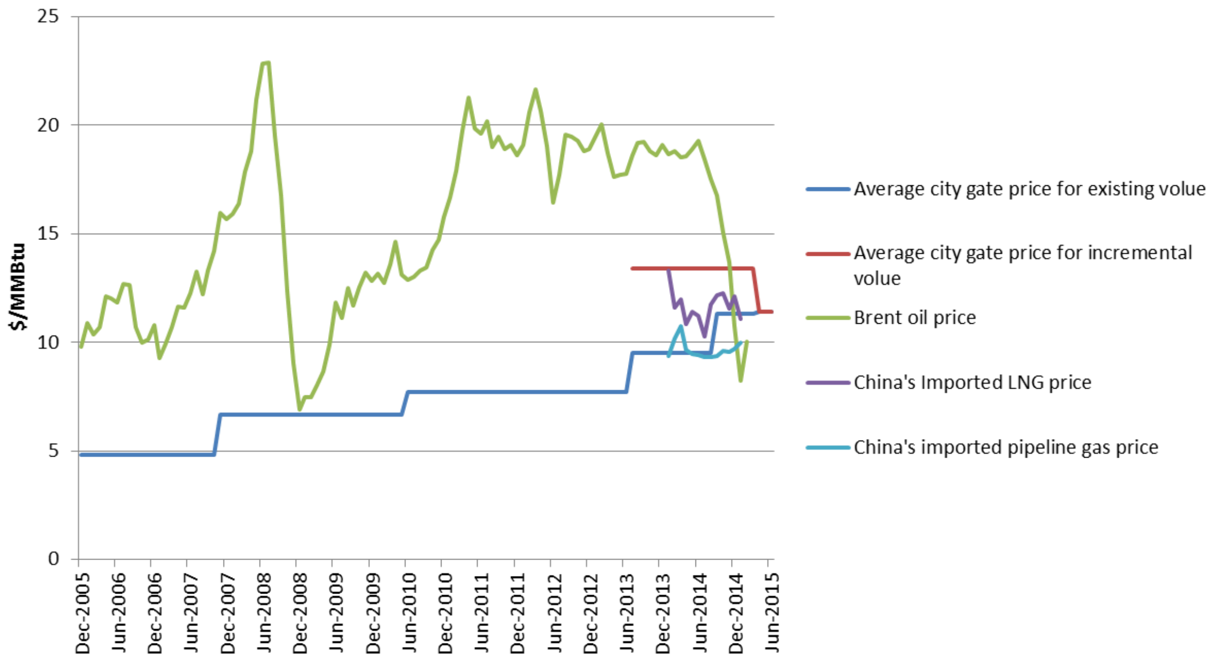


Figure 3.4 Chinese city gate prices for natural gas, weighted average import prices and Brent oil price. Data source: NDRC (2013), NDRC (2014a), NDRC (2015b), EIA (2015).

A decrease in the city gate price for the incremental volume is affected by a significant drop in the oil price in the international market since October 2014 as shown in **Figure 3.4**. Since the new natural gas pricing approach is based on a weighted composite of the imported fuel oil price and the imported LPG price, natural gas prices in the third period of the reform reflect such price changes in the international oil market. There is no information how long the third period will last and when new price recalculation will occur.

As can be seen in **Figure 3.3**, the city gate price for the incremental volume is higher than for the existing volume in all provinces, indicating that the introduction of the new pricing approach increased the gas price level for the whole nation. The approaches for local distribution fee charging and retail pricing under the new pricing paradigm are essentially the same as under the old one. In practice, the local pricing authorities take into account a difference in city gas price between the existing volume and the incremental volume when determining the level of retail prices for end users, but often do not provide the existing volume-specific or incremental volume – specific retail prices. Instead, the local authorities provide only one price for each category of gas end users. Such price combines the service prices from the existing volume and incremental volume. **Figure 3.5** lists the end use prices by province in July 2014.

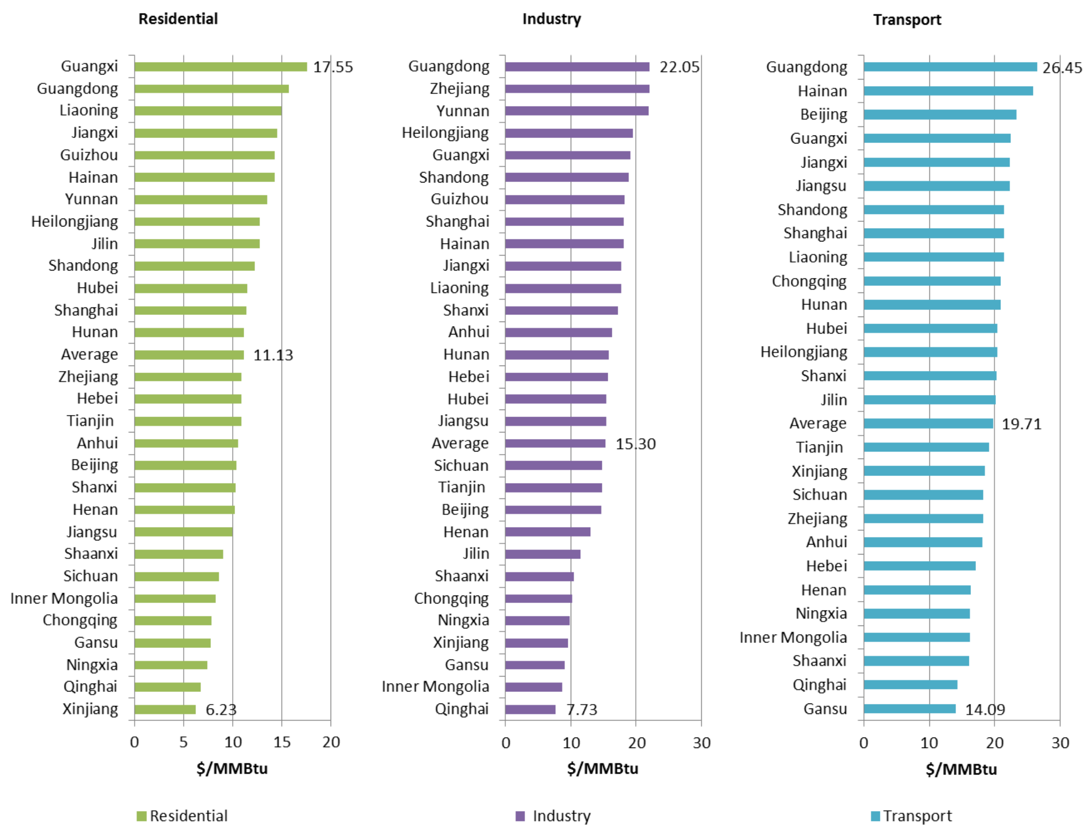


Figure 3.5. End user prices by region in July, 2014. Data Source: CNPC (2014). Prices reported by NDRC are converted into $/MMbtu using the following conversion factors: 1000 m^3 of natural gas = 35.7 MMBtu (BP, 2014), 1$ = 6.16 yuan (average exchange rate for 2014 from USForex, 2015).

As can be seen, the retail prices vary by province. The average price level for residential use was 11.13 $/MMBtu, which is slightly higher than the average city gate price for existing volume gas supply (which was 9.50 $/MMBtu during that period), but much lower than the average city gate price for incremental volume gas supply (which was 13.40 $/MMBtu). The retail price for industry sector averaged at 15.30 $/MMBtu, ranging from 7.73 $/MMBtu to 22.05 $/MMBtu by province. The price level for industrial use is higher than for residential use in all provinces. The retail price for transportation sector is among the highest in all provinces. The average price level for transportation use was 19.71 $/MMBtu.

Residential prices for natural gas are lower than industrial in China, which is the opposite of the price levels in developed countries. For example, in USA in 2013 with Henry Hub price of 3.66 $/MMBtu, delivery prices to electric power users were 4.39 $/MMBtu, industrial users – 4.66 $/MMBtu, commercial users – 8.44 $/MMBtu, residential users – 10.54 $/MMBtu, and transportation - $15.68 $/MMBtu (EIA, 2014). In Italy in 2011 residential prices were 19.45 $/MMBtu, while prices for industry were 12.05 $/MMBtu (Honore, 2013). A relationship between residential and industrial prices in China is driven by the desire to subsidize residential use of natural gas.

3.4 Price Predictability Simulation of the New Pricing

Transparency in price formulation is critically important for market players and analysts. Prices provided in **Figures 3.3** and **3.5** are based on the NDRC documents that give the resulting prices but they do not provide the detailed information on how they are calculated. To replicate the results, formula (1) is used with the publicly available data for inputs. In order to simulate the resulting prices, a procedure depicted in **Figure 3.2** is followed. At first, the $P_{CGPIN@SH}$ is calculated. Then the ex-plant prices are determined for the major natural gas production areas and also establish the city gate gas prices by region.

Table 3.1 Data used for city gate price calculation

Parameter	Value	Source
$\boldsymbol{K}$	85%	NDRC 2013
$\boldsymbol{\alpha}$	60%	NDRC 2011
$\boldsymbol{\beta}$	40%	NDRC 2011
$\boldsymbol{H_{NG}}$	8000kcal/m3	NDRC 2011
$\boldsymbol{H_{FO}}$	12000kcal/kg	NDRC 2011
$\boldsymbol{H_{LPG}}$	10000kcal/kg	NDRC 2011
$\boldsymbol{R}$	15%	NDRC 2011

Data source: NDRC (2011a), NDRC (2013).

Table 3.1 present the input data provided in NDRC documents. It should be noted that NDRC does not provide all the details of their price calculations. Therefore, several assumptions have to be made. First, NDRC states that formula (1) is calculated based on the price of imported fuel oil and imported LPG. However, there is no information on which prices were actually used in their calculation, what are the corresponding data sources, and prices for what period were chosen. In my calculation I use the data from the reputable source for public data on import and export information – China Export and Import Statistics released by General Administration of Customs of China (GACC). I focus on the third adjustment period, so the average prices for imported fuel oil and LPG during a period from July 2014 to December 2014 are used. **Table 3.2** shows the assumptions for the imported fuel oil and LPG prices.

Table 3.2 Average price of imported fuel oil price and LPG, July 2014-December 2014

	Imported Volume (million kg)	Value (million yuan)	Average price (yuan/kg)
Fuel Oil	8,040	28,650	3.56
LPG	12,419	57,258	4.61

Data source: GACC (2014a), GACC (2014b).

NDRC also did not release the transmission tariffs that they used for the price adjustment. For this information, I rely on my individual communications with Chinese natural gas experts. **Table 3.3** presents the transmission tariffs of the natural gas transmission pipelines. They are based on a distance from Xinjiang. For example, a tariff from Xinjiang to Gansu is 0.3 yuan/m3 (or 1.35 $/MMBtu), while a tariff from Xinjiang to Shanghai is 1.1 yuan/m3 (or 5.00 $/MMBtu). **Figure 3.6** provides information on geographic locations along the West-East pipeline.

Using the information provided above I re-calculated city gate and ex-plant prices, which are provided in **Table 3.4**. Ex-plant prices are estimated to be 1.775 yuan/m3 (which is an equivalent of 7.93 $/MMBtu). NDRC does not provide ex-plant prices in their documents on pricing. Comparing the simulated city gate prices and those provided by NDRC show that they are in a relatively close agreement for most of the locations. The differences are smaller than 4%, except for Shaanxi, where the difference is about 6.5%. Except for Shaanxi again, the simulated prices are slightly lower than the NDRC prices, which suggest that the assumptions about the input prices and/or transmission tariffs are slightly lower than those used by NDRC. As mentioned before, Shaanxi is a province with a domestic natural gas production and a large portion of its natural gas demand is provided by local production. Price difference there can be explained by negotiations of the local governments with NDRC. There are reports that the Shaanxi municipal government negotiated with the NDRC for a lower gas price.

Table 3.3 Transmission tariffs

From	To	Transmission tariff (yuan/m3)
Xinjiang	**Gansu**	0.3
	Ningxia	0.35
	Shaanxi	0.4
	Shanxi	0.75
	Henan	0.85
	Anhui	0.95
	Jiangsu	1.05
	Zhejiang	1.08
	Shanghai	1.1

Source: Author's estimates based on communication with industry experts

Figure 3.6 West-East natural gas pipeline in China. Source: PetroChina (2002).

In general, the simulations show that new pricing mechanism is more transparent than the old regime when price information was hard to obtain. Transparency and predictability can be further improved if the complete information about all inputs required for calculations are provided by NDRC. It will help market players to establish a confidence in the new pricing scheme.

Table 3.4 Comparing published regional city gate prices with results from our simulation (yuan/m^3)

	Our calculation			NDRC*	Difference
	Transmission Tariff	Ex-plant price	city gate price	City gate price	
Xinjiang	-	1.775	1.775	1.85	-0.075
Gansu	0.3	1.775	2.075	2.13	-0.055
Ningxia	0.35	1.775	2.125	2.21	-0.085
Shaanxi	0.4	1.775	2.175	2.04	0.135
Shanxi	0.75	1.775	2.525	2.61	-0.085
Henan	0.85	1.775	2.625	2.71	-0.085
Anhui	0.95	1.775	2.725	2.79	-0.065
Jiangsu	1.05	1.775	2.825	2.86	-0.035
Zhejiang	1.08	1.775	2.855	2.87	-0.015
Shanghai	1.1	1.775	2.875	2.88	-0.005

*Source: NDRC (2015b)

3.5 Results and Discussion

3.5.1 Impacts on Gas Producers and Importers

Gas producers and importers appear to benefit the most from the price reform because it causes an increase in the city gate prices and ex-plant prices. **Figure 3.7** shows the natural gas market share (in terms of domestic production) among the three state-owned oil and gas giants - PetroChina[3], Sinopec and CNOOC. These three companies together own and operate over 90% of China's gas infrastructure covering gas production, import, transmission, and storage business. PetroChina is the largest gas supplier and pipeline operator in China and provided 67.3% of China's domestic gas supply in 2013.

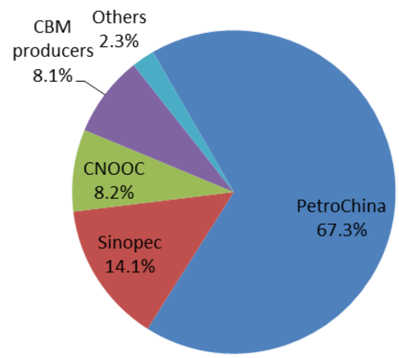


Figure 3.7 Major gas suppliers in China in 2013. Data Source: Xinhua News(2014).

[3] PertoChina is controlled and sponsored by China National Petroleum Corporation (CNPC).

Below I focus on PetroChina to see the impacts of the natural gas pricing reform. **Figure 3.8** compares the margins of PetroChina's gas and pipeline business under the old and new pricing paradigm. Under the old pricing regime, the ex-plant pricing approach applied for both domestic and imported pipeline gas. According to their 2013 annual report (PetroChina, 2014), in 2012 PetroChina earned about 40 billion yuan on the sales of natural gas and pipeline operations. At the same time, they paid about 42 billion yuan for the imported gas from Central Asia. As a result, the company lost 2 billion yuan in 2012. In 2013, PetroChina paid a similar amount for imported gas, but after the introduction of the new pricing system in 2013 PetroChina earned about 71 billion yuan from the sales of natural gas and pipeline operations. As a result, PetroChina earned 31 billion yuan (or about 5 billion dollars) more in 2013 when natural gas pricing was reformed.

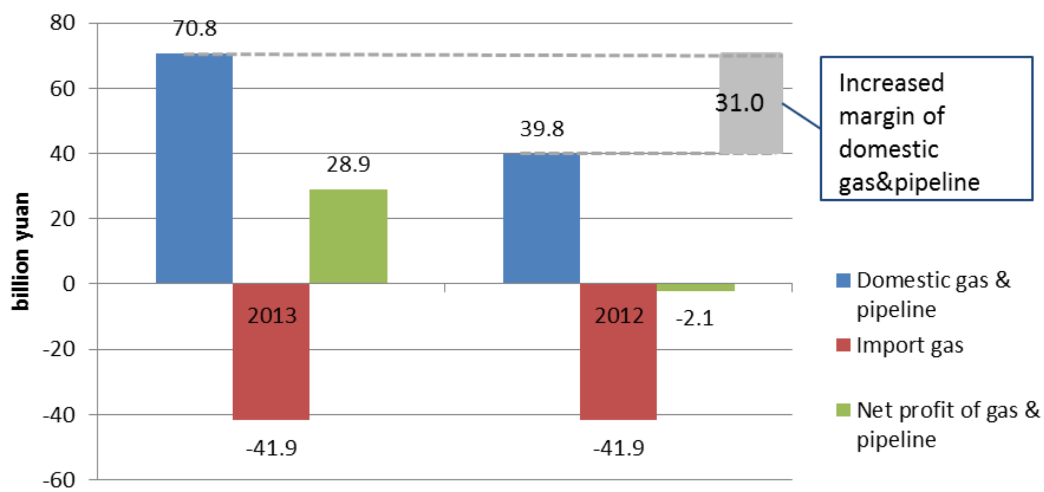


Figure 3.8 Margins of PetroChina's gas and pipeline business in 2012 and 2013.
Data source: PetroChina (2014).

The details of the difference in performance in 2012 and 2013 can be illustrated by price information provided in **Figure 3.9**. In 2012 and 2013, VAT-included border prices of pipeline imports were similar, 11.10 $/MMBtu and 11.00 $/MMBtu, respectively. However, the ex-plant prices at Xinjiang were quite different. In 2012, they were 5.50 $/MMBtu, while in 2013 they were increased by 1.82 $ /MMBtu for existing volume and by 4.64 $/MMBtu for incremental volume. The new pricing system increased the ex-plant prices and allowed PetroChina to make a profit of 28.9 billion yuan in 2013.

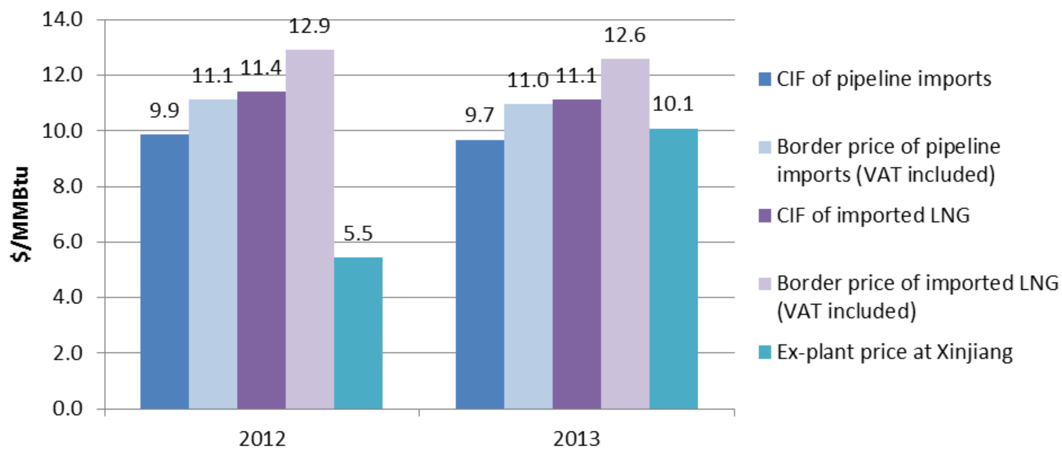


Figure 3.9 Border price vs ex-plant price 2012 &2013.

Data Source: import LNG & pipeline gas prices (CNPC, 2014), ex-plant prices at Xinjiang (authors' estimates based on NDRC, 2010; NDRC, 2013a). Prices are converted into $/MMbtu using the following conversion factors: 1000 m^3 of natural gas = 35.7 MMBtu (BP, 2014), 1$ = 6.16 yuan (average exchange rate for 2014 from USForex, 2015).

3.5.2 Impacts on Distribution Companies

Since the end user gas prices are regulated by the local governments, the interests of natural gas distributors may be undermined if the local distribution companies fail to pass the increase in the city gate price to the end users. This issue is illustrated in **Figure 3.10**, which compares the margins of a gas distributor in Harbin City in 2012 and 2013. The distributor sells natural gas to industrial users under the old and new pricing paradigm. Panel (a) of **Figure 3.10** shows the price components under the old pricing. Panel (b) provides information for pricing with new regime for the existing volume. Panel (c) represents pricing information for the new regime for the incremental volume. The data on all three panels in **Figure 3.10** have the same ex-plant price of 7.32 $/MMBtu (or 1.61 yuan/m3). The old and new pricing regimes added different amount to that price to determine the city gate prices.

Under the old pricing, the city gate price was 8.68 $/MMBtu. Natural gas reform raised the city gate prices to 9.18 $/MMBtu for the existing volume and to 13.18 $/MMBtu for the incremental volume. Under old pricing, gas distributors made a gain of 1.60 $/MMBtu on a difference between their cost of supply and end user price. After the reform, with the same distribution costs and slightly different taxes, gas distributors now make a profit of 3.11 $/MMBtu (0.69 yuan/m3) on the existing volume natural gas being sold to the industrial users, but lose 0.88 $/MMBtu (0.19

yuan/m3) on the incremental volume natural gas to the same users. The city gate prices are regulated by NDRC, while the end user prices are regulated by the local governments. Depending on their objectives, they may keep the end user prices low, which may result in a loss of money for a distribution company, as it happened in Harbin.

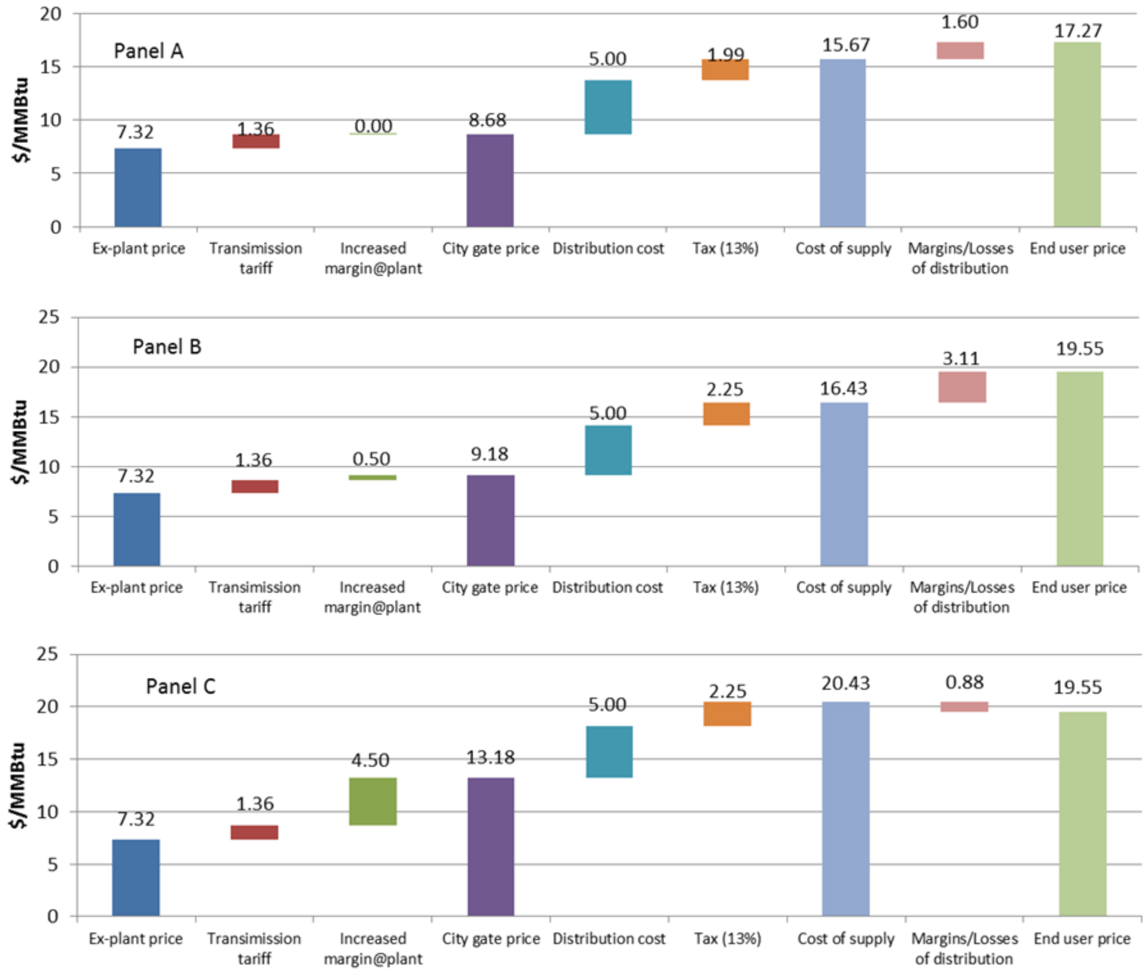


Figure 3.10 Margins of natural gas distributors in Harbin for non-residential use: (a) with old pricing; (b) with new pricing for existing volume; (c) with new pricing for incremental volume. Data source: Ex-plant prices (NDRC, 2010), City gate prices (NDRC, 2013a), Distribution costs (Xinhua News, 2012), End user prices (Harbin Pricing Bureau, 2013), Transmission tariffs (authors' estimates based on personal

3.5.3 Impacts on End Users

As discussed before, the major end use sectors are industry, residential and power & heating. In the residential sector, gas tariffs should increase because of the rise in the city gate prices. However, China's retail prices for natural gas are regulated by the local governments. Social stability considerations might give some reluctance for an increase of residential prices. For example, the residential prices were unchanged for years in Shanghai and Beijing, including the period of the pricing reform. **Figure 3.11** compares the retail price for the residential sector, the city gate price for existing volume gas supply, and the city gate price for incremental volume gas supply for the first adjustment period of July 10, 2013 to August 31, 2014 (CNPC, 2014; NDRC, 2013a). The retail price for the residential sector is lower than the city gate price for the incremental volumes in most provinces, and for some provinces (e.g., Xinjiang, Ningxia, Sichuan, Jiangsu) even lower than the city gate price for the existing volumes. It means that the natural gas use in the residential sector is subsidized either by the government or by other end users. The natural gas pricing reform at this stage has not substantially affected the residential sector as consumers are protected by the subsidy scheme. For the long term, however, it would be difficult to maintain the current residential gas price level unchanged forever if the cite gate prices keep changing in future.

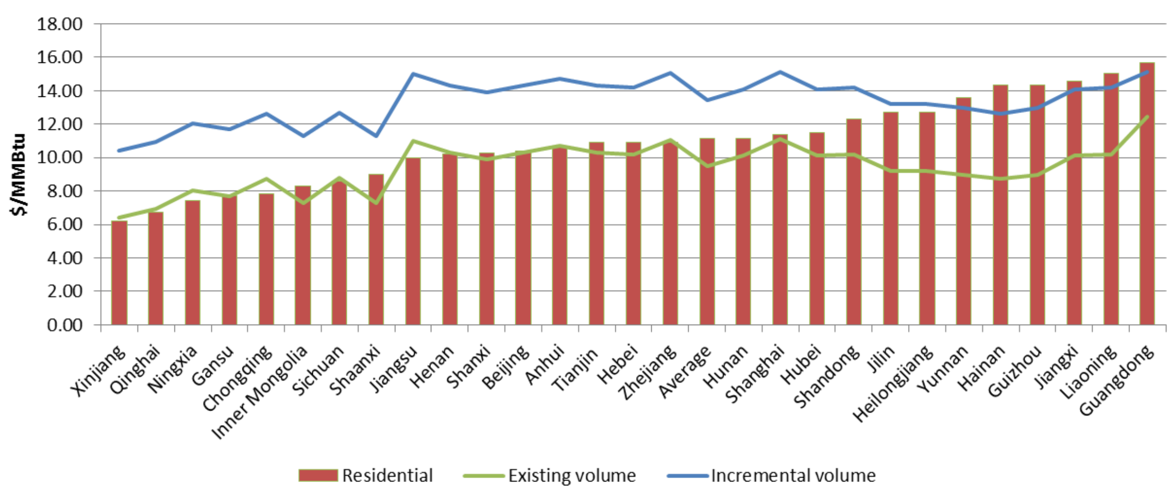


Figure 3.11 Natural gas prices for residential sector for the first adjustment period. Data Source: CNPC (2014), NDRC (2013).

The industry prices are higher than residential in all provinces. **Figure 3.12** provides a comparison between the prices for different users for Beijing, Shanghai, and Zhejiang for the first adjustment period. While the residential prices in these provinces were 10.40, 11.40, and 10.90 $/MMBtu, respectively, the industrial prices were 14.70, 18.10, and 22.00 $/MMBtu. The prices in the industrial sector have not been protected by the government. It appears that industry is the sector which is impacted the most by natural gas price increase. Even more, the sector often has to pay for a part of the natural gas use in the residential sector through a cross-subsidy scheme arranged by the local governments.

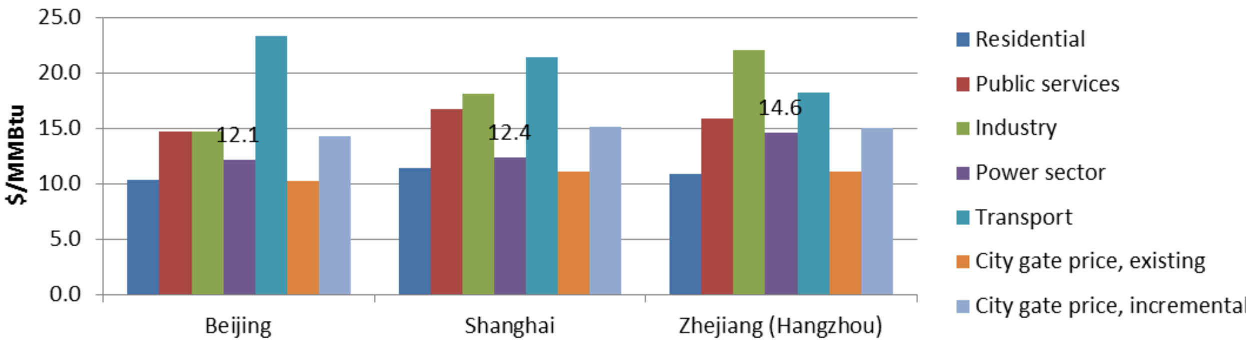


Figure 3.12. End user gas prices in Beijing, Shanghai and Zhejiang in the first adjustment period. Data Source: CNPC (2014), NDRC (2013).

The third largest natural gas user, the power & heating sector, is especially sensitive to the changes in natural gas prices. The price of gas as an input and the price of heat as an output are mostly regulated by local governments, while the price of electricity as an output is regulated by the Central government. The price level of the gas use in the power and heating sector varies by province. It is higher than the gas price for the residential sector in all provinces. In **Figure 3.12** power sector prices in three provinces are also provided. The local governments often provide subsidy for the space-heating in households as well as for power generation that contributes to a local air pollution control. In this context, the profitability of the power and heating sector depends heavily on a subsidy from the local governments. Based on natural gas prices for power sector (shown in **Figure 3.12** as 12.10 $/MMBtu for Beijing) and electricity price (that is also regulated by the Central government), it is estimated that in Beijing the gas fired combined heat and power plant (CHP) takes a loss of 0.11 yuan for one kilowatt hour (kWh) of energy supply due to the rise in price of gas associated with the new pricing approach[4].

[4] The estimate is obtained with the following assumptions: Fuel cost accounts for 70% of the production cost for a typical gas fired CHP in China (Ji and Cheng, 2013), 1 cubic meter of natural gas generates 5kWh electricity. Electricity price for gas-fired CHP in Beijing is 0.65 yuan/kWh (BMCDR, 2014).

3.5.4 Limitations of the Current Pricing Reform

China's natural gas pricing program has been successful in terms of addressing the major deficiencies of the old pricing regime and has made substantial progress toward establishing a market-based natural gas pricing system. It encouraged producers and importers to provide additional natural gas supplies. At the same time, the reform has its limitations. The program has introduced a new pricing approach but a complete market pricing mechanism was not created. The old pricing scheme largely ignored that both supply and demand have their impact on the price formulation. The new pricing approach created a link with international prices of imported fuel oil and LPG, two main substituting products of natural gas, and it reflects the market pricing principles to a larger extent. However, it is still not a true market system, where prices are constantly determined based on the interaction of supply and demand.

Currently, the prices in the new mechanism are established for a period with a starting date, but with no clear indication for the duration of the period when these prices will be in effect. There is also no clear information on the rules and conditions under which the ex-plant price and the city gate price will be changing as a response to the changes in the traded prices of imported fuel oil and LPG. Government authorities provide the city gate prices, but they do not list the data sources used for the prices of imported fuel oil, LPG, and transmission tariff as well.

Understanding the exact rules of the price formulation and the duration of the periods for which a new price is set would help natural gas produces and users to make their sound economic decisions that increase the economic welfare of China. Currently, the reform is mostly focused on producers and importers, while the end user prices are still mostly controlled by local authorities. The true market reform allows flexibility in price formulation at all levels. The industry sector and the power and heating sector are the two largest drivers of China's natural gas consumption growth, but they appear to be the biggest losers of the new reform initiative. A similar situation is for transport sector. As the pricing reform largely ignores the demand-side dynamics, it may be problematic to expand natural gas use in industry and transportation to achieve the government objective of increasing the contribution of natural gas in China's energy mix.

The new initiative also fails in correcting price distortions and squeezing out cross-subsidies.

Natural gas prices in industry and power sectors are higher than in the residential sector, while supply costs in the residential sector are often the highest compared to other sectors. In the liberalized markets of developed countries the gas prices for residential end users are usually among the highest. The new reform initiative has ignored such distortions between the costs and the resulting prices. The new initiative also pays little attention to encouraging competition, which would lower the price levels. In China the three state-owned oil and gas companies dominate natural gas supply. In order to create an efficient natural gas market in China it is important that private companies have the same rights as state-owned companies in terms of the access to natural gas pipelines, LNG facilities, and gas storage facilities.

3.5.5 Discussion of the Future Reform Directions

Though the natural gas pricing reform has made a substantial progress, China needs to take further efforts to achieve its objectives. China's natural gas pricing is still not only heavily regulated but also lacks transparency. To improve the situation, NDRC needs to enhance the new pricing approach by setting the clear rules and conditions under which the city gate prices could be adjusted automatically in response to the changes in international oil market price. It will allow creating the solid fundamentals for a movement to a complete market-based natural gas pricing system in China. It is also important to start deregulating the distribution market to correct the price distortions in the retail markets. NDRC and the local governments should work together to address the regional institutional barriers to the integration of the wholesale markets with the retail markets.

Competition often leads to a more efficient allocation of resources and ultimately to lower prices. PetroChina, Sinopec, and CNOOC contribute to about 90% of China's natural gas supply. They also own major pipeline infrastructure. To provide a better efficiency, the government should formulate regulations that will secure equal access to capital, pipeline and distributional infrastructure to private companies. An experience with shale gas in the United States shows an importance of these small and independent companies in the fast development of new production.

Establishing a complete market-based natural gas pricing system is important, but, most likely, it would not be enough to substantially increase the contribution of natural gas in China's energy mix. Natural gas is more expensive than coal when prices do not reflect additional costs related to health and environmental effects of the energy use. The government needs to correct this externality, as natural gas produces less pollution than coal, both at the local, regional, and global levels. Natural gas has a relative environmental benefit compared to coal (Zhang et al., 2014), but the current energy pricing is unable to reflect it. A recent study shows that a substantial substitution of natural gas for coal could take place when coal resource tax and/or carbon tax is introduced (Zhang et al., 2015). Coal use reduction is needed to reach China's goals to peak its carbon emissions by 2030 (China Daily, 2014). Substituting to natural gas offers such an option and introduction of incentives (e.g., carbon tax or cap-and-trade system) is an efficient mechanism to mitigate emissions (Paltsev et al., 2015).

3.6 Policy Implications

China's top leadership made decisions to deepen its reform at the Party's Third Plenary in 2014, emphasizing the decisive role of the market in resources allocation (Xinhua News, 2015a). A market-oriented natural gas pricing reform is in line with China's national reform policy. NDRC's natural gas pricing reform aims at establishing a market-based natural gas pricing system, ultimately increasing the contribution of natural gas in China's energy supply mix. Such increase will most likely rely both on domestic production and imports. A successful price reform will also help in finding the right balance of import infrastructure development (both pipeline and LNG) and domestic production.

Experiences of the U.S., where natural gas prices are determined by interaction of supply and demand, and the E.U., where the regions are segmented and some prices are still linked to oil, offer an illustration of the relative efficiencies of the gas pricing mechanisms and benefits of moving to a more complete market system. A complete natural gas pricing reform in China would allow natural gas producers and importers to provide adequate amounts of natural gas and eliminate shortages. Competition will push producers to be more efficient thereby providing a greater value for the scarce resource. At the same time, careful market design and pacing of the reform is needed to minimize the potential negative effects, such as monopolistic power and impacts on consumers from different income groups.

The new natural gas pricing regime in China has a better predictability and transparency compared with the old pricing regime. It has a strong connection with the international fuel oil market and LPG prices. To minimize potential political opposition during the new regime implementation, the government adopted a two-tier pricing approach for the period of transition. Because it focuses mostly on a supply side, the current reform falls short in establishing a truly market pricing system. Among the major limitations of the current reform is a failure to address the issues at the level of local distribution and retail prices. It also has created biased incentives and favors the large natural gas suppliers. An immediate step for improving the new pricing approach would be to set the transparent rules and conditions under which the city gate natural gas prices could be adjusted automatically in response to the changes in international oil and gas market prices. For a long-term development, the Chinese government should investigate the pathways for moving to a complete market-based natural gas pricing system. It will establish a better resource allocation system and results in an increased welfare of China.

Chapter 4 The EPPA Model and Its Modification

4.1 Brief Introduction to the EPPA Model

4.1.1 Model Structure

For natural gas scenario development I use the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev et al., 2005; Chen et al., 2015), which is a multi-region, multi-sector dynamic model of the global economy. It has been broadly applied to the impact evaluation of climate and energy policies on the economic and energy systems for global and regional studies. As a computable general equilibrium model, the EPPA model projects the interactions among production sectors and between the producers and consumers under the impact of commodities and resources prices. Thus the model can provide an overall examination of the general effects of the policy on the economy. Moreover, the EPPA model incorporates detailed technology modules to enable the model to provide detailed technology approaches for policy implementation. As a global framework, the EPPA model can also be used for the assessment of policy effects on international trade and on global emission mitigation.

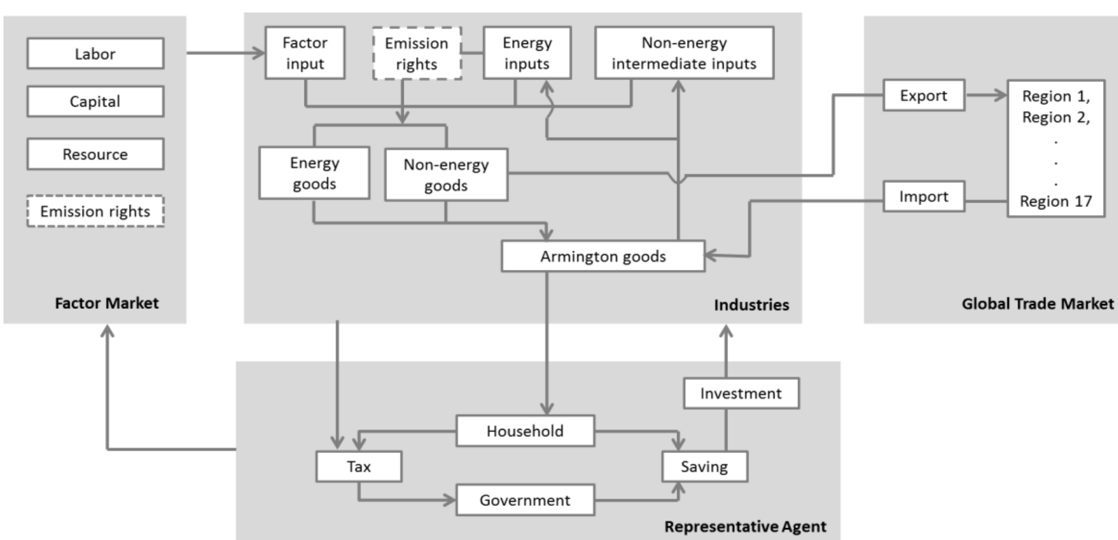


Figure 4.1. The circular flow of goods and resources in EPPA. Source: Adopted from Qi (2014)

The arrows in **Figure 4.1** show the flow of goods and services in the economic system in each world region. EPPA describes the economy as market interactions between two agents: producers and consumers. Producers buy intermediate goods and services from the products market and buy labor and capital from the factor markets. The outputs of the production enter the domestic market for consumption, where they compete with imports from other regions. Consumers get income by providing capital and labor to the factor market and they spend their earnings on consumption and saving to maximize their welfare. The market balances the supplies and demands in the products and factors market by establishing an equilibrium price. Government in the EPPA model is presented as a passive agent that collects tax revenue from the firms and transfers the money to the representative agent. Global regions are connected through international trade.

4.1.2 Regions and Sectors

The EPPA model provides a representation of the global economy with China as a separate region of the model. The GTAP data set (Narayanan et al., 2012) provides the base information on the input-output structure for regional economies, including bilateral trade flows. The GTAP data are aggregated into 18 regions and 24 sectors. **Figure 4.2** represents geographical regions represented explicitly in the EPPA model.

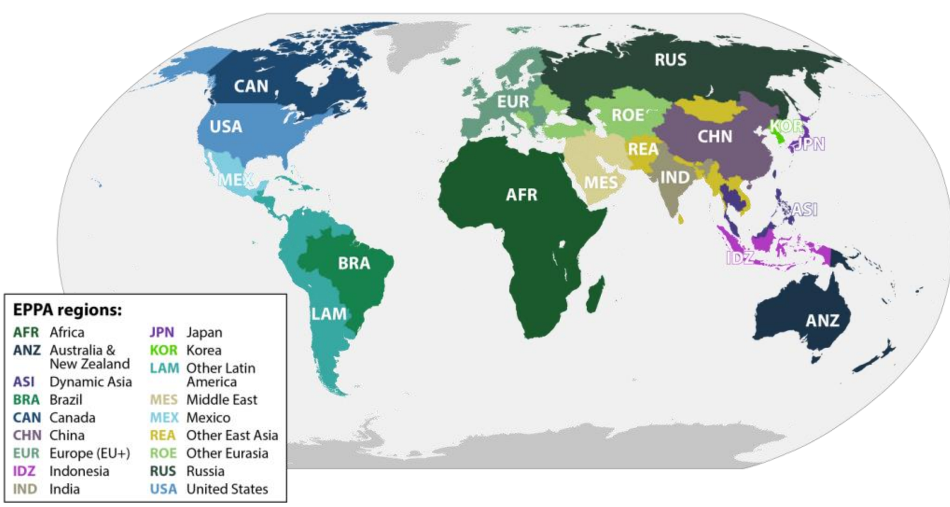


Figure 4.2. Regions in the EPPA model. Source: Adopted from MIT Joint Program (2014) and Chen et al (2015)

The EPPA model explicitly represents interactions among both sectors, through inter-industry inputs, and regions, via bilateral trade flows. The model simulates economy-wide production in each region at the sectoral level. Sectoral output is produced from primary factors including multiple categories of depletable and renewable natural capital, produced capital, and labor (**Table 4.1**). Intermediate inputs to sectoral production are represented through a complete input-output structure.

Table 4.1 Sectors and Factor Inputs in the EPPA model

Sector		**Primary Factor Inputs**
Production Sectors		***Depletable Natural Capital***
Agriculture – Crops	CROP	Conventional Oil Resources
Agriculture - Livestock	LIVE	Shale Oil
Agriculture - Forestry	FORS	Conventional Gas Resources
Food Products	FOOD	Unconventional Gas Resources
Biofuels	BIOF	Uranium Resources
Coal	COAL	Coal Resources
Crude Oil	OIL	***Renewable Natural Capital***
Refined Oil	ROIL	Solar Resources
Natural Gas[1]	GAS	Wind Resources
Electricity[2]	ELEC	Hydro Resources
Energy-Intensive Industries	EINT	Land
Other Industries	OTHR	***Produced Capital***
Services	SERV	Conventional Capital (Bldgs & Mach.)
Transport	TRAN	***Labor***
Household Sectors		
Household Transport	HHTRAN	
Ownership of Dwellings	DWE	
Other Household Consumption[3]	HHOTHR	

[1] Natural Gas production includes production from conventional resources, shale gas, tight gas, coal-bed methane, and coal gasification.

[2] Electricity production technologies include coal, natural gas, oil, advanced natural gas, advanced coal, hydro, nuclear, biomass, wind, solar, wind with natural gas backup, wind with biomass backup, advanced coal with carbon capture and storage, advanced natural gas with carbon capture and storage, advanced nuclear.

[3] Other Household Consumption is resolved at the production sectors level

Source: Adopted from Chen et al (2015).

As described by Chen et al (2015), the EPPA model projects CO_2 emissions and other greenhouse gases (GHGs) such as methane, nitrous oxide, hydrofluorocarbon emissions, perfluorocarbon emissions and sulfur hexafluoride. The model also projects pollution emissions from the sulfates, nitrogen oxides, black carbon, organic carbon, carbon monoxide, ammonia, and non-methane volatile organic compounds. Mitigation options are also reprensented in the model.

The dynamics in the EPPA model is driven by endogenously determined capital accumulation resulting from savings and investments as well as exogenously determined factors including labor force growth, resources availability, and the rate of technological change (e.g, explicit advanced technologies and productivity improvement in labor, land and energy) (Chen at al., 2015). GDP and income growth drives up demand for goods which are produced from each sector (Octaviano et al., 2015). Fossil fuel production costs increase as fossil fuel resources deplete. Increasing the use of advanced technologies (including energy from renewable sources) leads to learning-by-doing and a reduction in scarcity rents (associated with shortages in skilled labor and monopoly rents). With increasing prices of fossil fuel and reduced costs of advanced technologies, the new technologies can become competitive with the technologies relying on fossil fuels (Morris et al., 2014). These features enable the EPPA model to simulate a dynamic evolution of technology mixes for different energy and climate-related policies. **Figure 4.3** presents the data process in EPPA.

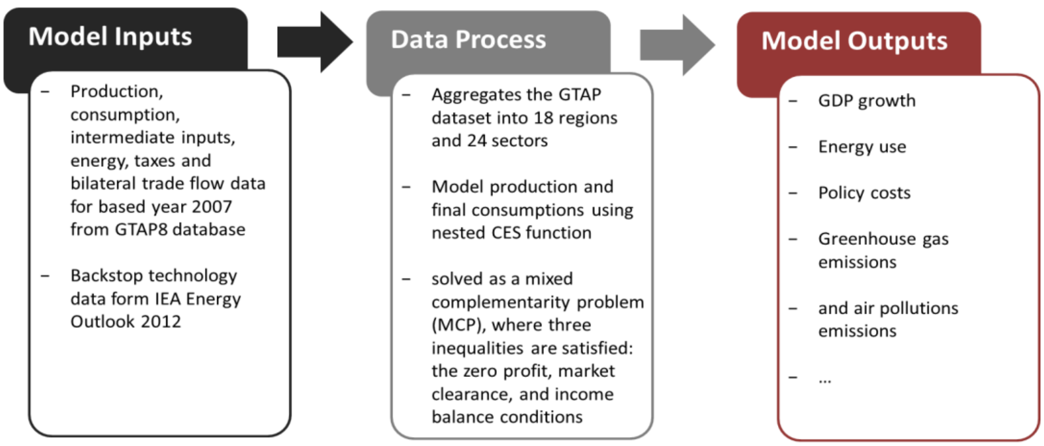


Figure 4.3 Data process in EPPA

4.1.3 Backstop Technologies

Based on engineering data, EPPA includes advanced technologies that are not widely deployed but have a large application potential in the future, namely “backstop technologies” as shown in **Table 4.2** (Chen et al., 2015). These technologies are usually more expensive than the conventional technologies in the base year, but they may become cost efficient with technology improvement and favorable policies. The model has calibrated the output of these backstop technologies for historical years (2007 and 2010) based on the information from the World Energy Outlook from the International Energy Agency (IEA, 2012a)

Table 4.2 Backstop technologies

Backstop Technology	EPPA6
First generation biofuels	bio-fg
Second generation biofuels	bio-oil
Oil shale	synf-oil
Synthetic gas from coal	synf-gas
Hydrogen	h2
Advanced nuclear	adv-nucl
IGCC w/ CCS	Igcap
NGCC	Ngcc
NGCC w/ CCS	Ngcap
Wind	Wind
Bio-electricity	Bioelec
Wind power combined with bio-electricity	Windbio
Wind power combined with gas-fired power	Windgas
Solar generation	Solar

Source: Chen et al (2015)

4.2 Natural Gas Sector Representation in the EPPA Model

Production in each sector is represented by series of nested constant elasticity of substitution (CES) functions in the EPPA, where nesting structures, input cost shares and elasticity values differ across sectors (or groups of sectors) to reflect the characteristics of each industry. The nesting structure for natural gas is shown in **Figure 4.4**, which illustrates how various inputs are aggregated in the nest to get domestic natural gas output.

As shown in **Figure 4.4**, the nest includes the resource input of nature gas, which works as a resource limit to represent the scarce character of fossil fuels, and other inputs. Other inputs nest, which is incorporated in the second level, contains a Leontief combination of intermediate inputs and the Capital-Labor-Energy (KLE) bundle. The KLE bundle is comprised of a CES structure between energy and a value-added bundle. Capital and Labor are combined as a Cobb-Douglas structure, and energy is further divided into electricity and fossil fuels bundle (including coal, crude oil, refined oil, and natural gas). Combined in the Leontief way with the fossil fuel consumption, GHG and non-GHG emissions are calculated with the specific emission factor for each fossil. Emission permits are considered as a necessary input when emission constraint policies are imposed.

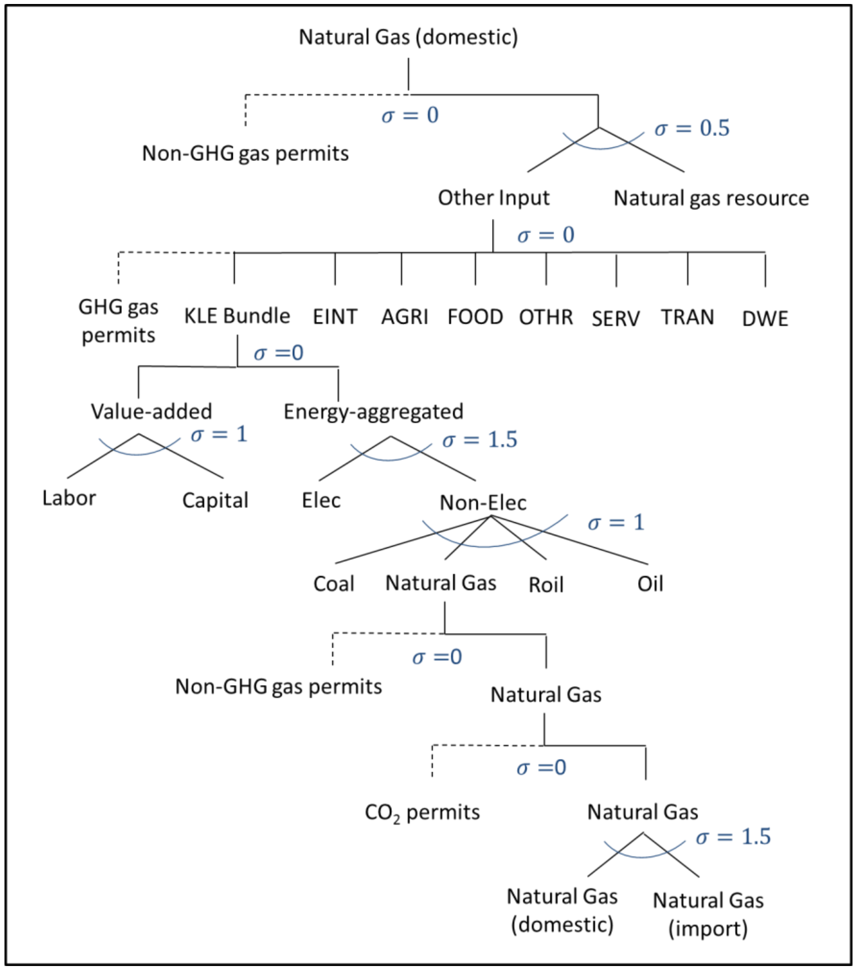


Figure 4.4 Production structure for natural gas in EPPA.
Source: Adopted from Chen et al (2015) and Qi (2014) .
(The dash line represents emission permits which could be turned on or off when simulating emission constraint policies).

Based on the structure shown in **Figure 4.4**, the CES production function for natural gas sector can be represented in the following form:

$$Y_r = [\alpha_r \times F_r{}^{\rho} + (1 - \alpha_r) \times \sum (X_{1,r}, \ldots, X_{g,r}, E_{e,r}, V_r)^{\rho}]^{\frac{1}{\rho}}$$

Where Y_r denotes the natural gas production in each region (indexed by the subscript r). α_r represents the share of resource supply. F_r refers to the resource factor. $\sigma = \frac{1}{1-\rho}$ is the elasticity of substitution between resource factor and other non-resource input. $X_{g,r}$ is the intermediate non-energy inputs. $E_{e,r}$ is the energy input. V_r is the labor-capital bundle which are combined with a Cobb-Douglas structure.

4.3 Representing Characteristics of China's Energy Sector in the EPPA model

4.3.1 Estimating Costs of Advanced Technologies

Like production for other commodities, advanced technologies in the EPPA model are represented by nested CES production functions. Key features of production functions for some advanced technologies include resource inputs and the representation of transition costs for scaling up production, which is expressed as a mark-up relative to the price of pulverized coal technology in 2010. Based on a detailed survey of local information from the latest publications, including government statistics on capital cost, government announcements on fuel cost, and project-based peer-reviewed studies, I updated the assumptions for capital cost, fixed operation and management (O&M) cost, variable O&M cost, and fuel cost of each advanced technology in China. The survey of production cost and input structure of advanced technologies in China is represented in **Table 4.3**.

Currently, the coal price in China ranges from 310 to 445 yuan/ton depending on heating values (CQCOAL, 2015). For the thesis analysis, I use the price for Bohai-rim steam-coal (5000Kcal/Kg) to calculate the levelized costs for coal-fired electricity generation technology. The capital cost for pulverized coal–fired power plant is estimated to be about 3979 yuan/kW (NEA, 2014). The variable O&M cost and fixed O&M cost are assumed at 0.04 yuan/kWh and 67 yuan/kW respectively according to Huang et al (2012). The levelized cost of pulverized coal technology is calculated to be around 0.264 yuan/kWh or 42.86$/MWh with a discount rate of 8.5%.

The levelized cost of Natural Gas Combined Cycle (NGCC) in China is calculated to be at 83.6 $/MWh, which is about twice as much as the cost for pulverized coal-fired technology. According to China Electricity Council, the capital cost for NGCC power plant is around 2772 yuan/kWh. The variable O&M and fixed O&M costs are estimated to be 0.02 yuan/kWh and 106 yuan/kW respectively. I use the power sector natural gas price in Shanghai to calculate the fuel cost for NGCC. Currently, the natural gas price for power sector in Shanghai is 2.5 yuan/m^3 (SHDRC, 2015), which is about 70.0 yuan/MMBtu assuming that 1000 cubic meter natural gas contents 35.7 MMBtu (BP, 2014). Natural gas prices for power sector vary across regions. There are several considerations for the reason that I use natural gas price in Shanghai in my calculations. Firstly, this largely reflects natural gas prices used by NGCC plants in China as most of the NGCC power plants are located in the east of China in places such as Beijing, Shanghai, Jiangsu, and Zhejiang, where natural gas prices are among the highest. Secondly, most likely, majority of the future NGCC plants will be also located in the eastern part of China. NGCC plants emit less SO_2 and NOx than coal-fired power plants. The eastern regions in China are heavily impacted by the air pollution issues. Promoting NGCC plants to replace coal-fired plants in those regions will contribute to mitigating local air pollution.

Based on the calculations provided in **Table 4.3**, the costs for advanced nuclear, wind, solar PV and biomass are estimated to be 72.1 $/MWh, 58.6 $/MWh, 124.5 $/MWh, and 77.1 $/MWh respectively. In the EPPA model, there is an improvement in power production efficiency. EPPA use an autonomous energy efficiency improvement (AEEI) rate of 0.3% per year for electricity sector in China. The AEEI rate represents the long-run rate of efficiency improvement attribute to technological change and capital stock turn over. Some additional efficiency improvement will be price-driven, as higher fuel prices will lead to use more capital to increase efficiency of production.

Table 4.3 Levelized Costs of Electricity in China

		Units	Pulverized Coal	NGCC	NGCC with CCS	IGCC	IGCC with CCS	Advanced Nuclear	Wind	Biomass	Solar PV
[1]	"Overnight" Capital Cost	yuan/kW	3979	2772	4500	7777	9161	11911	8103	9744	14788
[2]	Total Capital Requirement	yuan/kW	4616	2994	5040	9332	10993	16675	8751	11303	15971
[3]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[4]	Fixed O&M	yuan/kW	67	106	320	396	478	-	183	94	60
[5]	Variable O&M	yuan/kWh	0.04	0.02	0.17	0.01	0.02	0.13	-	-	-
[6]	Project Life	years	20	20	20	20	20	20	20	20	20
[7]	Capacity Factor	%	85%	85%	80%	80%	80%	85%	35%	80%	26%
[8]	Operating Hours	hours	7446	7446	7008	7008	7008	7446	3066	7008	2278
[9]	Capital Recovery Required	yuan/kWh	0.066	0.042	0.076	0.141	0.166	0.237	0.302	0.170	0.741
[10]	Fixed O&M Recovery Required	yuan/kWh	0.009	0.014	0.046	0.057	0.068	-	0.060	0.013	0.026
[11]	Heat Rate	BTU/kWh	8740	6333	7493	7450	8307	10479	-	13500	-
[12]	Fuel Cost	yuan/MMBTU	17.1	70	75	17.1	17.1	7.4	-	21.6	-
[13]	Fuel Cost per kWh	yuan/kWh	0.149	0.443	0.562	0.127	0.142	0.078	-	0.292	-
[14]	**Levelized Cost of Electricity**	**yuan/kWh**	**0.264**	**0.515**	**0.854**	**0.334**	**0.396**	**0.444**	**0.361**	**0.475**	**0.767**
[15]	**Levelized Cost of Electricity**	**$/MWh**	**42.86**	**83.60**	**138.64**	**54.22**	**64.29**	**72.08**	**58.60**	**77.11**	**124.51**
[16]	**Markup Over Coal**		**1**	**1.95**	**3.23**	**1.26**	**1.50**	**1.68**	**1.37**	**1.80**	**2.91**

Source:

[1] Pulverized Coal: NEA, 2014
NGCC: China Electricity Council, 2012
NGCC with CCS: Liao, J., 2015
IGCC: Li, P., 2012
IGCC with CCS: Li, P., 2012
Wind: NEA, 2014
Advanced Nuclear: Huo et al, 2015

Solar PV: NEA, 2014

Biomass: China National Renewable Energy Centre, 2015

[2] [1]+([1]*0.4*y) where y=construction time in years: coal=4, NGCC=2, IGCC with CCS=5, NGCC with CCS=3, nuclear=5, wind=2, biomass=4, solar=2, wind with biomass=2, wind with NGCC=2. For nuclear there is additional cost of ([1]*0.2) for the decommission cost. EPPA assumption.

[3] =r/(1-(1+r)^(-[6])) where r is discount rate. The discount rate is 8.5% for all technologies. EPPA assumption.

[4] Pulverized Coal: Huang. W., 2012

NGCC: Chen et al, 2012

NGCC with CCS: Liao, J., 2015

IGCC: Li, P., 2012

IGCC with CCS: Li, P., 2012

Wind: Lan, L., 2014

Advanced Nuclear: Aggregated to Variable Costs

Solar PV: Lan, L., 2014

Biomass: Huang et al, 2008

[5] Pulverized Coal: Huang. W.H., 2012

NGCC: Chen et al, 2012

NGCC with CCS: Liao, J., 2015

IGCC: Li, P., 2012

IGCC with CCS: Li, P., 2012

Wind: included in Fixed O&M

Advanced Nuclear: Li, Y., 2010

Solar PV: included in Fixed O&M

Biomass: included in Fixed O&M

[6] Input, from EIA 2010. EPPA assumption.

[7] Input, EPPA assumption

[8] =8760*[7] (8760 is the number of hours in a year)

[9] =([2]*[3])/[8]

[10] =[4]/[8]

[11] Input, from EIA 2010. EPPA assumption.

[12] Puverilized Coal: Bohai-rim steam- coal 5000Kcal/Kg, 340 yuan/ton in September 2015. CQCOAL News, 2015.

NGCC: Natural gas price for power generation in Shanghai, 2.5 yuan/m^3. Shanghai Municipal Development and Reform Commission, 2015

NGCC with CCS: Natural gas price for power generation in Shanghai, 2.5 yuan/m^3. Shanghai Municipal Development and Reform Commission, 2015

IGCC: Bohai-rim steam- coal 5000Kcal/Kg, 340 yuan/ton in September 2015. CQCOAL News, 2015.

IGCC with CCS: Bohai-rim steam- coal 5000Kcal/Kg, 340 yuan/ton in September 2015. CQCOAL News, 2015. ht

Wind: zero fuel cost

Advanced Nuclear: Li, Y., 2010

Solar PV: Zero fuel cost

Biomass: 300yuan/t, 14653kj/kg. Huang et al, 2008

[13] =[11]*[12]/1000000

[14] =[5]+[9]+[10]+[13]

[15] =[14]/6.16. Exchange rate: 1 US$ = 6.16 yuan (average exchange rate for 2014 from USForex, 2015)

[16] =[15]/([15] for coal)

4.3.2 Implementing Feedstock Natural Gas in Energy Intensive Sector

In the current version of EPPA (Chen et al., 2015), natural gas is treated as fuel which will be fully combusted in all intermediate and final consumption sectors. However, in China around 30% of the natural gas input in industry is used as feedstock to produce chemicals such as acetylene and chloromethane (NBS, 2014). The difference between feedstock input and fuel input is important for the resulting emissions. Feedstock inputs are not combusted and they emit little greenhouse gases. Assuming that all natural gas is being used as a fuel will overestimate the amount of greenhouse emissions in manufacturing sector.

In order to disaggregate the gas consumption into fuel input and feedstock input based on their actual usage, I introduce a new commodity titled "feedstock gas" into the production function in the energy-intensive (EINT) sector (see **Figure 4.5**) of the EPPA model. The feedstock gas comes from a combination of both domestic gas and imported gas. Since feedstock gas is a non-energy commodity, it is aggregated in the same layer with other non-energy inputs.

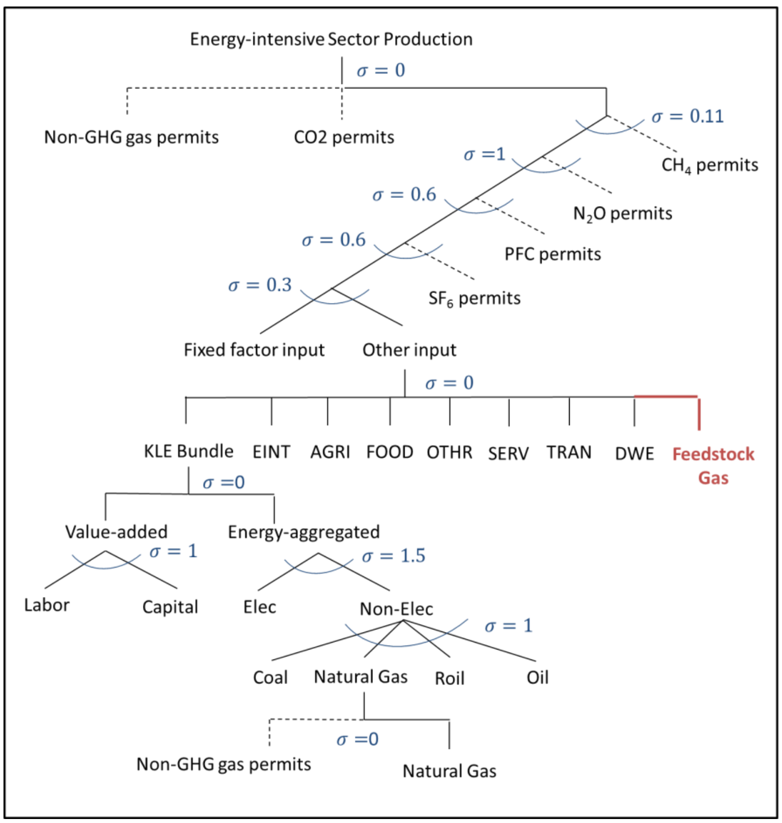


Figure 4.5 Production structure for energy-intensive sector (EINT) in EPPA

Source: Adopted from Chen et al (2015)

4.3.3 Calibrating Energy Consumption in China

Energy consumption (both fossil and non-fossil) in 2010 in the standard EPPA model (Chen et al., 2015) is calibrated to match the 2012 IEA data (IEA, 2012b). In September 2015, the National Bureau of Statistics of China (NBS) released official statistical revision on energy consumption data from 2000 to 2013 (IEA, 2015). The revised statistics suggests that the coal consumption has been underreported up to 17% each year than the data previously released by the NBS (The Guardian, 2015), which causes a large correction. I calibrated the energy consumption of China in 2010 according to the latest official data information.

EPPA runs in five-year interval. Although the official statistics for annual energy consumption in 2015 is not available, I use the 2014 energy consumption as a base to calibrate the 2015 energy consumption. National Energy Agency (NEA) of China estimates that the energy consumption in the first half of year 2015 is 0.7% higher than the first half of year 2014. The NEA also estimates that energy consumption in the second half year of 2015 will grow more than 0.7% during the second half year of 2014 (NEA, 2015). The total energy consumption in 2014 is 4260 Mtce or 124.85 EJ, of which 66% from coal, 17.1% from oil, 5.7% from natural gas and 11.2% from non-fossil energies (NBS, 2015).

Nuclear energy is calibrated to match the projected installed capacity in 2015 (SGCC, 2015) and 2020 (State Council, 2014). Nuclear energy from 2025 to 2050 are calibrated to match the *High nuclear* scenario (Paltsev and Zhang, 2015b). Hydro power is calibrated to match the installed capacity projected by Zhang el al (2015) from 2015 to 2050 and it reaches 400GW by 2050.

There is substantial uncertainty about wind and solar development. According to Chinese government, the installed capacities of wind and solar will reach 200GW and 100 GW respectively by 2020 (State Council, 2014). Therefore, wind and solar are calibrated to the planned capacity provided by the government. Wind and solar energy consumption after 2020 are endogenously determined by the model. Due to the lack of information, I did not recalibrate biomass energy consumption. Therefore, bioelectricity and bio oil consumption in 2010 are still matched to the historic data presented in the IEA 2012 Energy Outlook. The targets that are used for calibration are summarized in **Table 4.4**.

Table 4.4 Projected installed capacity of non-fossil energies in China (GW)

	2015	2020
Wind	100	200
Solar	35	100
Hydro	300	350
Nuclear	30	58

GTAP dataset is based on 2007 and it does not reflect a fast natural gas development in China that occurred after 2007. To better reflect the current natural gas prices in China, I introduced a correction factor that adjusts the domestic price level by 28%. This correction leaves the values from the GTAP unchanged, but increases the corresponding amount of natural gas in physical units. The correction amount is chosen to match China's statistics in 2010 (as discussed in Chapter 2).

In the standard EPPA model, the share of imported gas in 2015 does not reflect the real natural gas supply situation in China. Imported natural gas has increased rapidly since 2010, when the Central Asia – China pipeline started operations. However, the model fails to capture this infrastructure development. Based on the GTAP data, the standard EPPA model keeps the share of imported gas at 12% in 2015, which is much lower than the 31% import share in 2013 reported by the Chinese statistics (see Chapter 2). Since most of the increased gas imports are from Central Asia, I increased the bilateral trade flow between Central Asia and China in 2015 by 840% relative to the 2010 level. This number is justified by the fact that, during the first ten months in 2010, China imported a total value of 0.75 billion US dollars (Urumqi Custom, 2011) from Central Asia. In 2015, the number has grown by 840%, reaching 7.0 billion US dollars (Urumqi Custom, 2015). Even after increasing the value for the imported gas from Central Asia based on the custom statistics, the share of total gas imports in 2015 was still less than 31%. Hence, another adjustment was made to reflect the growth in LNG imports.

4.4 Modeling Oil-linked Natural Gas Pricing Policy

In Chapter 3, I discussed the directions for China's future natural gas pricing reform and found that the current oil-linked pricing scheme can create biased incentives and favors the large natural gas suppliers. I also proposed that the Chinese government should move towards a complete market-based pricing system in a long run. In this section, I will deliberate more on this argument by simulating the oil-linked pricing scheme using the modified EPPA model.

Firstly, I will describe methodology that I applied to model the oil-linked policy in EPPA. Then I will simulate the trajectories of the oil-indexed natural gas price and the market-determined natural gas price. The simulation will be focused on the impacts of natural gas price linkage to the refined oil price on the future natural gas consumption in China.

4.4.1 Modeling Oil-linked Policy in EPPA model

Two issues are critical to modeling the oil-linked policy. First, the approach which would enable the natural gas price be linked with the refined oil price in EPPA should be developed. Second, to determine how long the oil-linked policy will last. To model the oil-indexed natural gas price in EPPA the following approach is developed. Recall the current oil-linked natural gas pricing formula:

$$P_{NG@SH} = K \times [w_{FO} \times P_{FO} \times \frac{H_{NG}}{H_{FO}} + w_{LPG} \times P_{LPG} \times \frac{H_{NG}}{H_{LPG}}] \times (1 + R)$$

In the formula, $P_{NG@CG}$ represents the city gate price of natural gas in Shanghai. K, w_{FO}, w_{LPG}, H_{NG}, H_{FO}, H_{LPG}, R are constants provided by the government which represent discount rate, the weight for fuel oil, the weight for LPG, the heating value of natural gas, the heating value of fuel oil, the heating value of LPG, and value-added tax rates for natural gas respectively. P_{FO} and P_{LGP} are variables which represent the average imported prices of fuel oil and LPG respectively. Therefore, the oil-linked formula can be simplified as following:

$$P_{NG@SH} = \alpha P_{FO} + \beta P_{LPG}$$

Where α and β are constant coefficients. The city gate price in Shanghai is the base for pricing city gate prices in other provinces. All city gate prices are calculated by deducting the transmission tariff from the Shanghai city gate price:

$$P_{NG@i} = P_{NG@SH} - T_i$$

Where $P_{NG@i}$ represents the city gate price in province i. T_i represents the transmission tariff of province i. Therefore, the average city gate price of China (P_{NG}) which also presents the average level of natural gas price received by natural gas suppliers could be written as below:

$$P_{NG} = \frac{\sum_i^{N-1}(P_{NG@SH} - T_i) + P_{NG@SH}}{N} = P_{NG@SH} + \delta$$
$$= \alpha P_{FO} + \beta P_{LPG} + \delta$$

In EPPA, fuel oil and LPG are represented by "refined oil (ROIL)" commodity. To simplify the modeling approach, I assume that the refined oil price is expressed as a linear function of the fuel oil price and the LPG price. Therefore, the average wholesale level natural gas price could be further simplified as a linear function of the refined oil (ROIL) price:

$$P_{NG} = \gamma P_{ROIL} + \varepsilon$$

All prices in EPPA are relative prices and they can be expressed as price indexes. Therefore, the oil-linked natural gas pricing scheme could be modeled by equating the natural gas price index to the refined oil price index.

$$P_{NG}' = P_{ROIL}'$$

Natural gas price index may be higher than the refined oil price index during some periods and may be lower in other periods. When the natural gas price index is higher than the refined oil price index, there are two approaches to reduce the natural gas price index to match the refined oil price index in EPPA. One approach is to increase natural resource supply, which reflects a larger natural gas availability to producers. In this approach, there is no explicit representation of the government revenue flows to natural gas producers. The other approach is to directly subsidize natural gas suppliers. A simple illustration of the economic principles behind the two approaches is provided in the **Figure 4.6 (a) and (b)**.

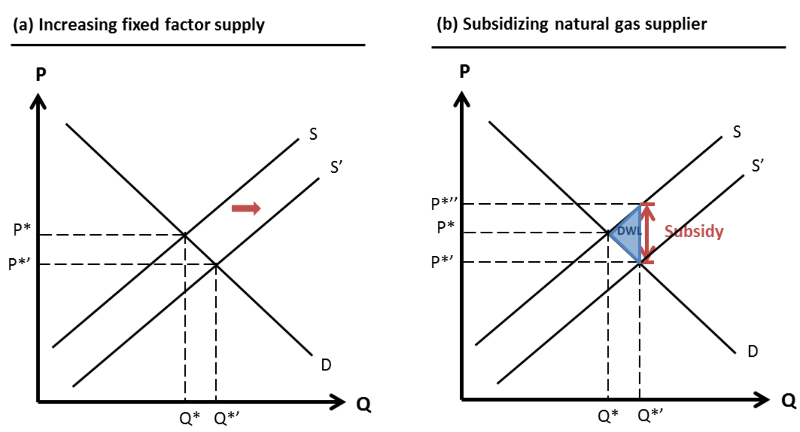


Figure 4.6 Economic consideration of modeling oil-linked natural gas price

As shown in **Figure 4.6(a)**, increasing natural resource moves the supply curve *S* to the right *S'*.

As a result, price of natural gas decreases and consumption of natural gas increases. Note that increasing natural resource approach only changes the supply curve of domestic producers because they own the natural resource in a particular region. Gas importers do not own natural resource in this region and thus their supply curve remains unchanged. This modeling approach creates a biased incentive that favors domestic gas producers.

Figure 4.6(b) shows the economic diagram for subsidized natural gas supplier. With subsidy, natural gas suppliers are willing to provide *Q*'* of natural gas at price *P*''* and natural gas consumers are willing to pay *P*'* to consume *Q*'*. The gap between *P*''* and *P*'* is the subsidy. The subsidy can be set at the level at which the new equilibrium price *P*'* would be equal to the refined oil price in the model. This approach creates similar incentives for domestic producers and importers to increase their natural gas supply. It also allows estimating the amount of government revenue required to provide this incentive to natural gas suppliers.

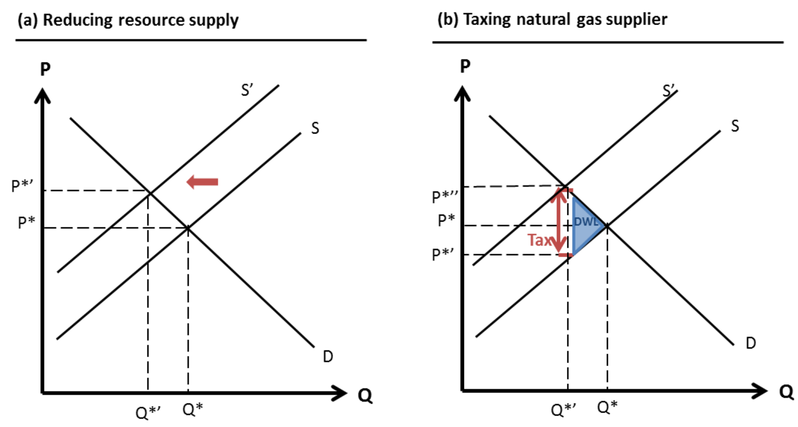


Figure 4.7 Economic theory of modeling oil-linked natural gas price

Similar considerations can be applied to the situation when the natural gas price index is lower than the refined oil price index. Again, there are two possible approaches to increase the natural gas price index to match the refined oil price index in EPPA. One approach is to reduce natural resource supply. The other approach is to tax natural gas suppliers. The economic principles behind these two approaches are illustrated in the **Figure 4.7 (a) and (b)**.

As shown in **Figure 4.7(a)**, reducing natural gas resource moves the supply curve *S* to the right *S'*. As a result, price of natural gas increases and consumption reduces. Note again that reducing natural gas resource only changes the supply curve of domestic producers and in this situation this approach creates biased incentives that favor gas importers.

Figure 4.7(b) shows the economic principles of taxing a natural gas supplier. Being taxed, suppliers increase wholesale natural gas price from P^* to $P^{*''}$ to reflect the tax. At $P^{*''}$, consumers are willing to consume $Q^{*'}$ amount of natural gas. $P^{*'}$ is the after-tax price received by gas suppliers. The gap between $P^{*''}$ and $P^{*'}$ is the tax. The tax can be set in the model at a level such that the new equilibrium gas price $P^{*''}$ is linked to the refined oil price. I introduced additional conditions in the EPPA model that determine the amount of tax or subsidy necessary to match the natural gas price and the import price of refined oil in China.

4.4.2 A Comparison of the Oil-linked Pricing Scheme and the Market-determined Pricing Mechanism

The initial price trajectories of the natural gas and the refined oil are generated in the *Market-Determined* scenario, where neither CO_2 constraint policy, nor oil-indexed pricing policy is introduced. Energy prices, including natural gas, coal, electricity, and oil, are determined by the interaction of their supply and demand. In this section I consider two scenarios for natural gas pricing. As mentioned, in the *Market-Determined* scenario, natural gas price in China is determined by interaction of supply and demand. In the *Oil-Linked* scenario, I impose a linkage of natural gas price with imported refined oil price (as described above). I also explore two time intervals of price linking: up to 2020 and up to 2050. **Figure 4.8** shows the price indexes of natural gas obtained from the *Market-Determined* scenario and the *Oil-Linked* scenario (when prices are linked up to 2050) in the EPPA model. As can be seen, without any pricing policy regulations, the natural gas price index is higher than the oil-linked natural gas price index in 2015 and lower after 2020. In the *Market-Determined* scenario, the price trajectory reflects the producer margins and resource availability as modelled in the standard version of EPPA 6 (Chen et al., 2015) that envisions a return to oil price growth in the long-run. The price trends derived from the *Market-Determined* scenario imply that a shift to the completely market-determined pricing system in China in 2015 may result in a further increase in natural gas price in 2015 compared with implementing the oil-linked pricing mechanism.

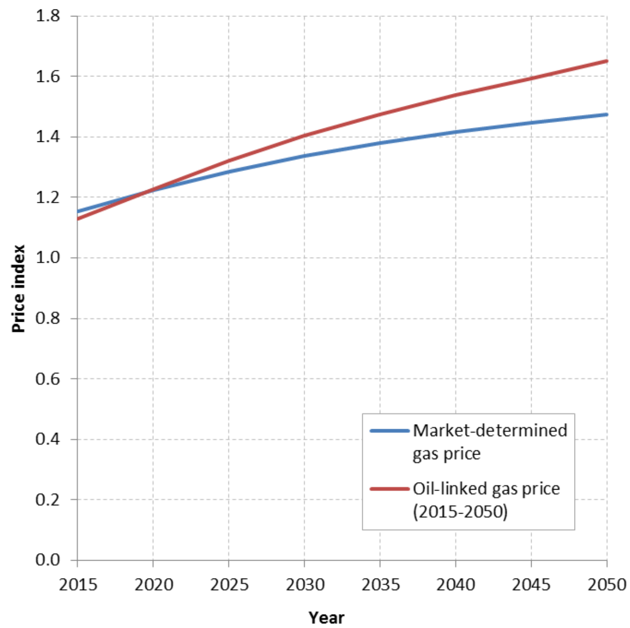


Figure 4.8 Price index of natural gas in the Market-Determined and Oil-Linked scenarios

As shown **Figure 4.8**, the oil-linked natural gas price grows faster than market-determined gas price after 2020. There is an increasing deviation between the two price trajectories after 2020. This is because the supply and demand patterns for refined oil and natural gas are different from each other. As the refined oil price increases faster than the natural gas price, having the natural gas be linked to the imported refined oil price would constrain natural gas consumption. This is not in line with the objective of the China's natural pricing reform which is to promote natural gas utilization.

China now encourages market-oriented energy system reform. NDRC and NEA are drafting the development plan for oil and natural gas reform for the thirteenth five-year plan period (2016 – 2020). The plan aims at establishing a market-based pricing system covering the business of resources exploration, import, transmission and distribution (Xinhua News, 2015b). In this regard, the current oil-linked natural gas pricing scheme should serve as a transition to a complete market-determined pricing system. Base on the modeling results and the government policies discussed above, a likely scenario is that China's natural gas price will be oil-linked during 2015 - 2020 timeframe and then will be market-determined after 2020.

To represent oil price-linking in the EPPA model, the price of refined oil is used as it contains both fuel oil and LPG**. Figure 4.9** presents China's natural gas consumption in three scenarios: *Market -Determined*, *Oil-Linked* pricing policy during 2015-2020 time frame, and *Oil-Linked* pricing policy during 2015-2050 timeframe. As can be seen, linking the natural gas price to the refined oil price during 2015 to 2020 time frame increases gas use by about 1.8% compared to a market-determined pricing mechanism. However, forcing gas price to move in line with the refined oil price results in a reduction in gas consumption by 3.5% in 2030 and 9.2% in 2050 compared to a market-determined pricing mechanism.

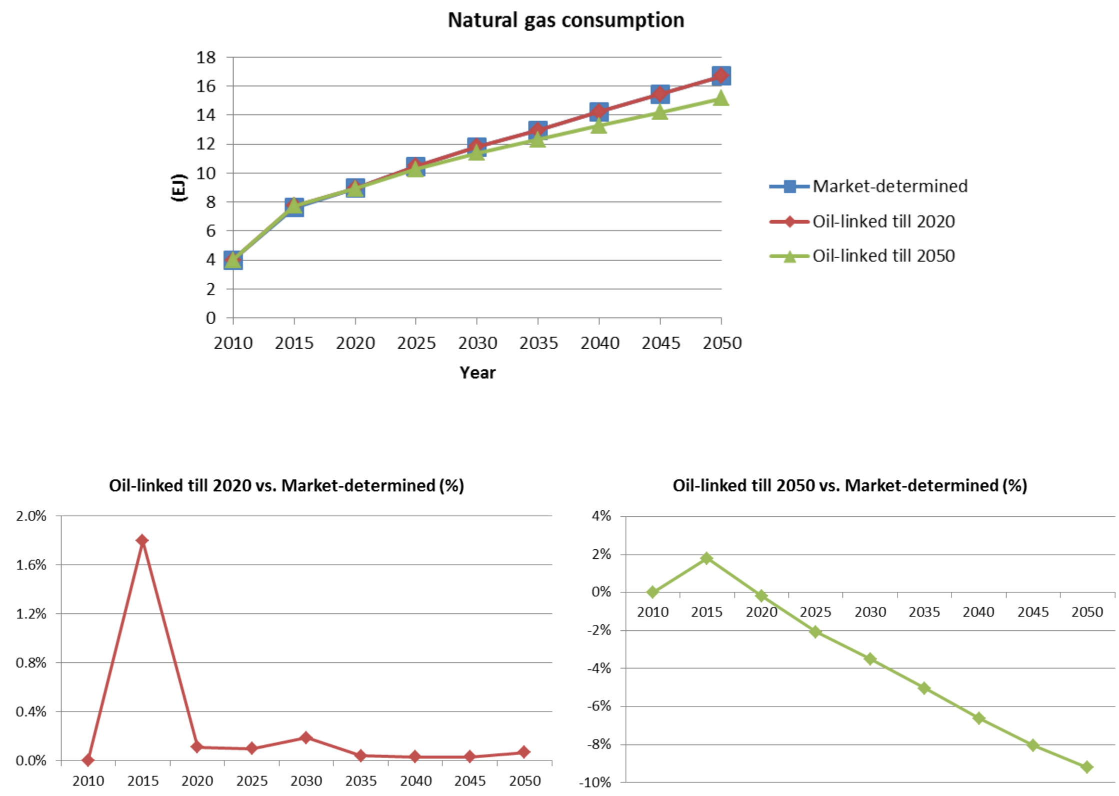


Figure 4.9 Natural gas consumption derived from Market-determined pricing policy, oil-linked pricing policy till 2020, and oil-linked pricing policy till 2050 scenarios.

Chapter 5 China's Natural Gas Future: Alternative Policy Scenarios

5.1 Description of the Scenarios

After a large number of model simulations, I focus on the main scenarios which represent the three representative paths of China's natural gas future development. The three scenarios are *Reference*, *CapOnly* (also referred as climate policy), and *Cap+Subsidy* (also referred as integrated policy). **Table 5.1** summarizes the description of three scenarios.

Table 5.1 Assumptions and highlights of the three typical policy scenarios

	Reference	CapOnly (climate policy only)	Cap+Subsidy (Integrated climate mitigation and gas subsidy policy)
[1]	Oil-linked gas price from 2015 to 2020, market-determined gas price after 2020	The same as in *Reference*	The same as in *Reference*
[2]	No carbon cap	Carbon cap-and-trade scheme introduced to achieve a 4% CO_2 intensity reduction per year after 2020	The same as in *CapOnly*
[3]	No gas subsidy	No gas subsidy	Allocate a part of carbon revenue to subsidize natural gas use to achieve a 10% of natural gas contribution in primary energy consumption since 2020
Scenario Remarks	Represents the current natural gas pricing approach and future directions for pricing.	Introduces a cap-and-trade scheme to achieve China's pledge —peaking its CO_2 emission around 2030.	Integrated climate mitigation and natural gas promotion policy is introduced to achieve the objective of climate mitigation and natural gas promotion simultaneously.

5.1.1 Reference Scenario

Under the *Reference* scenario, the natural gas pricing will be based on the oil-linked approach during 2015-2020, and completely market-determined afterwards. In this scenario, neither CO_2 cap nor subsidies on natural gas consumption are introduced. Therefore, this *Reference* scenario could be used as a base case to assess the effects of the climate policy and the natural gas promotion policy on natural use. Most of the results will be presented as deviations from the

Reference.

5.1.2 Climate Policy Scenario (*CapOnly*)

China's INDC lists its major actions to address climate change. According to INDC, China will decrease its carbon intensity by 60-65% from 2005 levels by 2030, and peak its CO_2 emission around 2030. The INDC also cites establishing a nationwide emissions trading system (ETS) as a critical tool to enable China to achieve its INDC pledges (NDRC, 2015a). The ETS is planned to be launched in 2017 according to the US-China Joint Presidential Statement on Climate Change (The White House, 2015).

By 2014, China achieved a CO_2 intensity reduction of 33.8% compared to the 2005 levels (NDRC, 2015a). If China can achieve a carbon intensity reduction of about 4% per year during the period from 2015 to 2030, it will accomplish a carbon intensity reduction of approximately 65.5% from 2005 to 2030, very close to the range of its INDC CO_2 intensity reduction pledge. Therefore, in the *CapOnly* scenario I use the 4% CO_2 intensity reduction rate as a constraint to generate CO_2 cap in EPPA to simulate China's INDC starting in 2020.

5.1.3 Integrated Carbon Cap-and-Trade and Natural Gas Subsidy Policy Scenario (*Cap+Subisdy*)

The *Cap+Subsidy* scenario is designed to investigate how much subsidies are needed to meet China's natural target for natural gas development in the context of China's implementing a nationwide ETS to achieve the INDC targets. The ETS caps CO_2 emissions and generates CO_2 penalty. Fossil fuel consumption is expected to be substantially decreased with the implementation of ETS. Although natural gas has less carbon content than coal, it is still a fossil fuel and is expected to be reduced by a sizeable amount due to the CO_2 penalty. As a result, China's climate policy might be inconsistent with China's natural gas promotion policy aimed at reaching a 10% share of natural gas in the primary energy supply.

If the government intends to reduce CO_2 emissions and increase natural gas consumption at the same time, it may need to subsidize natural gas consumption. Natural gas subsidy plays an important role in promoting natural gas utilization under climate policy. In China, coal burning is the major cause of air pollution. Burning coal generates more SO_2 and particulates than natural gas. Therefore, natural gas subsidy is justified by the fact that it internalizes the air pollution externalities of coal.

In this scenario, in addition to the CO_2 cap, I implement subsidies to natural gas consumption in all sectors except for the chemical manufacturing sector. This setting is intended to be in line with the government's natural use guidelines which have restrictions on gas use for chemical production (NDRC, 2012b). In this scenario, residential sector, energy intensive sector, electricity sector, transport sector, services and other sectors are subsidized for their natural gas consumption as fuel since 2020. I set the subsidy levels on different gas users until the total natural gas supply accounting for 10% of the total energy supply in each period since 2020. The subsidy rates (relative to natural gas price) used for this scenario simulation are summarized in **Table 5.2**. I further calculate the amount of subsidies as a share of CO_2 tax revenue in each period. The results might be informative for policy makers to illustrate the amount of CO_2 tax revenue (or CO_2 permit revenue) which should be allocated to subsidize natural gas consumers and reach natural gas consumption targets. The results will be discussed in the next section.

Table 5.2 Subsidy rates on natural gas consumers

	2020	2025	2030	2035	2040	2045	2050
EINT, SERV, OTHR, TRAN	80%	82%	84%	85%	90%	92%	94%
ELEC	95%	80%	80%	80%	81%	82%	83%
HH	68%	78%	83%	87%	90%	92%	93%

In all scenarios, energy consumption in 2010 is calibrated to match the Chinese statistics released by National Bureau of Statistics (NBS, 2015). China's natural gas consumption in 2015 is calibrated to match projections which are based on the 2014 data. In both scenarios with CO_2 policy, I also implement the CO_2 cap on the rest of the world to reflect the UN agreement in Paris in December of 2015. The emission caps on the other EPPA model regions are based on the MIT Energy and Climate Outlook 2015 (Reilly et al., 2015)

5.2 Results and Discussion

5.2.1 CO_2 Emissions and Carbon Price

As shown in **Figure 5.1**, the CO_2 cap-and-trade policy can substantially reduce CO_2 emissions from the *Reference* case after 2020. This is because that policy creates a CO_2 price which reflects the marginal cost of CO_2 emission abatement. Under this policy scenario, the (explicit or implicit) CO_2 price is added to all fossil energy used as a fuel. As a result, the energy price increases and consumers need to pay more when purchasing fossil energy. This creates incentives for consumers to use less fossil fuel and switch from using fossil energy to using cleaner types of energy such as wind, solar, nuclear and hydro. Therefore, the demand for fossil energy decreases, resulting in CO_2 emissions reductions.

The stringency of the CO_2 mitigation policy in terms of carbon intensity reduction rate is the same in the *CapOnly* scenario and the *Cap+Subsidy* scenario. Therefore, the trajectories for the CO_2 emissions in both scenarios are the same as well. However, the CO_2 prices to achieve the CO_2 emissions policy targets are somewhat different. In 2030, the CO_2 price to peak CO_2 emission is about \$11.4/ tCO_2 in the *CapOnly* scenario but is \$16.6/tCO_2 in the *Cap+subsidy* scenario (see **Figure 5.1**). Natural gas subsidies encourage consumers to consume more natural gas. Though natural gas is cleaner than coal, burning of natural gas emits CO_2. Under the same CO_2 emission constraint, the increased CO_2 emission from increased use of natural gas should be offset by the decreased emissions from reduced use of other fuels such as coal which needs a higher CO_2 price.

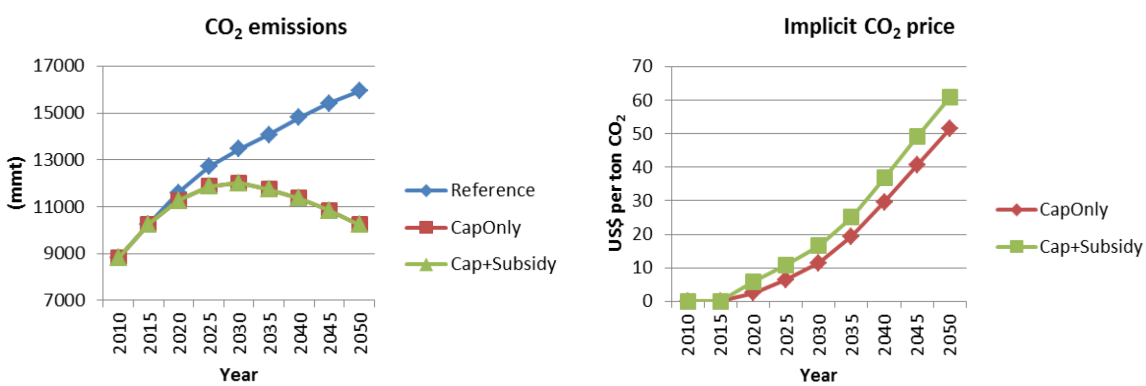


Figure 5.1 CO_2 emissions and implicit CO_2 price

5.2.2 Energy Consumption

Figure 5.2 (a), (b), (c), and (d) compares energy consumption and gas consumption in the three scenarios. As can be seen, the total energy consumption under the two policy scenarios is lower than under the *Reference* scenario. The difference in total energy consumption between the *CapOnly* scenario and the *Cap+Subsidy* scenario is not large. The energy consumption structure in the *CapOnly* scenario, however, is different from in the *Cap+Subsidy* scenario.

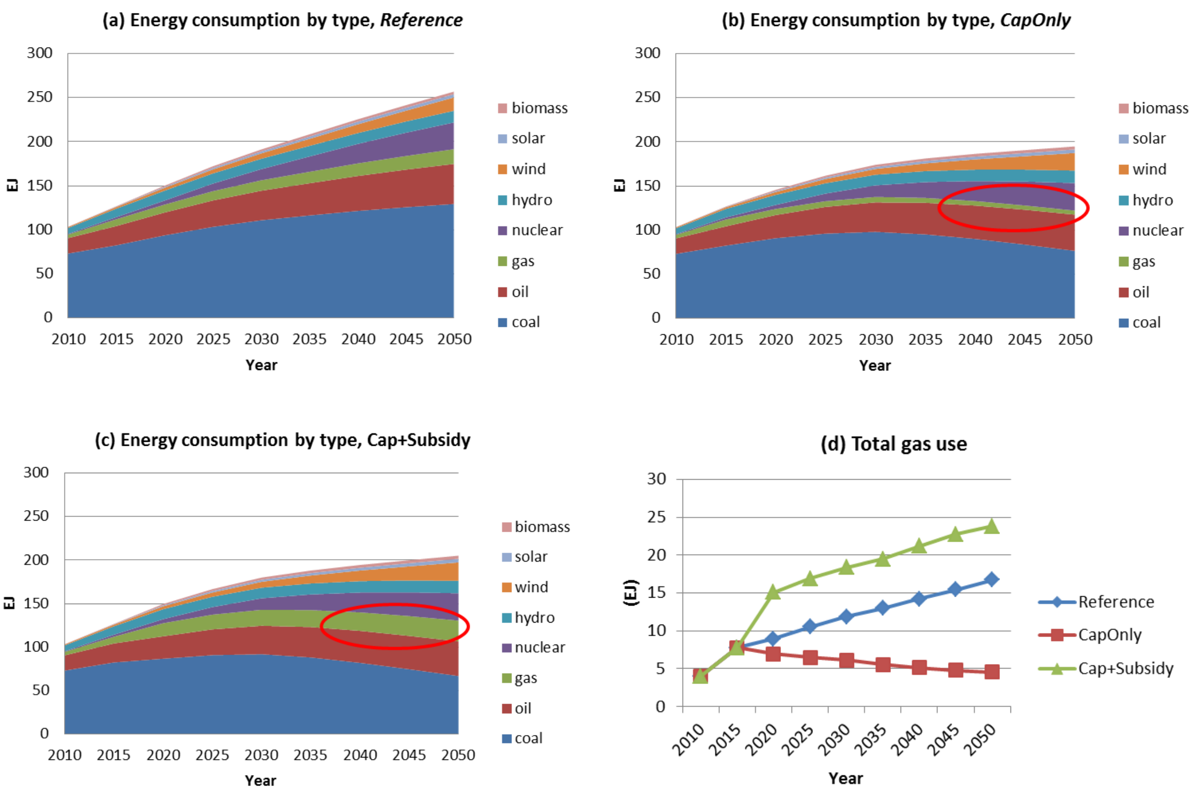


Figure 5.2 Energy consumption by fuel under different scenarios

In the *CapOnly* scenario, coal and natural gas decrease by 12% (from 110.8 EJ to 98.0 EJ) and by 48% (from 11.8 EJ to 6.1 EJ) in 2030, respectively, compared with the *Reference*. The share of natural gas in primary energy supply declines from 6.2% to 3.5%, which is much below the 10% natural gas target. Non-fossil energy in 2030 climbs from 35.0 EJ to 36.4EJ, accounting for 20.9% of the primary energy supply, which is above the 20% share target[5].

[5] INDC sets the goal to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 (NDRC, 2015a).

The *Cap+Subsidy* scenario suggests that natural gas can reach the 10% natural gas target in 2020 under substantial subsidies. The total subsidy amount accounts for 15% of CO_2 revenue in 2020. With a subsidy (the schedule of subsidy levels is provided in **Table 5.2**), natural gas consumption can climb to 18.4 EJ in 2030 in the *Cap+Subsidy* scenario, which is 55% higher than in the *Reference* scenario and is 199.7% higher than in the *CapOnly* scenario. The coal consumption in the *Cap+Subsidy* scenario is reduced by 19.0 EJ relative to the *Reference* scenario and by 6.2 EJ relative to the *CapOnly* scenario in 2030, indicating that gas subsidy plays a vital role in promoting natural gas substitution for coal. The non-fossil energy supply in the *Cap+Subsidy* scenario increases by 2.1 EJ and by 0.7 EJ compared with in the *Reference* scenario and the *CapOnly* scenario in 2030, respectively. This demonstrates that natural gas subsidy plus a higher carbon tax will result in coal consumption reduction as well as an increase of non-fossil energy supply.

5.2.3 Changes in Coal and Natural Gas Use

In the *CapOnly* scenario there is no substitution of natural gas for coal happened. The introduction of a CO_2 price could improve the competiveness of natural gas with coal due to a lower carbon content of natural gas. But the carbon price level is still not high enough to offset the big price difference between natural gas and coal. As is shown in **Figure 5.3(a)**, a CO_2 price reduces gas consumption. One sector where carbon pricing may introduce a switch from coal to natural gas is electricity. In China the natural gas combined cycle (NGCC) generation cost is more than two times of that of pulverized coal-fired electricity generation technology. Since the natural gas-fired electricity is much more expensive than coal-fired electricity, a relatively low CO_2 price would not be able to lead to the coal-to-gas switching in the power sector.

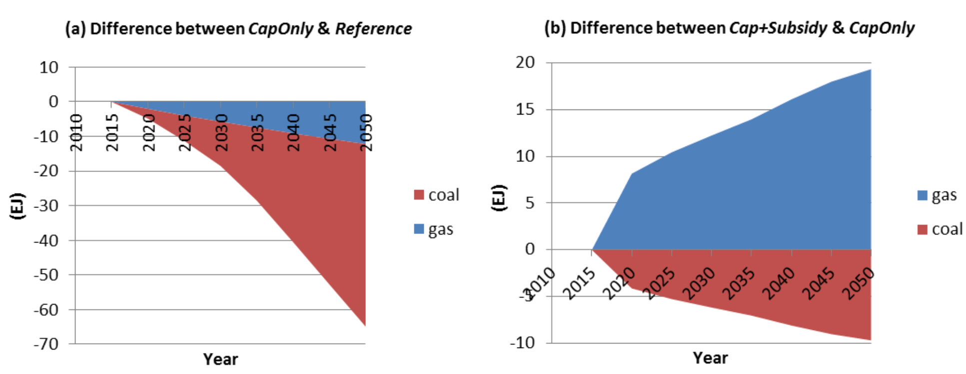


Figure 5.3 Change in coal and natural gas consumption in different scenarios (EJ)

Figure 5.3(a) shows that both coal and gas consumption will decline in the *CapOnly* scenario relative to the *Reference* scenario due to the introduction of CO_2 price. Compared with in the *CapOnly* scenario, natural gas consumption rises while coal consumption declines in the integrated policy scenario, as shown in **Figure 5.3 (b)**. Note that compared with the *CapOnly* scenario, the carbon price is higher in the integrated policy scenario. The integrated policy enhances the externalization of the environmental damages associated with coal use.

5.2.4 Natural Gas Consumption by Sector

Natural gas consumption patterns are different among the three scenarios. As represented in **Figure 5.4**, natural gas use declines substantially in the *CapOnly* scenario with the introduction of climate policy without gas subsidies. Natural gas use in the household sector reduces the most. The residential sector appears to be the most sensitive to natural gas price changes. It is also noticed that the natural gas use in chemical manufacturing sector are hardly affected by the CO_2 price. That is because the natural gas use as feedstock will emit little CO_2 and will not be heavily penalized. The change in natural gas use in electricity generation sector is relatively small because CO_2 price imposes more penalty on coal than natural gas as coal has higher carbon content.

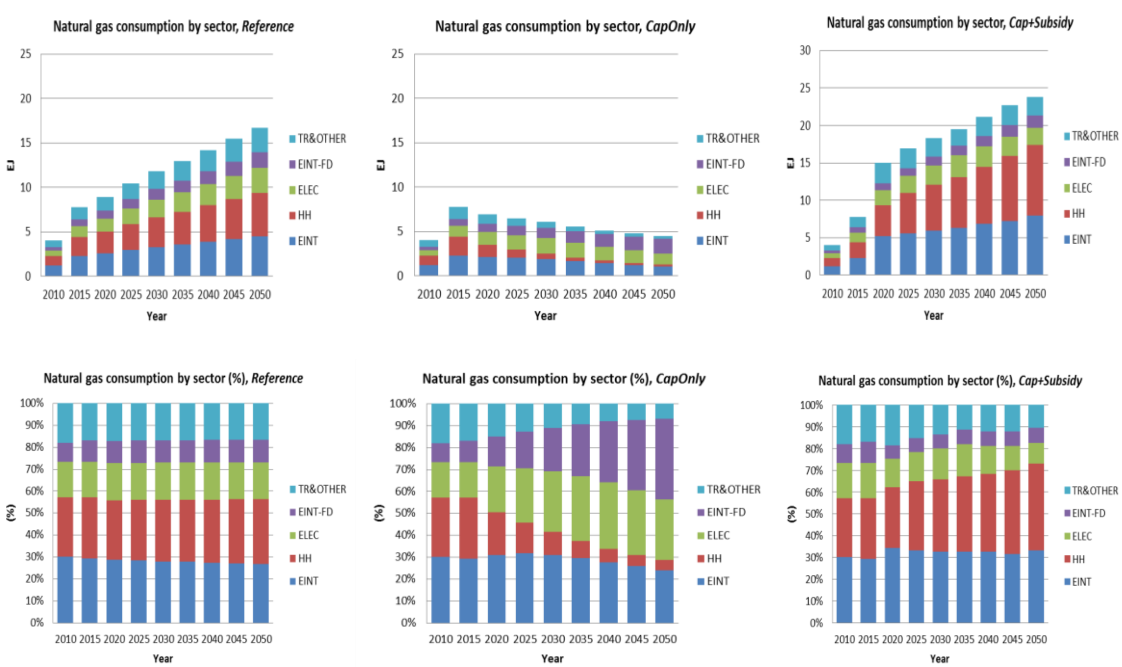


Figure 5.4 Natural gas consumption by sector in different scenarios

In the integrated policy case, the CO_2 penalty for gas users is offset by the gas subsidy, which makes natural gas more competitive than coal. As a result, the substitution of natural gas for coal happens. **Table 5.3** shows the amount of increased natural gas by sector in the integrated policy case relative to the climate policy scenario. A large amount of the increased natural gas use takes place in the residential sector and the industry sectors, but not in the power generation sector.

Table 5.3 Increase in gas consumption in *Cap+Subsidy* compared to *CapOnly*

(EJ)	2020	2025	2030	2035	2040	2045	2050
EINT, SERV, OTHR, TRAN	4.8	5.3	5.9	6.4	7.6	8.4	9.0
ELEC	0.5	0.7	0.9	1.2	1.2	1.1	1.0
HH	2.8	4.5	5.5	6.3	7.3	8.5	9.3

5.2.5 Natural Gas Supply by Source

Both imported and domestic natural gas will substantially decrease due to the reduced demand under the *CapOnly* scenario (**Figure 5.5**), because both the imported natural gas and domestic natural gas are subject to the carbon price penalty. The supply structure is also affected by the climate policy. As can be seen in **Figure 5.5**, the imported gas will decrease more in volume and its supply share than the domestic one. While some imports remain, with carbon price penalty international natural gas trading flows re-allocate from China to the destinations without (or with less stringent) carbon policies (ASI and IDZ regions of the EPPA model).

Under the integrated scenario, the gas subsidy scheme boosts both domestic and imported supply (**Figure 5.5**). The subsidy scheme lowers the price that consumers pay for gas, increasing the competitiveness of natural gas relative to coal and oil. It increases the demand for natural gas. **Figure 5.5** shows that a large part of the increased demand is met by imported gas. The subsidy scheme favors imported gas because of domestic supply capacity constraints. With a limited increase in domestic production, gas suppliers need to increase the imported volume to meet the surging demand.

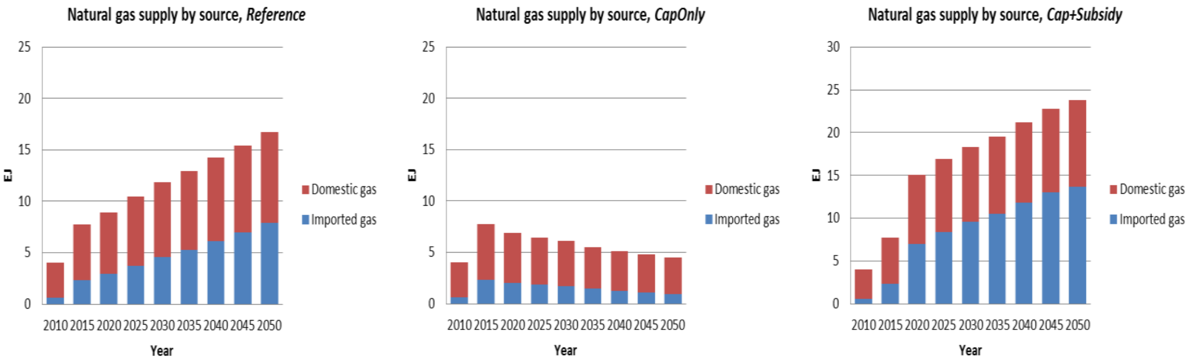
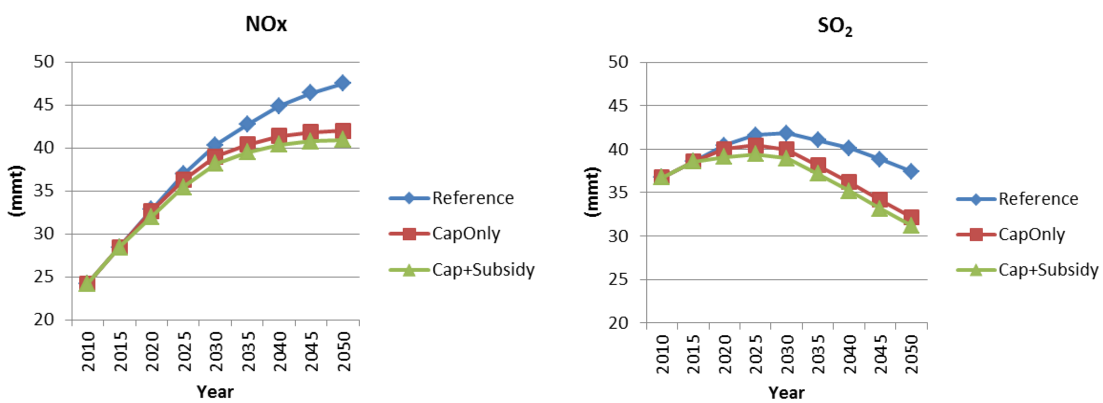


Figure 5.5 Domestic and imported natural gas as supply in different scenarios

5.2.6 NOx and SO_2 Emissions

NOx and SO_2 emission are largely attributed to burning of fossil fuels. The climate policy will cap the CO_2 emissions and fossil fuel use, thus NOx and SO_2 emissions to a large extent are also going to be reduced (**Figure 5.6**). Under the climate policy scenario, NOx emissions and SO_2 emissions will decline by 3.3% and 4.5% in 2030, respectively, compared with the *Reference* scenario. The integrated policy can result in additional reduction in air pollutant emissions: 5.4% of NOx emissions and 7.0% of SO_2 emissions in 2030, respectively. It is largely attributed to the substantial substitution of natural gas for coal which takes place in the integrated policy case. The switching from coal to gas increases natural gas use while decreases the coal use relative to the climate policy case.



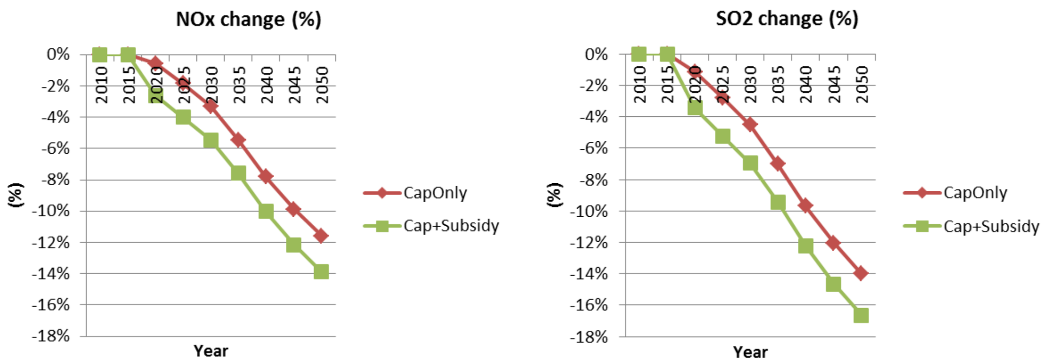


Figure 5.6 NOx and SO_2 emissions

5.2.7 Welfare

Welfare loss is a measure of climate policy cost (Paltsev and Capros, 2013). Because of additional constraints it is likely that welfare will decrease with implementing a climate policy. Introducing a carbon price brings the increases in the fossil energy prices. The fossil energy users need to pay more to purchase the same amount of fossil energy, which can possibly lead to welfare loss (**Figure 5.7**). The model simulations tell that the climate policy can bring a 0.27% welfare loss in 2030 and 0.38% welfare loss in 2050, respectively. The welfare loss is a little bit higher in the integrated policy scenario, which is 0.29% in 2030 and 0.51% in 2050, respectively. The integrated policy creates a mechanism that subsidizes relatively more expensive natural gas and reduces further the use of relatively cheaper coal. The EPPA model does not account for health benefits associated with air pollution, which can be substantial. The welfare loss numbers presented here can be reduced or compensated if the environmental benefits associated with lower air pollution are taken into account. Valuing benefits is a challenging task (Matus et al., 2012) which is beyond the scope of this study.

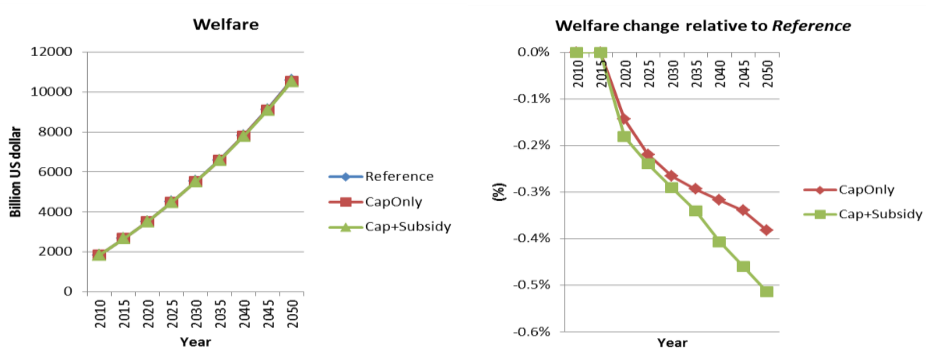


Figure 5.7 Welfare (consumption) change

5.2.8 Level of Subsidy

Based on the modeling results, the subsidy amount required to achieve the 10% natural gas goal is \$9.8 billion in 2020, \$30.8 billion in 2030, and \$140.5 billion in 2050, respectively (**Figure 5.8**). To finance such amount of subsidy, the Chinese government may need new income sources. The CO_2 tax revenue (or proceeds from the sales of CO_2 emission permits) can be used for such a new source of government revenue. In the policy scenarios, China's government earns from emission permit sales about \$67 billion in 2020, \$200 billion in 2030, and \$620 billion dollars in 2050, respectively. Therefore, the Chinese government would need to allocate 15% to 23% of its CO_2 permits revenue to subsidize natural gas consumers to achieve its natural gas promotion goal. Based on the EPPA model simulation, the total natural gas subsidy would account for approximately 0.8%, 1.4%, and 3.1% of the government's *total* tax revenue in 2020, 2030, and 2050 respectively. In 2014, the Chinese government's income totaled to 1,936.2 billion dollars (NBS, 2015) which is higher than the government expenditure in 2020 simulated from the model. Therefore, the natural gas subsidy will not become a relatively heavy burden of the government.

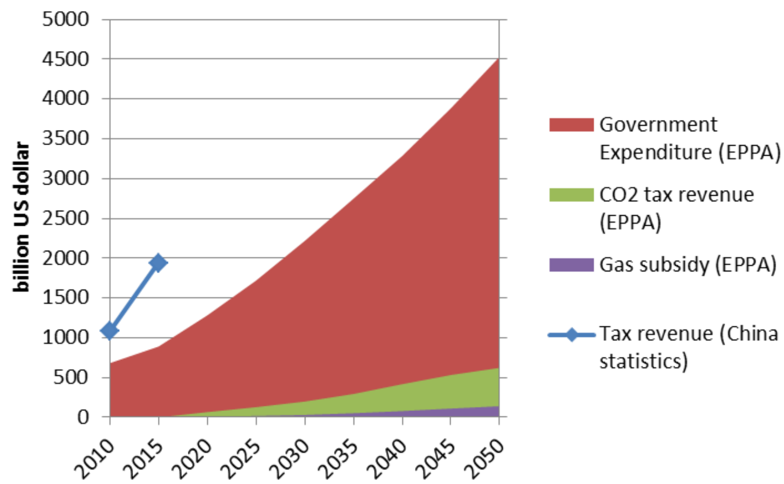


Figure 5.8 Level of subsidy

5.3 Sensitivity Analysis

In this section, I include several additional scenarios to assess the impacts of excluding residential sector from cap-and-trade policy, substitutability of fuels in final consumption, the technological innovation of Natural Gas Combined Cycle (NGCC) technology, and the pace of nuclear power development on China's natural gas use.

5.3.1 Removing Residential Sector from the Cap-and-Trade Scheme

Residential sector is the second largest natural gas user in China. Currently, the retail gas price for residential users is among the lowest. In additional to targeting an increase in the share of natural gas in primary energy consumption to 10%, the *Energy Development Strategy Action Plan (2014-2020)* also states that priorities should be given to the natural gas use in the residential sector. China also has a plan to let all urban residents to have access to natural gas by 2020. Associated with China's urbanization process, it is expected that its gas consumption in residential sector will keep growing in future.

As is mentioned in Section 5.2, the cap-and-trade policy would lead to a substantial reduction in residential gas use. I implement a sensitivity analysis to investigate to what extent the natural gas use in the residential sector will be affected by excluding the residential sector from the cap-and trade scheme. This scenario is called *CapExcludeH*. **Figure 5.9** tells that the total natural gas consumption will substantially increase relative to the climate policy scenario (*CapOnly*) if the residential sector is excluded from the cap-and-trade scheme (*CapExcludeH*), but still be lower than the integrated policy scenario (*Cap+Subsidy*) and the no policy case (*Reference*).

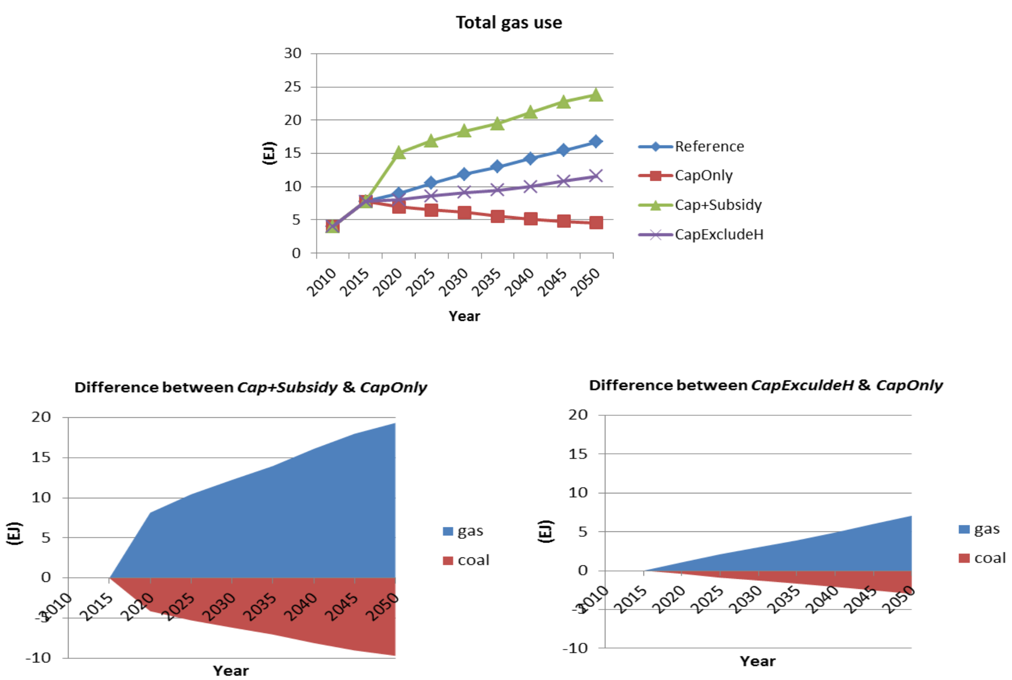


Figure 5.9 coal and gas consumption in Excluding Household scenario

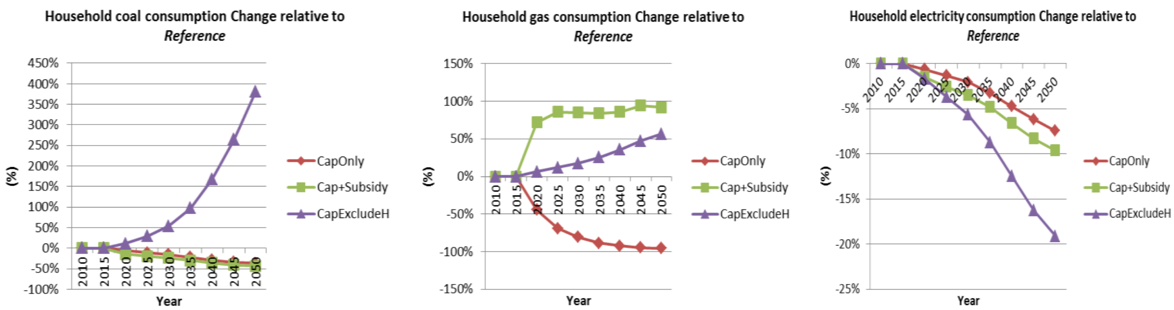


Figure 5.10 Changes in household coal, gas, and electricity consumption

Figure 5.10 presents the coal, gas, and electricity consumption in the residential sector under different policy scenarios. Without CO_2 cap, the residential sector in the *CapExcludeH* scenario consumes much more natural gas than in the climate policy scenario. The household gas use in this scenario is even larger than in the *Reference* scenario. It is interesting to see that if the residential sector is excluded from the cap-and-trade scheme, the coal consumption in the residential sector will be increased by 50% in 2030 relative to the *Reference* case while the electricity consumption in the sector will drop by more than 5%. In other words, if residential sector is excluded from the cap-and-trade scheme, the electricity use in the sector becomes less competitive, while coal becomes more competitive. This has an important policy implication. The primary objective of removing the residential sector from the cap-and-trade scheme is to increase natural gas use. But this policy can also result in the growth in coal consumption and decline in electricity consumption in the residential sector at the same time. Simple removing household sector from the emission cap leads to an increase in consumption of a relatively cheap coal.

5.3.2 Changing the Elasticity of Substitution among Coal, Natural Gas and Electricity in the Residential Sector

The elasticity of substitution between coal, natural gas and electricity can largely represent the easiness that the residential users switch among different energy types when their prices change. **Figure 5.11** presents how the consumption of coal, gas, and electricity changes in 2050 in the residential sector in the *CapExcludeH* scenario.

The substitution elasticity settings for the residential sector are changed in the EEPA model from the default value of 1.5 to 0.75 and 3.0. The results presented in **Figure 5.11** show that a higher elasticity setting will lead to a higher consumption of coal and natural gas while lowering the electricity consumption. The result shows that in the policy case of excluding the residential sector from the cap-and-trade scheme the higher substitution elasticity will make fuel switching from electricity to coal and gas easier. The city governments often take the switching from coal to electricity in households as an important measure to control air pollution and improve the living standards. In the context of excluding the residential sector from the cap-and-trade scheme, with high substitution elasticity, it would be difficult for the city governments to implement the coal-to-electricity switching policy in the residential sector. There is a need for more detailed studies that would investigate the ranges of elasticity of substitution in residential sector in China.

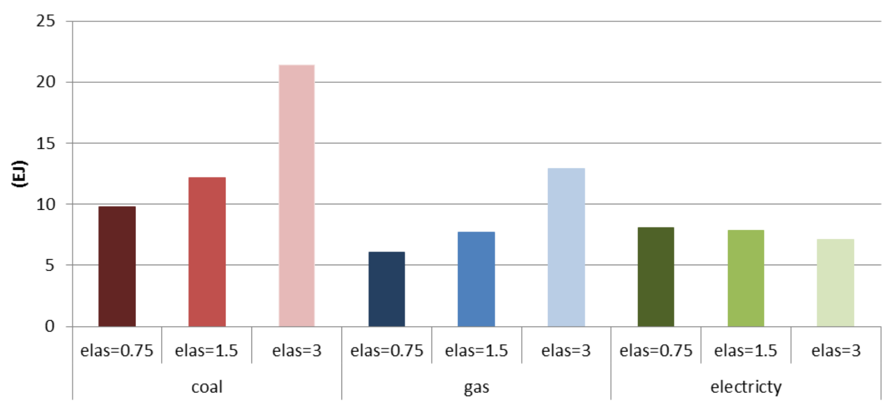


Figure 5.11 Coal, gas, and electricity consumption in household sector in 2050 with different elasticities

5.3.3 Changing the Cost of Natural Gas-based Electricity

The power sector is often regarded as a sector which has a great potential to use natural gas. The primary gas-fired power generation technology is of natural gas combined cycle (NGCC). Currently, in China NGCC is not encouraged as a base load electricity supplier but as a peaking load electricity supplier (State Council, 2013). The fuel cost accounts approximately for 70% of NGCC generation cost (Ji and Cheng, 2013) in China. As shown in **Table 4.3**, the levelized cost of NGCC technology is much higher than that of coal-fired power generation technology in China.

In the EPPA model, the "mark-up" is used to represent the relative cost of a power generation technology to that of a typical coal-fired power generation technology such as the super critical power generation technology. As shown in **Table 4.3**, the mark-up of NGCC technology is 1.95, which means that its levelized generation cost is 1.95 times that of coal-fired power plant. Such a high cost results in zero additional NGCC output in the scenarios with and without CO_2 cap (The EPPA model tracks both traditional natural gas-based power and the advanced NGCC power). The existing NGCC plants are accounted in traditional gas-based electricity category. NGCC reported here are referred to advanced natural gas power plants). With technological advancement, the NGCC cost is expected to decrease. After testing different NGCC markups, I find that if the NGCC mark-up drops to 1.15, NGCC becomes economically viable and with mark-up lower than that it expands its power generation in a substantial way.

I also prove the results for the mark-up of 1.058, which is derived from the U.S. mark-up of NGCC relative to coal generation. NGCC –based power generation is cheaper in the US than China due to the lower gas prices. The results show that with a mark-up of 1.058 NGCC will become a cost-effective technology after 2020-2025.

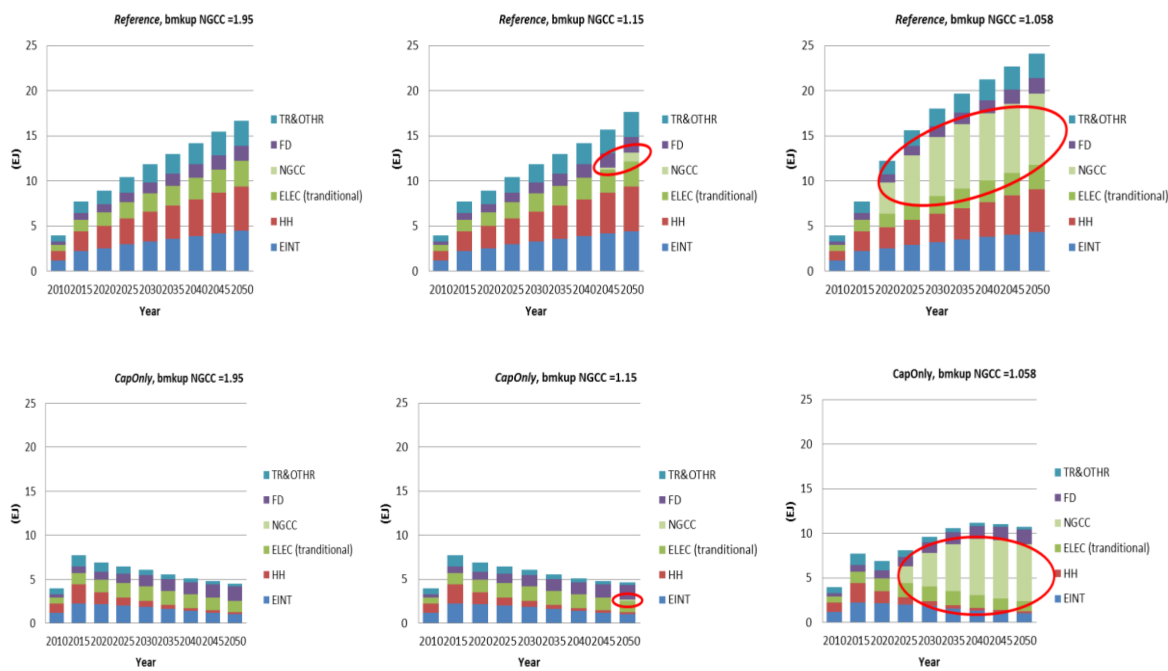


Figure 5.12 Natural gas consumption by sector in scenarios with different NGCC markups

Figure 5.12 presents how natural gas consumption changes with a reduction in NGCC generation cost. As can been seen, the power sector could become the largest natural gas consumer if the NGCC generation cost is close to that of the coal fired power plants in both the *Reference* and *CapOnly* scenarios. With a mark-up of 1.058, gas consumption in electricity sector in 2030 is 8.5 EJ in the *Reference* case and 5.4 EJ in the *CapOnly* case. In comparison, with a higher markup of 1.95, electricity sector consumes 2.0 EJ in 2030 in the *Reference* case and 1.7 EJ in 2030 in the *CapOnly* case. This implies that the reduction in NGCC generation cost could affect the natural gas consumption in this sector to a large extent.

5.3.4 Lowering a Penetration Rate for Nuclear Power Generation

The future of nuclear development largely relies on the government policy and the site resource availability in China. Based on site resource availability, China could build up to 400 to 500GW of nuclear plants by 2050 (World Nuclear Association, 2015; Wu, 2013), of which 60% are located inland and 40% are on the coast (Wu, 2013). Considering local political and security concern barriers to the inland nuclear projects, the high estimation of China's nuclear development by 2050 is about 160 GW. Based on the existing projects which are in operation and under construction, the total capacity is estimated to be 95 GW by 2050 in the low capacity scenario (Paltsev and Zhang, 2015b). I take this number as the low bound of China's nuclear capacity. The effects of different nuclear penetration rates on the natural gas use in China are summarized in **Figure 5.13**. As can be seen, with a lower nuclear penetration rate, China will need a higher CO_2 price to meet its CO_2 intensity mitigation targets. For instance, the implicit CO_2 price in 2030 in low nuclear scenario is \$15.80/tCO_2 while it is \$11.43/tCO_2 in high nuclear scenario. The higher CO_2 price will discourages natural gas use. Under a low nuclear penetration rate assumption, natural gas consumption is 5.7 EJ in 2030, which is 6% less than the gas consumption with high nuclear penetration rate assumption. This result is sensitive to the assumption about the nuclear development in the *Reference* scenario. If nuclear is built anyway, then in the policy scenario the emission reductions required by electricity sector are smaller, leading to a higher natural gas use in the policy scenario.

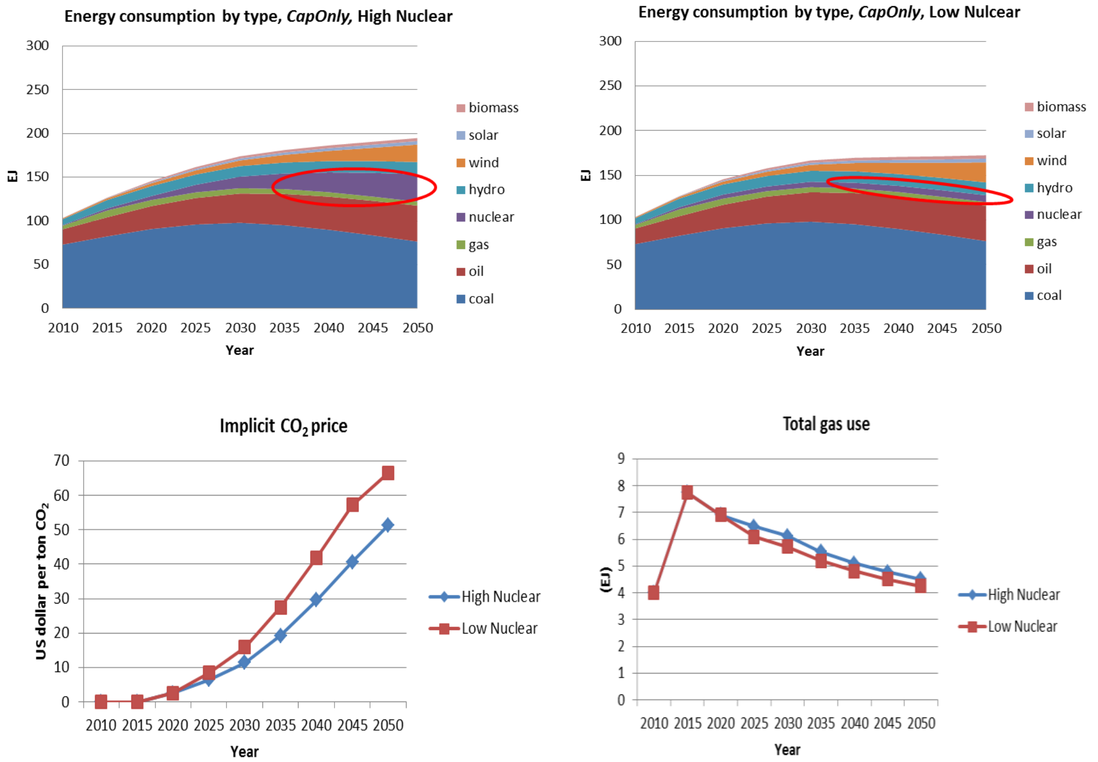


Figure 5.13 Energy consumption by type in scenarios with low and high nuclear penetration assumptions

5.4 Summary

Here I provide a summary of the simulation results presented in Chapter 5. China has pledged to reduce its CO_2 emissions by introducing a number of policy instruments including a national CO_2 emission cap-and-trade system. The modeling excise shows that the introduction of the CO_2 cap-and-trade scheme can substantially reduce natural gas consumption as it will impose penalty on all fossil fuels including natural gas. This tells that the climate policy would create substantive deviation from the natural gas promotion objective.

If China wants to achieve the two policy objectives of mitigating CO_2 emission and enhancing natural gas use simultaneously, it will need an integrated approach which coordinates both the climate policy (e.g., cap-and-trade) and the natural gas promotion policy (e.g., gas subsidy). Compared with the single climate policy, the integrated policy will lead to a rising of the CO_2 price from \$2.6 /ton to \$5.8/ton in 2020, from \$11.4 /ton to \$16.6/ton in 2030, from \$51.4/ton to \$60.8 /ton in 2050, respectively. The government would need to transfer 14.7%, 15.5%, and

22.6% of its carbon tax revenue to subsidize natural gas use in 2020, 2030, and 2050, respectively. The integrated policy can further reduce NOx emission by 2.1% and SO_2 emission by 2.5% relative to the climate policy case in 2030 while resulting in a further welfare loss of 0.02%. This welfare loss does not account for welfare improvements due to health effects from reduced air pollution.

Sensitivity analysis shows that removing the household sector from the CO_2 cap-and-trade scheme results in a larger increase in coal consumption than in natural gas consumption. A higher nuclear penetration rate, however, will contribute to an increase in natural gas use in comparison to the low nuclear scenario. Technology advancement will largely affect natural gas use. A 46% reduction in NGCC generation cost can increase natural gas consumption by 52.3% in 2030.

Chapter 6 Conclusions

Coal has accounted for more than 66% of China's primary energy consumption over the past three decades, causing significant local, reginal and global environmental pollutions. China has already become the largest CO_2 emitter and suffers from air pollutions. Natural gas is a cleaner energy source because natural gas use generates fewer pollutants than coal. Natural gas currently accounts for approximately 6% of China's primary energy supply. According to China's national energy strategy action plan, the share of natural gas in primary energy supply should reach 10% by 2020. Natural gas use is widely encouraged in Chinese cities as an important option to address the deteriorated air pollution and improve the household living standards. Enhancing natural gas use is an important policy objective of China.

Natural gas use is largely determined by the pricing mechanisms and public policy. Natural gas prices in China have long been determined by NDRC with less flexibility, predictability, and transparency. The highly regulated natural gas pricing resulted in supply shortages. To address the gas supply issue, NDRC launched nationwide gas pricing reform in early 2010s that link natural gas price to oil prices. The pricing reform leads to a better predictability and transparency. The reform also increases natural gas price that incentivizes gas suppliers to produce and import more gas. However, there are also some limitations of the reform. First, it creates biased incentives that favor suppliers. Second, natural gas and oil have different supply and demand patterns and linking natural gas price to oil price may create price distortions. The results from oil-linked pricing simulation show that the oil-linked price will be increasingly higher than the completely market-determined price after 2020, resulting in a natural gas consumption reduction by 3.5% in 2030 and 9.2% in 2050. The Chinese government should investigate the pathways for moving to a completely market-based natural gas pricing system to achieve the natural gas use target. It will establish a better resource allocation system and improve the welfare of China.

China has pledged to mitigate its CO_2 emissions by introducing a number of policy instruments including a national CO_2 emission cap-and-trade system. The analysis demonstrates that the introduction of the CO_2 cap-and-trade scheme can be used to achieve China's INDC, but it can substantially reduce natural gas consumption as it will impose penalty on all fossil fuels including natural gas.

Natural gas is promoted largely because it is cleaner than coal. The substitution of natural gas for coal has been treated as an important option to reduce local and regional air pollutions, and also as a way to improve living standards in China. As the price of natural gas is higher relative to that of coal, the switching from coal to gas may need a subsidy in addition to carbon price. Given the size of China's primary energy consumption, the amount of the subsidy needed to achieve a 10% of natural gas contribution is substantial ($9.8 billion in 2020). Such a large subsidy scheme may not viable unless the government has a new revenue source which will enable it to implement the subsidy scheme. In this regard, an integrated policy scheme is proposed and simulated in this thesis. Under the integrated policy scheme a part of the carbon revenue is used to subsidize natural gas use. The simulation excise shows that both the climate objective and the natural gas promotion objective can be achieved with the integrated policy.

According to the analysis, the integrated policy reduces the relative price of natural gas use on one hand and increase the cost of coal use on the other hand, promoting the substitution of natural gas for coal while meeting the climate policy objective. There is a modest welfare loss associated with the integrated policy compared to the only cap-and-trade policy case. While the integrated policy brings an additional 0.02% of welfare loss in 2030 relative to the cap-and-trade policy case, it leads to a further reduction in NOx emissions by 2.1% and SO_2 emissions by 2.5% relative to the cap-and-trade policy case in 2030. To study if the gains in environmental quality associated with the integrated policy can offset the welfare loss further research is needed. Further research calls for a broader integrated assessment framework which consists of the atmospheric chemistry model and the energy and economic model with health effects. My analysis shows that natural gas promotion goals and emission reduction goals are achievable with policy that integrates both of these targets. Policy makers should be aware of the challenges in meeting the stated objectives and inter-linkages of the actions towards the energy sector. An economy-wide modelling used in my study is a useful tool to support a solid decision making.

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