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The future of natural gas consumption in Beijing, Guangdong and Shanghai: An assessment utilizing MARKAL

BinBin Jiang [a,*], Chen Wenying [b], Yu Yuefeng [c], Zeng Lemin [d], David Victor [e]

[a] Program on Energy and Sustainable Development, Stanford University, CA 94503, USA
[b] Energy, Environment, Economy Institute, Tsinghua University, Beijing 100084, PR China
[c] Department of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, PR China
[d] Guangdong Techno-economic Research and Development Center, Guangzhou 510070, PR China
[e] Program on Energy and Sustainable Development, Stanford University, CA 94305, USA

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ABSTRACT

Natural gas could possibly become a si0gnificant portion of the future fuel mix in China. However, there is still great uncertainty surrounding the size of this potential market and therefore its impact on the global gas trade. In order to identify some of the important factors that might drive natural gas consumption in key demand areas in China, we focus on three regions: Beijing, Guangdong, and Shanghai. Using the economic optimization model MARKAL, we initially assume that the drivers are government mandates of emissions standards, reform of the Chinese financial structure, the price and available supply of natural gas, and the rate of penetration of advanced power generating and end-use. The results from the model show that the level of natural gas consumption is most sensitive to policy scenarios, which strictly limit SO_2 emissions from power plants. The model also revealed that the low cost of capital for power plants in China boosts the economic viability of capital-intensive coal-fired plants. This suggests that reform within the financial sector could be a lever for encouraging increased natural gas use.

1. Introduction

The world's natural gas market is rapidly globalizing. Traditionally, gas supplies have been delivered entirely within regional markets—usually with little geographical distance between the source of gas and its ultimate combustion. However, a significant and growing fraction of world gas is traded longer distances via pipeline and LNG. China is an emerging market for this gas, but its size and potential remains highly uncertain. Today, China's share of the global gas market is tiny, with a natural gas market that is smaller than California's (CEIC Database, 2007), but the future demand for natural gas in China is potentially enormous. With an average Gross Domestic Product (GDP) growth of 9.6% for the last 20 years (China National Bureau of Statistics Database, 2006) and no signs of slowing down, China's demand for energy commodities—coal and oil, notably—has also been expanding rapidly. With this burgeoning demand, along with appropriate policies, natural gas use could grow rapidly (Fig. 1).

The purpose of this study is to better understand the drivers of increased natural gas consumption for the energy systems of three major demand regions of China: Beijing, Shanghai and Guangdong. Analyzing the drivers of gas demand in China is crucially important for three reasons. First, understanding the increasingly global gas market requires assessment of the demand for natural gas in major emerging markets, such as China and India. Second, increased natural gas demand in China will have repercussions for global geopolitics as the state-owned China National Petroleum Company (CNPC) will be under increased pressure to seek out new supplies in politically sensitive regions. Third, fuel displacement of coal by less carbon-intensive natural gas could be a practical option for the government as it strives towards lowering carbon dioxide emissions. This issue has become increasingly pressing for China since it has emerged as top emitter of greenhouse gases for 2007 (Auffhammer and Carson, 2008).

As a starting point for this study, we assumed that the following were some of the major factors that are likely to affect future demand for natural gas:

- Rate at which more efficient end-use technology is made available;
- Stringency of local and regional environmental constraints;
- Financial reforms that affect the cost of capital for different sectors of the economy (i.e., power, industry, residential, commercial, transportation);
- Pricing and availability of gas.

* Corresponding author.
E-mail address: binji@stanford.edu (B. Jiang).

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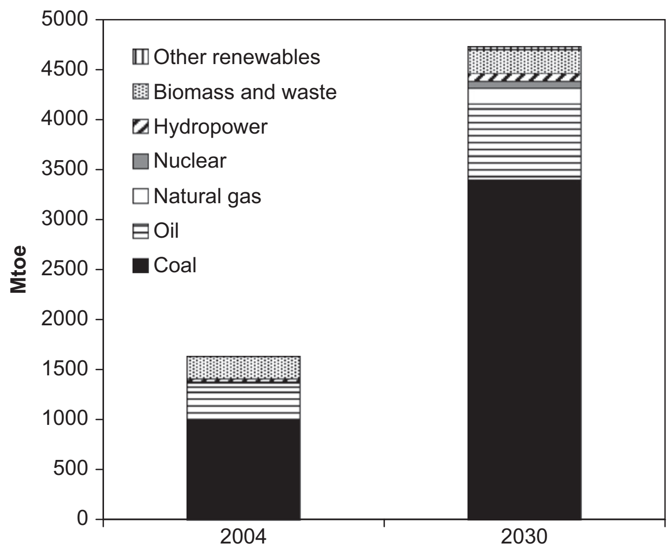

Fig. 1. Primary energy consumption in China for 2005 and 2030. (*Source*: BP Statistics Review 2006, IEA WEO 2007).

The findings of the report show that natural gas consumption (apart from polices that directly influence the price of natural gas relative to other fuels) is very sensitive to the implementation of government mandates that limit the amount of SO_2 that is allowed to be emitted. At the same time, we found that financial reforms may play an important role in determining what types of fuel gets consumed. We also find that a side benefit to SO_2 emissions reduction policies is a corresponding decline in CO_2 emissions on the order of 60 million tons CO_2 for some locales (equivalent to about a quarter of the entire stock of Clean Development Mechanism projects in China) (UNEP Riso Centre). This suggests that a leverage point for governments in developing countries like China to start addressing global concerns about climate change is through regulation of local pollutants that yield visible and immediate benefits while also fortuitously limiting growth of CO_2.

2. Background

To provide a context in which the models are operating, the subsections below will explain the natural gas supply and demand conditions in the country as a whole, and for each of the three regions that the study targets.

2.1. Demand

The major off-takers of natural gas in China are the chemical and fertilizer, industrial, power generation, and residential sectors (Fig. 2). IEA predicts that the power sector's share of the overall demand is increasing, consuming 39% of the gas in 2020 compared with 11% in 1997. Residential consumption is also estimated to increase to 25% of total gas off-take in 2020 from 11% in 1997. The consumption of gas by the chemicals and fertilizer sector is predicted to fall from 43% to 16%. Although these numbers describe the national market, regional demand can look quite different. Most noticeably, the chemical/fertilizer natural gas demand is non-existent for the fairly urbanized areas in and around Beijing, Guangdong, and Shanghai.

2.1.1. Beijing

In Beijing, end-use consumption of gas is dominated by space heating (60%), residential use (22%), commercial use (14%), industry (3%), and automobiles (1%) (Chen, 2007). Because space heating is such a large component of the consumption needs, one of the challenges for the system is how to accommodate the seasonality of the demand and how to deal with the extra supply in the summer. However, because Beijing is particularly motivated to rid the air of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and total suspended particulate matter (TSP) before the 2008 Olympics, the government is likely to support policies that encourage the use of natural gas. The Beijing government has forecasted optimistic future natural gas consumption levels (12% of end-use energy mix by 2020; the current level is 7%) (Chen, 2007).

2.1.2. Guangdong

Guangdong's situation is especially affected by the scarcity of local coal resources. This province is thus poised to become the biggest natural gas demand center in China. It faces high costs and unreliability associated with the transportation of coal from remote areas. Consequently, Guangdong is often the first among the provinces to explore alternative energy supply options. China's first LNG terminal, Guangdong Dapeng, was completed in 2006. Guangdong has also initiated several nuclear power plant projects. The major consumers of natural gas in this region include peaking power plants that would otherwise be run by expensive diesel generators (Zeng et al., 2007) (Table 1).

Industrial and residential/commercial demand is also projected to increase. The high level of development and income in the region means that its residents and officials have the financial and infrastructural capacity to put a premium on environmental protection. Natural gas is a more attractive fuel option for this region than in other parts of China due to these factors.

2.1.3. Shanghai

About 32% of the natural gas demand in Shanghai comes from six energy-intensive industries (Yu et al., 2007).[1] Industry is therefore poised to be the largest user of natural gas in this region, although some construction of natural gas-fired power plants is under way. Shanghai experienced a rapid increase in residential and commercial natural gas consumption in recent years due to the fact that much of the infrastructure that is needed to bring gas to each household was already in place. (The network of pipes originally enabled the distribution of synthetic gas, also known as town gas, produced by burning coal.) Shanghai also has one of the most comprehensive policies in support of natural gas market development in China. For example, the municipal government was the first in the country to subsidize the cost of natural gas conversion. Simultaneously, fees for SO_2 emissions have tripled from 0.20 to 0.60 RMB/kg in 2005 (Yu et al., 2007). However, with its cheaper fuel prices and entrenched infrastructure, coal remains dominant in the energy sector.

2.2. Supply

Most of the onshore gas supplies are controlled by PetroChina, a listed subsidiary of China National Petroleum Company (CNPC), China's largest state-owned enterprise (The offshore supplies are controlled by the China National Offshore Oil Company, CNOOC—another state-owned company.) Most of the gas that is being utilized in China today comes from the domestic gas fields controlled by one of these companies. Production levels in existing fields are declining, however, while the discovery of

[1] Figure calculated from data from Yu Yuefeng, Zhang Shurong, and Hu Jianyi using the total natural gas demand, percentage of natural gas in total gas use (including town and other gas types), and the total gas consumed in industry.

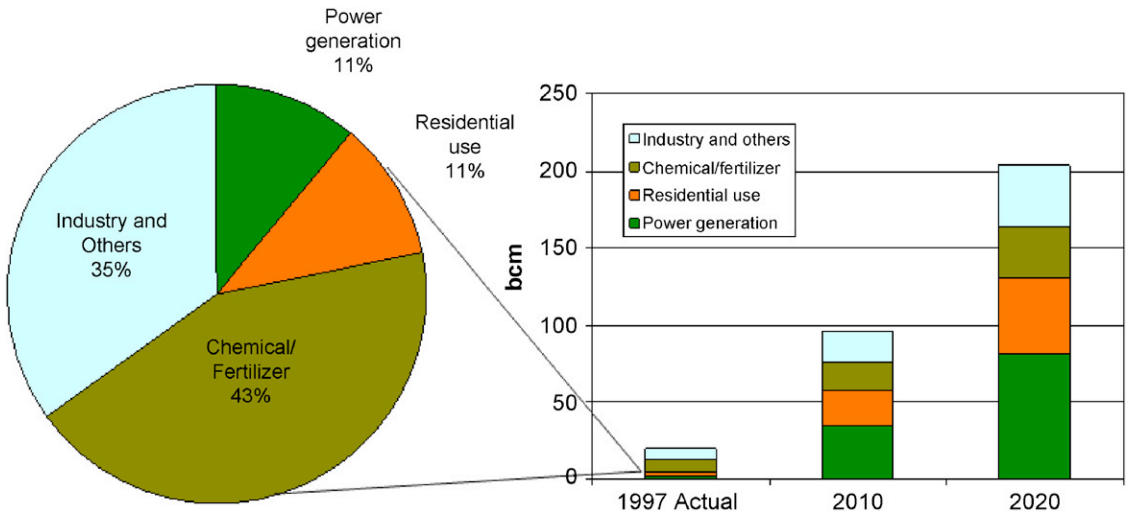

Fig. 2. National natural gas consumption in China by sector. (*Source*: IEA, "World Energy Outlook." 2006).

Table 1
Natural gas demand in three regions

Region	Dominant uses in status quo	Current natural gas demand (bcm)	Availability of competing fuel alternatives	Existing gas infrastructure
Beijing	Space heating; residential and commercial use	2.4	High (coal)	West–East Pipeline (WEP)
Guangdong	Power generation; residential/commercial use; industrial processes	3.5	Low	LNG terminal
Shanghai	Power generation; co-generation, transition from city gas for residential/commercial uses	4.3	High (coal)	West–East Pipeline (WEP); existing residential city gas pipe system

Source: Chen (2007), Yu et al. (2007), and Zeng et al. (2007).

new fields is slowing down and may not be able to keep up with the pace of demand growth. China has already started to look abroad for additional supply.

Imported liquefied natural gas (LNG) is another source of natural gas that China has tapped into and is planning to rely more upon in the future. Only the Dapeng Shenzhen LNG terminal in Guangdong is operational currently; two more in Shanghai and Fujian have been approved by the government and are likely to go forward. There is no foreseeable barrier to the construction of the other LNG terminals if demand continues to grow, although the growth in demand is slower than predicted originally (Petroleum Economist, 2007).

A third source of natural gas is international pipelines from Turkmenistan, Russia and Kazakhstan. Of these, the pipeline to connect Turkmenistan and Xinjiang seems to be the most promising option. Although talks have recently stagnated on the question of gas prices, groundwork is currently being laid down for pipeline construction. The Kazakh and Russian supplies appear less likely to be realized at the moment. Supplies from Russia's Kovykta gas field are a perennial source of interest yet also perennially stalled due to lack of strategy and commitment from Russia's Gazprom.

The graphs in Fig. 3 show all existing and potential natural gas supplies. The top graph indicates the specific names and locations of these sources. In the bottom graph, the existing sources are shown in the darkest gray, the likely but not yet delivered supplies in the lighter gray, and the most tenuous supplies are on top in the lightest color, and hatched. This graph also indicates countrywide demand estimates from various official Chinese agencies and western sources overlaid on top of the supplies. The Chinese sources, in general, have a more optimistic outlook on future natural gas use, while western sources show lower projections.[2] There is a difference of about 100 billion cubic meters (bcm) between the highest and lowest estimates for gas demand (more than nine times the capacity of the West–East Pipeline (WEP)). Despite this sizeable variation in future projections, the lowest estimate still requires China to look outside of its domestic resources for natural gas immediately. This means that regardless of which projection the government decides is most plausible, China remains a supply-constrained gas market that will continue to rely upon international supplies of pipeline gas and imported LNG.

3. Methodology

In analyzing the energy systems of Beijing, Guangdong, and Shanghai, we used three separate, regional MARKAL models. This regional model reflects that natural gas sourcing and the downstream natural gas market vary greatly by region due to climatic and geographical barriers that was detailed in Section 2.

Given a projected level of total energy demand services, each MARKAL model solves for a least cost optimal solution (Noble et al., 2005) over the course of 20 years (2000–2020), utilizing a menu of technologies that is provided as an input for the models.

[2] Our region-based study does not produce national demand projections for comparison, but it is broadly consistent with the range of estimates shown if one assumes that Beijing, Guangdong, and Shanghai together maintain a roughly constant share of national consumption.

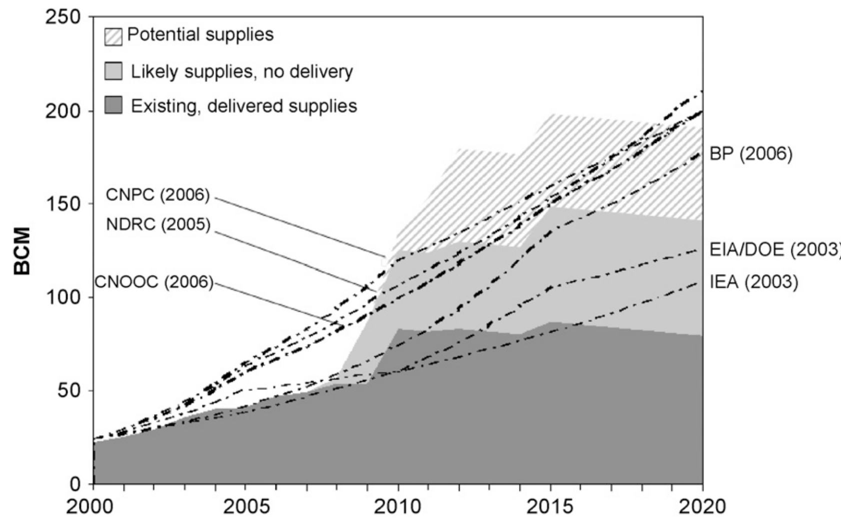

Fig. 3. Potential natural gas supplies and national demand projections. (*Source*: PESD estimates 2007, CNPC/Sinopec/CNOOC company reports 2007, ERI, IEA 2004 Chinese agencies: NDRC, China Energy Development Report 2003, CNPC, CNOOC Western sources: BP, EIA/DOE 2003, AIE/WEO 2002).

The specific types of energy and emissions control technology are characterized by performance and cost parameters. The model solves by selecting a combination of technologies that minimizes the total system cost and meets the estimated energy demand. Our goal is not necessarily to produce a firm prediction of future gas use, since key input assumptions, such as the level of demand services, are highly uncertain. Rather, such models are particularly well suited to reveal how sensitive natural gas demand is to key factors. In addition, because the models allow the system to meet energy demand in the most cost-effective manner, the results of the study can also help illuminate financially viable options for constraining emissions.

The pivotal policy driver for each of the regional model scenarios is the implementation of sulfur dioxide (SO_2) constraints upon the energy system. We do this for two reasons. One, SO_2 is the pollutant with which most local governments are most concerned. Its effects, unlike CO_2, are proximate and visible, and directly affect the health of their constituents. Second, data for SO_2 is the most complete and accurate of all the pollutants that are monitored in China (compared with data for NO_x, PM_{10}, $PM_{2.5}$, CO_2). Obviously, the accuracy and completeness of this data is essential in order to ensure the robustness of the model output. The quality of data cannot be guaranteed for other pollutants due to the lack of attention they have historically received from the Chinese government (Fig. 4).

To examine the influence of SO_2 constraints, we developed three "core" scenarios. In the base case reference scenario (R), we assume no changes are made to the status quo. The model operates on a least cost optimization paradigm so that it solves for the most economically favorable solution. In this situation, we expect coal to out-compete gas in all sectors due to the lower fuel cost. Some emissions control programs are already in place on the national and regional levels; the reference case scenario only includes policies that are currently implemented, as well as highly likely extensions of those policies. From this starting point, there are two main scenario developments.

Scenario "P" is the case in which the output SO_2 emissions are reduced by 40% from the reference case and is defined as the "plausible" scenario. This scenario tests the system response if SO_2 emissions are capped at a level 40% below what is currently expected in the status quo. Scenario "Ag" is the case in which SO_2 emissions are reduced by 75% from the baseline. This is defined as the "aggressive" scenario and is less likely to represent the future

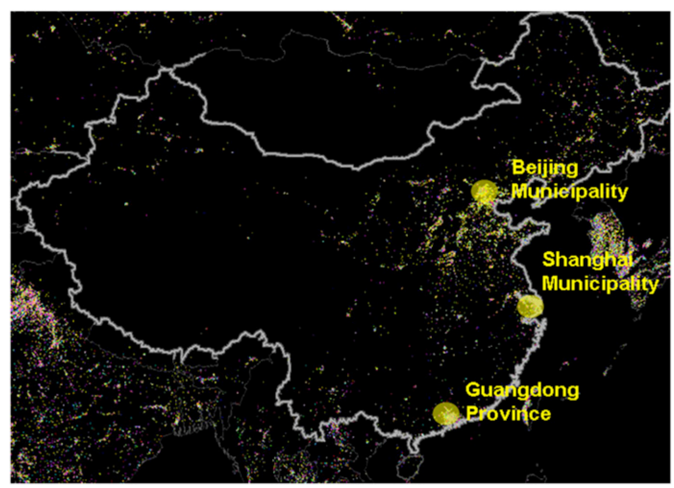

Fig. 4. Research locations. (*Source*: NASA photo-Earth from space-modified by PESD).

than scenario "P", but is not entirely out of the question. Having defined the core SO_2 scenarios, we then developed the "MoreGas" scenarios ("M"). The goal of these extensions is to find out how the system would react to sensitivity parameters with a plausible SO_2 constraint and more gas supply available to the region (such as might be available from a successful effort to develop international pipelines and price gas favorably). With the "MoreGas" scenarios, it is possible to determine the relative effects of gas availability and pricing as compared with the other drivers in the model. The levels of 40% and 75% were set after extensive discussions with energy experts in each of the regions as reasonable targets. Forty percent is seen as a practical goal that local governments are able to achieve, while 75% provides a high standard that is very optimistic and not likely to be reached without drastic policy changes.

Within each of the core scenarios, we also wanted to find out how gas demand would vary with two other factors. First, we changed the rate at which efficient, advanced end-use technology is allowed to enter the market (the "Fast" scenarios). Our assumption is that the type and efficiency of the technology used in each of the regions will have an effect on the amount and type of fuel consumed. This scenario allows us to test how the system

Table 2
Summary of scenarios in this study

Primary runs	Primary assumptions	Secondary runs	Secondary assumptions
Reference ("R")	Status quo emissions control		1.5% annual market share growth of new demand technology 10% discount rate for all sectors No gas supply from Russia (LNG availability unconstrained)
Plausible ("P" scenarios)	40% SO_2 reduction	P: Reference secondary assumptions	Same as reference
		P_Fast: faster penetration of demand technologies	3%, 5% annual market share growth of new demand technology
		P_Diffcost: different costs of capital	5.8% for power sector 10% for industrial 25% for residential and commercial
		P_Moregas: high availability of cheap gas	Gas supply from Russia available (LNG availability unconstrained)
Aggressive ("Ag" scenarios)	75% SO_2 reduction	Ag: Reference secondary assumptions	Same as reference
		Ag_Fast: Faster penetration of demand technologies	3%, 5% annual market share growth of new demand technology
		Ag_Diffcost: different costs of capital	5.8% for power sector 10% for industrial 25% for residential and commercial
		Ag_Moregas: high availability of cheap gas	Gas supply from Russia available (LNG availability unconstrained)
Plausible w/ more gas availability ("C" scenarios)	40% SO_2 reduction+Moregas	M_Fast: Faster penetration of demand technologies	3%, 5% annual market share growth of new demand technology+gas supply from Russia available (LNG availability unconstrained)
		M_Diffcost: Different costs of capital	5.8% for power sector 10% for industrial 25% for residential and commercial+gas supply from Russia available (LNG availability unconstrained)
		M_Exp: More expensive oil and gas	Gas supply from Russia available (LNG availability unconstrained) at a more expensive price

responds to not only policy changes, such as stricter emissions standard, but also to changes in the development of power plant and end-user technology. Second, we wanted to find out if specifying different costs of capital for each of the sectors would make an impact in consumption patterns (the "Diffcost" scenarios). No other study using MARKAL has analyzed the effect financial policies may have on the energy sector in China. We think that this is a viable hypothesis given the unique relationship that the state banking sector has with the power sector in this country. We also combined the factors with each other in ways shown in Table 2.

In all, we looked at 12 scenarios. These scenarios allow us to explore four broad hypotheses:

A. Policies which constrain total SO_2 emissions from the entire system lead to increased natural gas consumption.
B. The rate of technological diffusion significantly influences the amount of natural gas consumed within the system.
C. Varying the cost of capital for different sectors has an effect on energy consumption patterns.
D. Gas prices and the availability of gas are important factors in determining which sector consumes what volume of natural gas.

Below, we organize the results of the study according to the four hypotheses.

4. Results

4.1. Constraints on SO_2 emissions

Fig. 5 shows projections of natural gas consumption for the reference (R), plausible (P, 40% reduction in emissions), and aggressive (Ag, 75% reduction) scenarios from 2000 to 2020 in all three areas. The estimates for consumption vary widely depending on which SO_2 constraint is implemented in the system. From 2000 to 2020 in the reference base case, natural gas consumption increases by about six times in Beijing and 50 times in Shanghai. Guangdong goes from zero gas consumption to around 5 bcm. The natural gas consumed in 2020 in the aggressive scenario for all three regions is close to 50 bcm greater than the amount consumed in the reference scenario. These results suggest that a tighter SO_2 constraint leads to more gas demand. While these results shed some light on the sensitivity of the model to SO_2 policies, a deeper understanding of the system comes from looking at the projections within each of the three city regions.

Elsewhere we have detailed how our projections compare to official provincial targets[3]; in most cases, we found that provincial government targets were reasonably close to our model projections. Beijing targets appeared slightly optimistic, with a projection of about 1 bcm higher than the most aggressive model projections in 2020. In both Guangdong and Shanghai, the government projections are within the bounds of our highest and lowest scenarios. This shows that official provincial targets appear to be feasible goals for the most part if sufficient efforts are made to encourage gas use.

4.1.1. Beijing

The natural gas fields near Beijing were developed before supplies were made available to Shanghai and Guangdong. The result was that Beijing residents had connections to natural gas supplies before either of the other two regions. However, the

[3] Figs. 5–7 (pp. 20–21) in Jiang et al. (2007) "The future of natural gas vs. coal consumption in Beijing, Guangdong, and Shanghai: An assessment in MARKAL" (2007) Program on Energy and Sustainable Energy, Stanford University, Working Paper no. 62, http://pesd.stanford.edu/publications/china_gas_markal/.

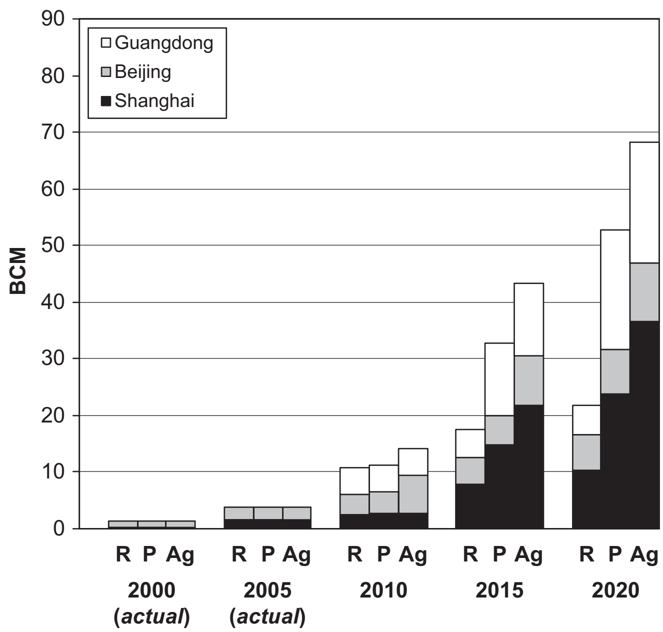

Fig. 5. Natural gas consumption for all study areas: comparison of results for reference and SO_2 constrained scenarios.

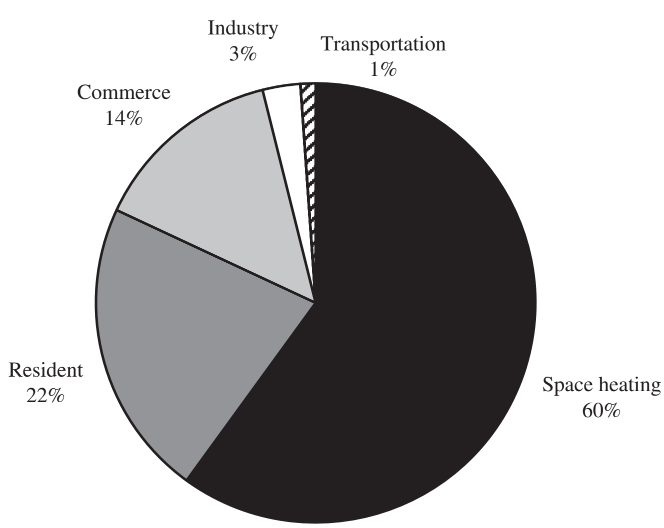

Fig. 6. Beijing natural gas demand in 2003. (*Source*: Beijing Statistic Bureau, 2004).

model results suggest that Beijing will consume less gas in 2020 than the other two regions for all scenarios. What stands in the way of rapid development of the natural gas? First, natural gas demand is highly seasonal. Fig. 6 shows that 60% of the consumption (in 2003) comes from space heating, which is not required during the summer. Expensive infrastructure to deliver gas continuously is especially costly to operate when it is under-utilized for significant periods of time during the year. The Shanghai government has engaged with this problem by encouraging the use of natural gas air conditioners to sustain the level of natural gas consumption during the summer when heating demand does not exist, but no such measures have been implemented in Beijing.

Second, reductions in pollutants thus far have been accomplished largely by closing down coal-fired power plants and installing generators in neighboring cities. Electrostatic precipitation (ESP) and flue gas desulfurization (FGD) have also been installed in coal-fired power plants to reduce pollutants. Further reductions in SO_2 emissions are achievable through expanding the options of desulfurization and importing electricity from outside regions before a switch from coal to natural gas becomes the more economic option. It is for this reason that there is very little difference in gas consumption between the reference scenario and the plausible scenario in Beijing (Fig. 7).

Starting in 2010, natural gas-fired power plants account for all of the additional gas consumed in scenario "P" compared with the reference case scenario, with demand 24% higher than the levels consumed for the reference case scenario by 2020. This tells us that when the system is forced to reduce its SO_2 emissions by 40%, the most cost-efficient sector in which to implement fuel switching in Beijing is the power sector. Specifically, the increased gas use comes from the Taiyanggong electric and thermal plant. As discussed above, the relative increase of gas use for this scenario is minor compared with other scenarios because the main strategy for reducing emissions by 40% is to clean existing fuel systems. The system does start to change more drastically when the SO_2 constraint becomes tighter and cheap desulfurization opportunities are exhausted. In scenario "Ag", the gas consumption in the industrial and residential sectors increases along with demand in the power sector. In addition to Taiyuangong, a combined cycle natural gas plant comes online, and more gas is consumed in existing gas power plants that were already operating in the plausible scenario ("P"). For 2010 and 2015, the power plants are still the main source of fuel switching in Beijing. In 2020, industrial coal and oil boilers, used primarily for process heat, are replaced by natural gas boilers.

Although there is pressure for the government to reduce pollutants such as SO_2 and NO_x and to increase energy efficiency for the upcoming 2008 Olympics in Beijing, there are no explicit policies to promote natural gas use. The exception is a partial government subsidization of the Beijing Gas Supply Group, the organization that is responsible for supplying natural gas to the area. Nevertheless, the Beijing government is still optimistic about the future of natural gas use, assuming that natural gas will account for 12% in end-use consumption by 2020, according to the Olympic Energy Action Plan and the Beijing City Master Plan 2004–2020.

For comparison, our "R" and "P" scenarios yielded 8% and 9% gas penetration, respectively. The "Ag" scenario, which reduces SO_2 by 16% from the baseline, is the most extreme case and goes far beyond pollution control measures the government has already put in place in preparation for the Olympic Games. The implication of these results is that while the goal set by the government is not impossible to achieve, such an outcome will not be realized without much tighter environmental policies that are well enforced along with specific policies to promote gas.

4.1.2. Guangdong

Guangdong is the southernmost of the three regions, where, in contrast to Beijing, space heating is rarely needed. Its economic growth is the most rapid in China, and it emits more pollutants than any other region. Guangdong, unlike Beijing and Shanghai, does not have easy access to coal. There are no indigenous sources, so all coal must be imported from other regions of China or from abroad, resulting in high prices. This presents a special opportunity for the use of natural gas. However, Guangdong also is currently not able to intercept piped natural gas from the WEP due to geographic constraints. Guangdong therefore relies on LNG to meet some of its energy demand and is home to China's first LNG terminal (completed in 2006).

In the reference scenario "R", the level of natural gas consumption stays constant from 2010 onwards. Consumption is

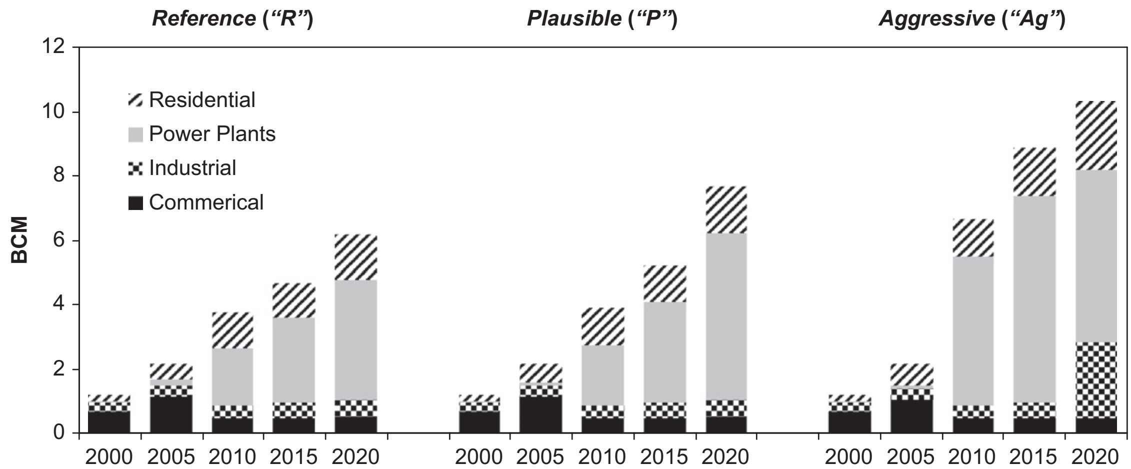

Fig. 7. Natural gas consumption in Beijing for reference, plausible, and aggressive SO_2 constraint scenarios.

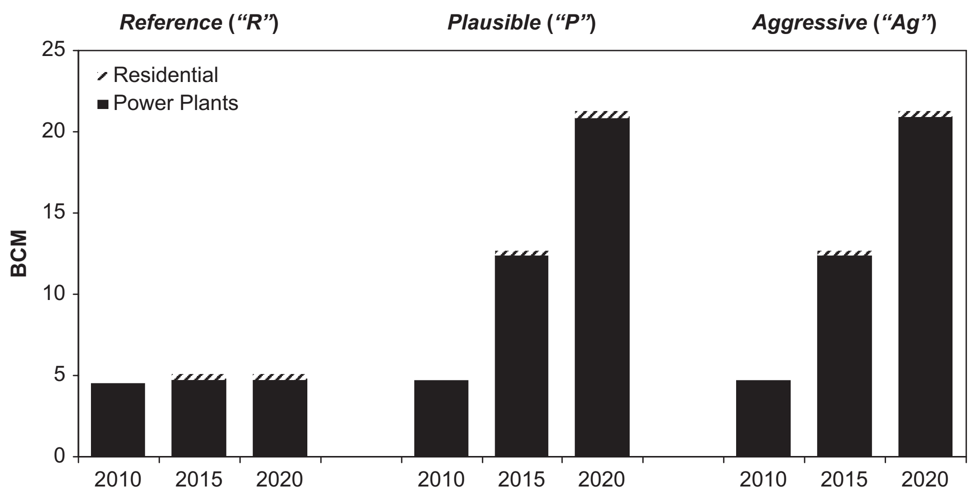

Fig. 8. Natural gas consumption in Guangdong for reference and plausible SO_2 constraint scenarios.

capped at the level corresponding to the volume of LNG imported from Australia under a cheap contract (approximately $3/mmbtu, compared with the $5–7 typical of current LNG contracts). Any volume of gas above this amount would be sold at the new, higher price. Since there is no incentive for the system to spend more money than what is necessary in the reference scenario, the amount of gas consumed stops at the volume limit of the contract. Gas is unable to compete with coal and nuclear in meeting new demand for power. In the reference scenario, nonetheless, most of the gas is consumed by power plants, with the residential sector taking a miniscule portion. When a 40% mandatory decrease in SO_2 emissions is imposed on the system in the plausible scenario, the consumption of gas increases for 2015 and 2020, although there is no increase in uptake before 2015 (Fig. 8). For this plausible scenario, the amount of gas consumed is no longer constrained by the volume of LNG under the Australian contract because the system has no choice but to pay higher prices in order to meet the SO_2 constraint. All of the increased gas demand comes from power plants. In particular, gas-fired combined cycle plants replace oil. Gas also finds use in co-generation and replaces two types of coal-fired technologies: small, inefficient peaking coal plants that are less than 135 MW, and one large coal-fired baseload power plant. The environmental constraints also push forward the construction of an integrated coal gasification combined cycle (IGCC) plant (Fig. 9).

At the same time that gas consumption is increasing, nuclear power is also on the rise. Nuclear provides baseload generation, while gas is used for peaking, so there is no direct competition between the two. Nuclear generation increases 14 times above 2020 reference scenario levels. Nuclear power development is uniquely far along in Guangdong, with four plants already operating in the area.[4] However, without a policy push to decrease SO_2 emissions, coal is still the preferred fuel since a coal plant facing modest limits to SO_2 is cheaper to build than a nuclear unit.

Natural gas consumption does not increase when a more stringent limitation is applied to the system (75% SO_2 reduction, scenario "Ag")—the operation of a new IGCC unit in Guangdong starting in 2010 allows additional energy demand in the model to be met by coal rather than natural gas. This suggests that even though the coal prices in Guangdong are higher than in other parts of China, it is still cheaper than natural gas, which makes clean coal operations competitive. The caveat to this outcome is that the actual cost of IGCC units may be higher than the one assumed in the study ($1400/kW), which is much cheaper than western estimates, although twice the cost of conventional coal plants. In reality, construction of IGCC units may be delayed due to

[4] Guangdong-1 (944 MWe), Guangdong-2 (944 MWe), Lingao-1 (938 MWe), Lingao-2 (938 MWe).

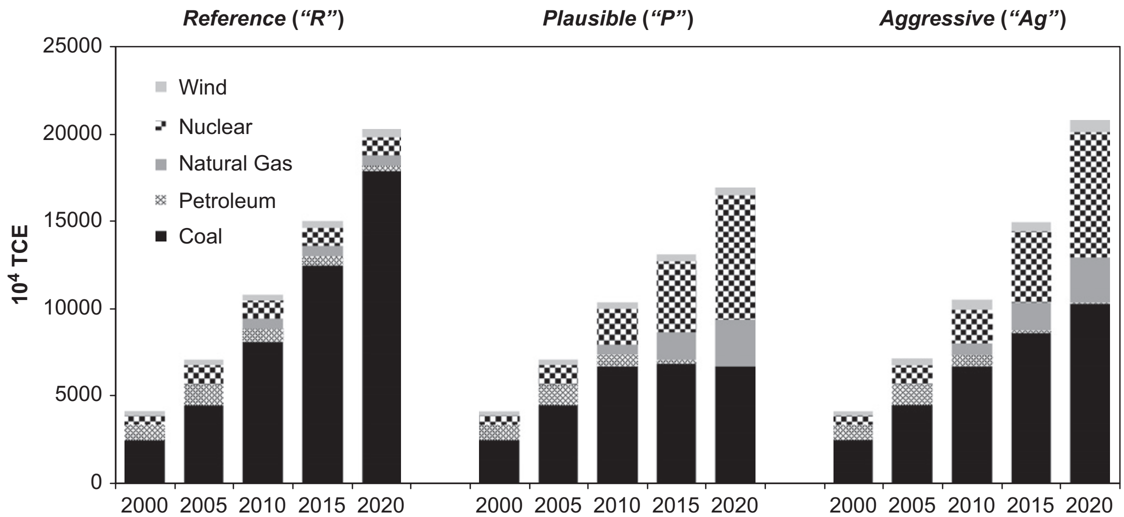

Fig. 9. Fuel consumption in Guangdong Power Sector for reference and plausible SO_2 constraint scenarios.

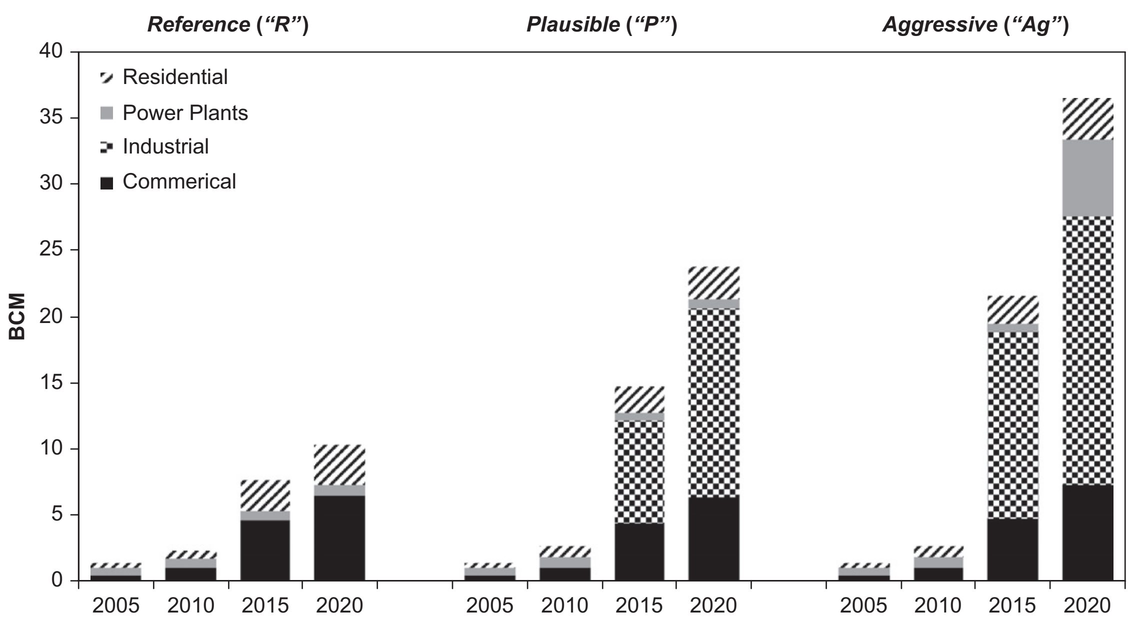

Fig. 10. Natural gas consumption in Shanghai for reference and plausible SO_2 constraint scenarios.

the unavailability of the technology. If so, our estimation is that advanced (ultra-supercritical) coal along with pollution control equipment, and some expansion in nuclear, would be favored over gas for baseload power.

4.1.3. Shanghai

Shanghai's economy is dominated by energy-intensive industries that thrive in and around the city. Six industries comprise 50% of the city's total energy demand—smelting/rolling of ferrous materials, oil processing, coking, nuclear fuel processing, textiles, and chemical production. In contrast to Guangdong, not much natural gas is used for power plants. This is mostly due to the fact that there is an abundant and relatively cheap supply of coal available for firing baseload plants. When the 40% SO_2 constraint is imposed on this system, there is an increase in the consumption of natural gas appearing in 2010 (Fig. 10). Almost all of this growth stems from the industrial sector. Rather than building new power plants that run on cleaner burning gas, it is much less costly in Shanghai to meet the SO_2 constraint by switching existing boilers in the industrial sector from higher sulfur heavy fuel oil and coal to natural gas (Fig. 10). Similarly, many of the coal boilers and kilns in the six energy-intensive industries get switched to natural gas fuel to meet SO_2 constraints. Replacing old, inefficient coal technology with natural gas boilers minimizes the cost of fuel switching. As a result, an increase in gas consumption in the power sector becomes attractive only after opportunities in the industrial sector are exhausted. In addition, Shanghai has access to domestic piped natural gas that is priced lower (for now) than LNG, which facilitates the switch to natural gas.

This increase in natural gas consumption in Shanghai seems feasible due to the current political support that is already in place. For example, the municipal government has provided various financial incentives such as tax credits and subsidies to industrial facilities that choose to retrofit coal boilers with natural gas boilers. To increase gas demand in the summer time, the government has invested in natural gas air conditioners throughout public facilities in the city. The firms in Shanghai are also among some of the most well financed and progressive in the country. These factors may make Shanghai fertile ground for further development of natural gas use.

4.2. Effects of the rate of diffusion of demand technologies

It is instructive to consider how the rate at which advanced, efficient demand side technologies diffuse into the market can affect natural gas demand. Based on a variety of sources,[5] we made reasonable assumptions for both the initial market share and subsequent growth rate of different end-use technologies. For "new" demand technologies that have longer life cycles and are more expensive to purchase, such as industrial equipment and mass transportation infrastructure (boilers, kilns, and buses), we assume a 5% share of the entire market in 2010. A 7% initial share of market is assigned to demand technology in the commercial and residential sectors, such as air conditioners, cooking stoves, heating appliances, and lighting. We created different scenarios by changing the rate at which this initial share grows. A 1.5% annual growth market share starting in 2010 was chosen for the reference case. For the scenario in which a faster rate of technological diffusion is expected, we used a 5% annual share growth. A 3% annual share growth was also tested to approximate the sensitivity of the model, but there were no significant changes in fuel consumption in any of the regions so the results are not included in the study.

In Beijing, under modest environmental constraints, faster technology diffusion reduces coal consumption by 6% and natural gas consumption by about 57% in 2020 relative to the base case diffusion scenario. Natural gas use decreases when more advanced technologies are introduced into the market because greater end-use efficiency affects energy demand where gas tends to be used, such as in cooking, heating water, and space heating. In the scenarios with faster technology diffusion, these natural gas using technologies are replaced by newer technologies that do not utilize natural gas, such as a heating network for cooking and heating water (fueled by coal-fired sources). The main assumption driving these outcomes is that advanced coal utilizing demand technology is likely to flood the market before natural gas equipment gets there. The speculation is that because coal-powered technologies have been out on the market for a longer period of time, there has been more time to develop more efficient versions of this equipment that can reach the market before new gas consuming technologies are introduced. Thus, the availability of efficient technologies, which are not fueled by natural gas is detrimental to the expansion of the gas market. As expected, the residential sector was especially affected by the fast scenarios due to the assumption of higher initial market share of advanced end-use technologies.

In Guangdong, under modest environmental constraints, coal consumption increases when the rate of technology penetration is increased. This is due not only to the replacement of old equipment with more advanced commercial coal stoves and boilers but also to an increased share of consumption by these technologies. In the industrial sector, new coal boilers and kilns replace older versions and also contribute to the increased consumption of coal. Oil consumption decreases slightly as improved LPG stoves and heaters that require less fuel to do the same amount of work in the residential sector replace older models. Electricity and natural gas consumption do not change much between the reference penetration (P) and the high technology penetration (P_Fast) cases. The technology diffusion trends are further magnified when the system is placed under a stringent environmental constraint (Ag, Ag_Fast).

In Shanghai, starting in 2010 there is a small decrease in the consumption of coal within the residential sector and a slight increase in the consumption of gas as old, inefficient coal-burning appliances are retired. In 2015, we see natural gas consumption decrease within the residential sector as more efficiency in end-use cuts demand and oil products became more competitive. The same trend on a greater scale occurs in 2020. We were surprised by the increased share of oil. Although in open markets oil is more expensive than gas (by heat content), refined oil products are made available to the domestic market at a subsidized cost supported by the central government, which could explain the system's overall reliance on oil in the residential sector. While this resilience for oil is interesting, it is useful to keep in mind that the total change in energy consumption between P and P_Fast here is only about 2.5% of the total amount of energy consumed within the system. In short, rate of technology diffusion is not a significant factor in determining fuel consumption patterns in the Shanghai case.

Overall, increasing the rate of technological diffusion may help to reduce the overall energy intensity of a system, but it does not generally encourage natural gas consumption. Natural gas consumption decreases in all three regions under the fast diffusion scenario, especially in the residential sector. Only Beijing, however, shows a very significant effect. Gas use is reduced because most of the new technologies utilize coal (or oil in the case of Shanghai). Thus when the technology penetration rate is increased, more efficient demand favors coal and oil.

4.3. Effects of differing costs of capital across sectors

An often overlooked aspect of the energy system is the financial realities that govern the flow of capital. Most importantly, the costs of capital offered to different sectors in the economy are highly variable. In particular, the cost of capital for building state-owned power plants has been much lower than for private projects and business. The purpose of this section is to simulate varying costs of capital reflective of the historical reality of the Chinese financial system (P_Diffcost) and to compare that with a behavior under a uniform cost of capital across all sectors. For our reference runs, we replicate what has done many times in other models, which is to assume that there is a uniform discount rate across all sectors (10%) reflecting the assumption that the cost of capital is uniform. For the scenarios that vary the cost of capital, however, we attempt to simulate the actual differentiated lending rate system under which the Chinese economy has been operating by assigning different lending rates for each sector in MARKAL. Taking into account these different discount rates should, we expect, lead to a significantly different energy system.

The power sector is viewed as a "pillar" industry by the government, which affords the industry special treatment such as indirect subsidies and access to political favors. One way indirect subsidies are distributed is via the China Development Bank, which at the time of the model runs was providing capital to government connected enterprises at a rate of 5.8%.[6] This same arrangement is not extended to the industrial sector, which is still given a 10% discount rate. The residential and commercial sectors experience significant barriers to obtaining loans at all—which we

[5] Our assumptions came from a study that enumerated the initial market shares of fluorescent light bulbs in several other studies: the US National Energy Modeling System database (NEMS), a joint study between the Energy Foundation and China National Institute of Standardization (EF/CNIS), a joint study between Guan Fu Min in Qingdao, China and Lawrence Berkeley Laboratory (Guan/LBL).

[6] Discussions with Pan Jiehua (CASS), Kejun Jiang (ERI), and Tao Wang (BP), November 2006, People's Bank of China website (www.pbc.gov.cn), Global Financial Data (www.globalfinanicaldata.com).

Table 3
Different assumed costs of capital by sectors

Sector/industry	Effective discount rate (%)
Power plants and other public service entities	5.8
Industrial sector	10
Residential	25
Commercial	25

simulate by applying a 25% discount rate (Discussions with Pan Jiehua (CASS), Kejun Jiang (ERI), and Tao Wang (BP), November 2006). One rationale that the government uses to justify preferential relative treatment of the large industrial players is that many are state-owned enterprises employing large numbers of people. The manufacturing companies within the industrial sector have also been the driving force behind China's economic development. The government therefore has a stake in maintaining the financial health of this important sector, and these enterprises (especially ones owned by the state) reinforce this view through their political connections. This multi-tiered cost of capital system is reflective of the reality of the Chinese economy and representative of the strategy that the Chinese government has employed since making a transition from a planned to a market economy: "Let go of small enterprises and engage with large enterprises" (Zhang, 2006). Smaller players in the market are always allowed to privatize first while larger entities are carefully "guarded" by government subsidies and regulations. The exact effective discount rates vary constantly, but after consulting experts, official statistics, and various rules and regulations of the People's Bank of China, we chose these tiers in Table 3 as more or less representative of the differentiated cost of capital structure that may be plausible in China.

In Beijing, coal consumption in the modest environmental constraints scenario is higher in the case of differentiated costs of capital between sectors. With their high investment and low O&M costs, coal-fired power plants benefit disproportionately from the low cost of capital for the power sector, while gas plants with their low fixed and high O&M costs are comparatively disadvantaged. Thus, coal consumption is higher by about 17% with differentiated capital costs, while natural gas consumption is lower by about the same percentage. The same story holds true when environmental controls are set tighter for Ag0 and Ag_Diffcost scenarios. The SO_2 constraints are not sufficient to induce fuel switching in favor of natural gas because cheap capital makes advanced coal technology such as flue gas desulfurization (FGD) even more economical (prices for FGD are already low in China). The exact numerical results for Beijing are reported in detail elsewhere.[7]

A similar story plays out in Guangdong. Coal consumption is a dramatic 88% higher under differentiated costs of capital, with natural gas consumption lower by about 40% (Fig. 11). Advanced coal plants with pollution control equipment (FGD, ESP) are built at the expense of LNG-fired power plants. In fact, the situation on the ground is already evolving in this direction due to rising LNG prices in recent years (Interfax, 2007a–c).

By contrast, there is little change in the amount of coal consumed as a function of capital cost assumptions in Shanghai. This is explained by the fact that the vast majority of natural gas consumed there is within the industrial sector, for which the cost of capital does not change between the reference case and the "Diffcost" runs. We are mindful that China is in the midst of accelerating reforms that are making state enterprises more competitive and also improving access to capital across the economy. It is possible to see a future where the cost of capital by sector varies less extremely than shown here, but our results help illustrate the sensitivity of the models and also help explain the capital-intensive nature of the industrial energy development so far (Table 4).

4.4. *Effects of gas supply*

In the following scenarios, we explore the effects of gas supply on gas consumption. Specifically, there are two scenarios (Table 5)—one in which international gas does not get piped to China and one in which there is additional international gas supply available. The availability of gas supplies affect the price of gas and thus, in turn, demand (Table 6 shows prices and supply constraints assumed for the Moregas scenario). Though Fig. 3 shows that China will be dependent on some or all of these projects at some time in the future, it does not guarantee that the projects will be available when they are needed. International pipelines are rarely motivated purely by economics and are sensitive to political moods and relationships between the relevant governments (Andrews-Speed, 2002). For example, even though China and Russia signed an agreement in March 2006 to develop pipelines between China National Petroleum Company (CNPC) and Gazprom (Interfax, 2007a–c), it is still not certain whether these plans will be realized due to a negotiation stalemate over gas pricing.

Beijing is not sensitive to the availability of gas in either the plausible or aggressive scenarios. This presumably indicates that the use of natural gas is not hindered by the availability of the supply. Indeed, because there is a domestic pipeline that supplies the city, and also because Beijing is the capital, it already gets preferential treatment when gas is allocated. The relatively low demand for natural gas in this area, as indicated by Fig. 5, is also relatively easy to satisfy.

Guangdong is responsive to the availability of gas only if additional gas (and lower gas prices) coincides with tight rules on SO_2. Fig. 12 shows the major consumers of natural gas by sector in both the Ag and Ag_Moregas scenarios (there is no effect of gas availability on consumption under the plausible SO_2 constraint conditions). The black bars indicate bounds for different types of supplies available to Guangdong. The main difference between Ag and Ag_Moregas is that for Ag_Moregas, an additional source of piped gas becomes available to Guangdong at a cheaper price than expensive LNG.

Even though the amount of expensive new LNG that is consumed does not decrease in Ag_Moregas, the major consumers of gas change in this scenario. What we see here is that the additional cheaper supply of gas allows major off-takers *outside* of the power sector to consume gas. The transportation, residential, industrial, and commercial sectors all dip into the natural gas supply once it becomes available. When cheap gas supplies are limited, almost all of the gas is funneled into power generation in order to meet the requirements of the SO_2 emission constraints.

In Shanghai, greater availability of cheap gas does not significantly change the consumption patterns ($<0.1\%$) in the industrial sector. Given Shanghai's abundant domestic gas supply (Shanghai, like Beijing, has access to gas from the WEP) at favorable prices, it was not expected that supply constraints would drive scenarios in this situation.

In summary, as a supply-constrained market, Guangdong is the only region that is sensitive to the availability of new supplies of gas. This sensitivity hinges on a set of assumptions—notably the

[7] Fig. 15 (pp. 33) in Jiang et al. (2007) "The future of natural gas vs. coal consumption in Beijing, Guangdong, and Shanghai: An assessment in MARKAL" (2007) Program on Energy and Sustainable Energy, Stanford University, Working Paper no. 62, http://pesd.stanford.edu/publications/china_gas_markal/.

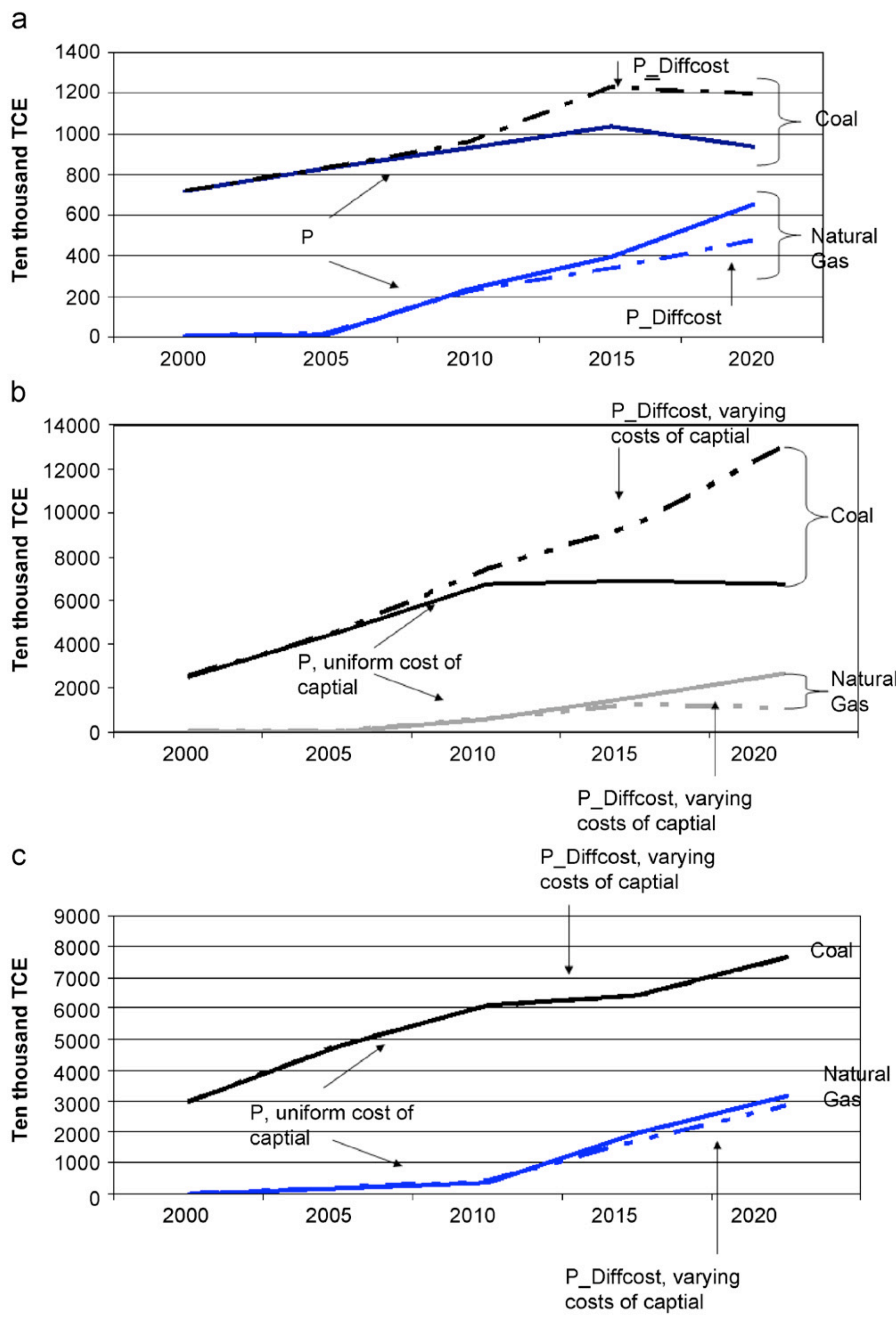

Fig. 11. Coal and natural gas consumption in the Guangdong (power sector). (*Source*: Yu et al., 2007, Shanghai Jiaotong University/PESD study).

Table 4
Investment costs for various types of power plants in China (2006)[a]

Technology	\$/kW (300 MW)
Pulverized coal-fired power plant	600–676
PC w/ FGD	620–1100
Combined cycle natural gas	500–600
Ultra supercritical coal	1000–1100
IGCC	1000–1300

Source: Chen (2007), Yu et al. (2007), and Zeng et al. (2007).
[a] Cost in Beijing, Guangdong, and Shanghai.

availability of piped natural gas from a second WEP from Central Asia in 2010 that will face political, financial, and geographic challenges. When new sources become available, there is a diversification in the use of the natural gas that extends beyond the original power plant off-takers. If an international gas pipeline is built for Guangdong, the fuel will be cheaper than any new LNG contracts that the government will be able to obtain and will have a significant impact on energy consumption patterns.

The gas demand in Beijing and Shanghai, on the other hand, is not affected by additional sources of gas because these regions are already connected to existing pipelines that deliver adequate gas supplies.

4.5. Implications for CO_2

Next, we explore what effect some of scenarios discussed in the paper may have on CO_2 emissions. In particular, we explore the hypothesis that limits on SO_2 could yield, incidentally, some reduction in CO_2 due to greater use of natural gas. CO_2 emissions reductions in response to SO_2 limits are most apparent in Guangdong. If we take the case of the aggressive scenario, about 99 million tons less of coal would be used in 2020 compared with the reference case. Fig. 13 explains the carbon consequences of this fuel switch for Guangdong. About 57 million tons of carbon dioxide emissions can be averted by imposing a 75% emissions cap on SO_2 emissions. For comparison, 50 million tons is about a quarter of the CO_2 saved by the entire stock of Clean Development Mechanisms (CDM) projects in China in 2006 (UNEP, 2007). It is also a quarter of Europe's Kyoto commitment (Victor et al., 2006). While in absolute numbers these savings alone will not alter the global trajectory of climate change, they do suggest new ways of thinking about the climate issue, especially with regard to how to bring developing countries to the climate negotiation table. Developing countries are wary of emission caps that may hinder economic growth. However, they are more strongly motivated to engage in discussions related to local and regional pollution. Perhaps a stringent SO_2 policy could be a more acceptable scenario compared with one that addresses CO_2 emissions directly. The caveat to these results is that while the carbon dioxide savings come from fuel switching in a particular region, there is no guarantee that demand could not also be met by importing electricity from power plants outside the city, particularly, if emissions controls are less stringent elsewhere. Most likely, any imported electricity will be coal-fired—although in the past Guangdong has imported substantial quantities of electricity from large government hydroelectric projects. This implies that while carbon dioxide emissions are decreasing in one area, they could be increasing in another, diluting any benefit. We do not expect that this countervailing effect from electricity importation will be significant in the cases modeled here, but it could become a much more important issue in the future, particularly if imported electricity becomes cheaper than developing regional energy resources.

As shown in Fig. 14, SO_2 limits can also drive significant CO_2 reductions in Shanghai. The effect is not strong in Beijing due to limited fuel switching to gas as discussed previously.

Financial reform also has an effect on CO_2. When the cost of capital is made uniform across sectors, the amount of CO_2 reduction that occurs in the system is close to that of when *aggressive* SO_2 constraints are implemented, according to the model. This reinforces the idea that there are alternative ways of thinking about controlling CO_2 emissions other than directly targeting factories and power plants, the engines of China's economic growth. Standardizing discount rates across sectors, for example, is already a policy that the Chinese government is moving towards because its enactment is in line with the greater goal of moving the economy towards a stable market economy. Utilizing leverage points such as this to negotiate with China and other developing countries on reducing carbon emissions will be an important element in creating a practical climate regime.

Table 5
Gas availability scenario

Name of run	Gas supply
Ag	Only domestic pipeline and LNG terminal in Guangdong
Ag_Moregas	Domestic pipeline, international pipeline, LNG terminal in Guangdong

Table 6
Gas prices and supplies for in Moregas Scenario

Gas supply	Price[a]	Supply limit
Cheap LNG	$5.50/MMBtu (regasified to delivery)	5.1 bcm
Imported Central Asia pipeline	$7.12/MMBtu	5 bcm in 2010 10 bcm in 2020
Expensive LNG	$9/MMBtu (regasified to delivery)	No limit

[a] Present day prices.

5. Conclusions

The study suggests five key findings on the competitiveness of natural gas in China over the next two decades.

First, China is a supply-constrained environment for natural gas. Growth in gas demand in China could lead to a surge of

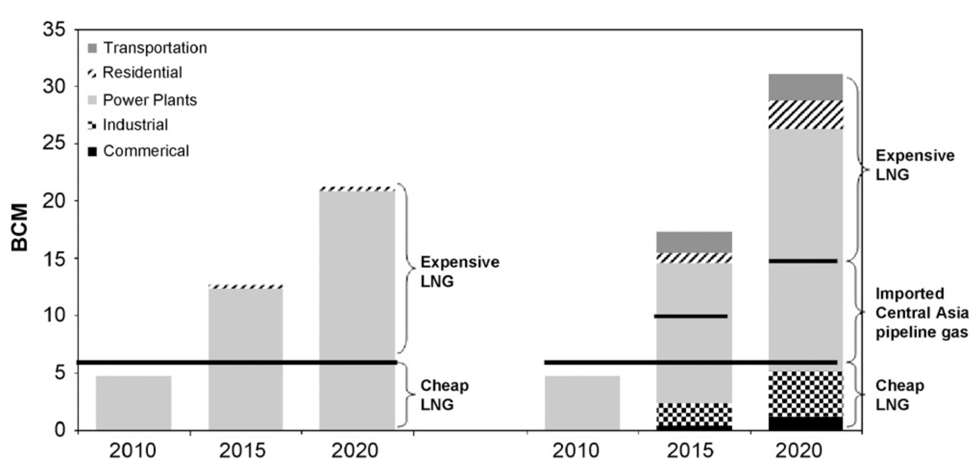

Fig. 12. Gas supply options for Guangdong and natural gas demand by sector.

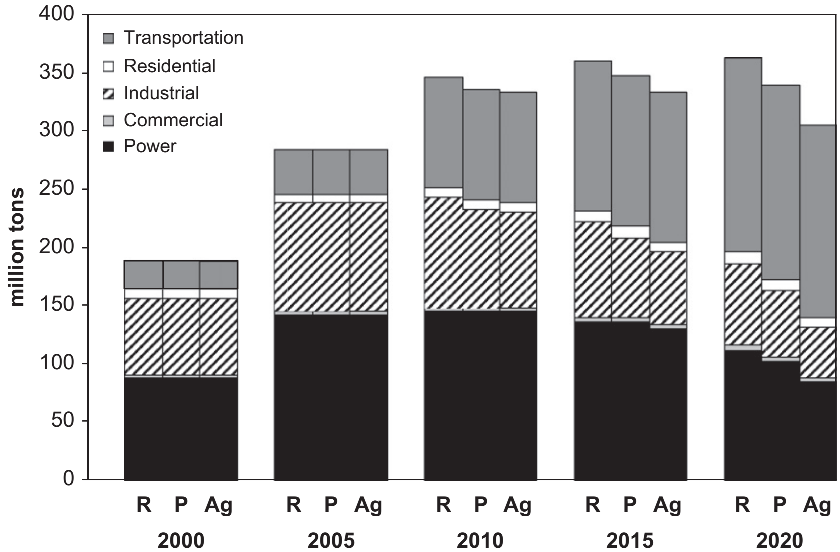

Fig. 13. CO_2 emissions from Guangdong in the reference, plausible, and aggressive scenarios.

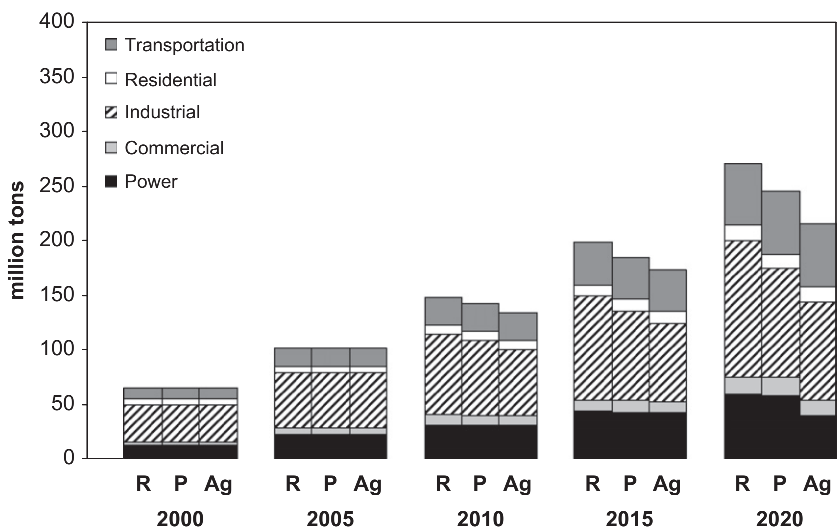

Fig. 14. CO_2 emissions from Shanghai in the reference, plausible, and aggressive scenarios.

natural gas imports as demand is likely to far outstrip domestic supplies in certain parts of the country. This supply constraint provides an impetus for the Chinese government to seek out new supplies, such as a large international pipeline from Russia, Kazakhstan, or Turkmenistan, and more LNG regasification terminals. It should be noted, however, that such international supplies (especially via pipelines) are often challenging and time consuming to realize.

Second, gas demand is highly dependent on financial policies. The current Chinese financial system provides extremely low costs of capital for the power sector. This makes the construction of capital-intensive coal-fired power plants especially attractive. Because coal and natural gas are in direct competition as the fuel source in most cases, this diminishes the opportunity for more natural gas combined cycle plants to be built. In Guangdong, for example, the MARKAL model would predict almost 50% lower coal consumption by 2020 if a 10% discount rate were applied to all sectors. While policies related to the banking system do not usually factor into considerations for planning an energy system, our study shows that this is an important aspect to consider in creating the right incentives for a sustainable energy plan.

Third, the industrial sector can in some cases be more attractive for fuel switching than the power sector. The study found that looking outside of the power sector for fuel switching opportunities could prove to be a cost-effective option. According to the model, a switch from coal to natural gas boilers would be cheaper than forcing a switch in power plants in the case of Shanghai where the industrial sector is currently dependent on inefficient coal boilers. Replacing an inefficient coal boiler requires much less up front capital than converting a power plant from coal to natural gas. When there are enough boilers in the industrial sector to make a difference in emissions, this is an especially attractive alternative.

Fourth, the fuel mix for electricity generation is unlikely to change dramatically. In all of the scenarios that were tested in the model, coal remains the dominant fuel in the energy mix. Coal is simply too cheap and abundant to leave unused (China has the world's third largest coal reserves). Aggressive sulfur reductions do shift the electricity mix somewhat towards a greater role for natural gas, but sulfur reductions can often be met more cheaply through fuel shifts in the industrial sector and by installing end-of-pipe solutions on coal plants.

Fifth, non-climate policies could have a large impact on carbon emissions. While China is unlikely to accept binding carbon dioxide emissions reductions targets in the near future, very large CO_2 reductions might be realized as a side benefit from other policies enacted for reasons other than climate concerns. For example, in the case of China, a cap on SO_2 emissions could have a significant effect on CO_2 emissions by promoting the use of cleaner burning fuels and more advanced technology. An SO_2 policy might be more palatable to the Chinese government than explicit CO_2 regulation because it addresses immediate local concerns about air quality and health, which directly affects its citizens. Such issues are much more likely to gain traction and spur change in the near term.

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