China Energy Issues:
Energy Intensity, Coal Liquefaction, and Carbon Pricing

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ABSTRACT

In my dissertation I explore three independent, but related, topics on China's energy issues. First, I examine the drivers for provincial energy-intensity trends in China, and finds that technology innovation is the key driver. Then, to understand how technology innovation takes place, I examine coal-to-liquids technology and argue that companies' business diversification strategies are the key driver for the coal-to-liquids development in China. Third, I study the carbon pricing carbon capture and storage, which supplements the other two from the perspective of finance: the impact of carbon price on investments on carbon capture and storage for power plants.

(1) Provincial energy-intensity (EI) change in China: a case study of three provinces
EI trends of individual provinces vary, although the whole country shows declining energy intensity. The energy-intensity trends in the following three provinces seem especially interesting: Inner Mongolia, Liaoning, and Ningxia, because they represent three typical EI trends in China, increasing, nearly constant, and decreasing. Then why and what is the driver for this difference in energy-intensity trends? I argue that technology innovation plays a key role. I also explore the economic structures and development of renewable energy in three provinces to shed light on how these might affect energy-intensity change in these regions.

(2) Coal to liquids: why and how it makes the case in China
Different from Europe and the United States, China is actively developing coal-to-liquids technologies and projects. In contrast to the conventional wisdom that in China the central government mandates and guides coal liquefaction to ensure energy security, I argue that the diversification strategy of state-owned coal companies is another key driver for coal-liquefaction development in China, in addition to the state interest and policy that initiated this move. Given current extensive conversation and debate on Chinese technology innovation capability, my research sheds light on the innovation system in China and provides implications for technology policy and investments.

(3) The impact of future carbon prices on CCS investment for power plants in China
I answer two related questions about the development of carbon capture and storage (CCS) and power generation technologies in China: (1) what is the breakeven carbon-dioxide price to justify CCS installation investment for Integrated Gasification Combined Cycle (IGCC) and pulverized coal (PC) power plants, and (2) what are the risks associated with investment for CCS. In this analysis, I also advise investors on the impact of capital and fuel costs on the carbon price and suggest optimal timing for CCS investment.

ACKNOWLEDGEMENTS

First, I thank my academic advisor and dissertation committee chair, Professor Karen R. Polenske, for her support and encouragement throughout the course of my PhD program. I started working with Karen on my first-year paper in the summer of 2007, and later on worked as her research assistant for a few projects related to China energy, and then for my dissertation. Through working with Karen on China projects, I discussed with her the idea of doing a three-essay dissertation on China's energy issues, and Karen expressed great encouragement and offered advice and resources, which later proved to be key for the completion of my dissertation. Her insights, advice, and support made every step of progress of my dissertation possible. Upon the completion of my dissertation, I also received invaluable guidance and help from Karen for my career development. Her advice, trust, and introductions to leaders in the industry, means a lot to me, now and in the future. My appreciation is beyond words, and my most sincere appreciation goes to Karen.

I also extend my most sincere gratitude to Professor Edward S. Steinfeld and John. E. Parsons. Ed and John are two other members in my dissertation committee, and without their support, completing my dissertation would be impossible. John's interest and support when I proposed the carbon pricing topic to him was the first and key step to start this analysis. Discussion with John, and his insights in energy and finance, and significant experience in consulting, all kept me going further for the analysis, and benefited me in the long run. Ed always offered insightful and feasible guidance for my research. Importantly, he provided critical resources to help my field trips in China to interview coal companies and collect first-hand data. I had also the fortune to take his class, Comparative Politics and China. I benefit from working with John and Ed not only in academics, but from the way they view, analyze, and solve problems and their insights into the industry: these will carry me a long way.

I also thank many other professors and professionals. Professor Joseph Ferreira Jr. was another big help for my PhD study. He supported my application to DUSP in 2006, and I had the fortune of working with him for my first year at DUSP, which laid down the solid foundation for later years' study and research. Besides, I also thank Professor Frank Levy, JoAnn Carmin, Michael Flaxman, and several others. I thank in particular Dr. LI Wenhua at GE (China), Dr. REN Xiangkun at Shenhua Group, Dr. LI Yongwang at Synfuel China, and Dr. SUN Qiwen at Yankuang Group. They provided information and data that are critical for my research.

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Most importantly, I take this opportunity to thank my parents and my sister. It is they who made who I am and where I stand today. Without their care, sacrifice, support and encouragement, I cannot imagine how I could make my way.

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Abstract

China has incurred a steady decrease of energy intensity (EI, energy consumption per unit of gross domestic product (GDP)) since the 1980s, for example, a decrease of 29.3% from 1995 to 2004. EI trends of individual provinces vary, although the whole country shows declining energy intensity. The energy-intensity trends in the following three provinces seem especially interesting: Inner Mongolia, Liaoning, and Ningxia, because they represent three typical EI trends in China, increasing, nearly constant, and decreasing. It brings forth a puzzle that Ningxia and Inner Mongolia, with developed renewable energy industry and clean energy technology, have increasing or almost constant EI, while Liaoning, which has a heavy industry base and does not have much renewable energy capacity, experienced an EI decrease. Whether or to what an extent does the renewable energy development impact energy intensity? What are other reasons driving the EI trends in these regions? How is economic development interacting with energy-intensity issues? In this paper, I examine underlying reasons for differences in energy-intensity trends. Furthermore I tackle that puzzle by analyzing determinants of the EI trends and examining economic structures of these regions.

1. Introduction

China has embraced a steady decrease of energy intensity (EI, energy consumption per unit of GDP) since the 1980s. This trend continued in the past decade. From 1995 to 2004, the EI of China decreased from 163.25 to 115.42 kilograms standard coal equivalent (kgce) per thousand Yuan (1995 deflated value), a decrease of 29.3% (Table1-1 and Figure 1-1).

Scholars have studied China's EI at the national level from the perspectives of structural change and real energy intensity (Smil 1990, Polenske & Lin 1993, Sinton & Levine 1994, Lin & Polenske 1995, Garbaccio 1999, Zhang 2003, Polenske 2007). There are mixed opinions. Some argue that structural change was a main factor responsible for the EI decrease in the early 1980s when China started the "Open-door" policy, while some find that technology innovation was the main driver for the intensity change (For instance, Polenske & Lin (1993) finds that technology innovation accounted for 80% of the reduction in this period). This structural change factor still worked in decreasing China's EI in the late 1980s and 1990s, but its effect was less significant than the factor of real energy intensity, which is caused by technology innovation. Based on firm-level data, Zhang (2003) further argues that 88% of the cumulative energy savings in the industrial sector were attributed to real energy intensity change, with approximately 80% of such savings from the four chief energy-using sub-sectors (i.e., ferrous metals, chemicals, nonmetal mineral products, and machinery). Polenske & McMichael (2002) also find that technology innovation is the primary factor for the EI decrease in those firms in the coal industry.

Few analysts have conducted studies concerning EI trends of individual provinces in China. In fact the EI trends of individual provinces vary, while the whole country shows declining energy intensity. Among all the 30 provinces or municipalities (not including

Taiwan and Hong Kong Special Administration Region and Macau), the following three provinces are especially interesting: Inner Mongolia, Liaoning, and Ningxia (Table 1-1 and Figure 1-1). They represent three typical EI trends in China, increase, no significant change, and decrease, respectively. As shown in Table1-1, Ningxia, a less developed province in the northwest but with a well-developed solar power industry, has experienced an EI increase over the past decades, from 308.24 in 1995 to 427.60 kgce per thousand Yuan in 2004 (1995 deflated value), an increase of 38.7% over ten years. Inner Mongolia, famous for wind and solar power and coal gasification industries, exhibits a roughly constant EI over this period, from 258.26 kgce per thousand Yuan in 1995 to 220.53 in 2004 (1995 deflated value), but basically fluctuating around 200. Liaoning, a province with considerable heavy industry, like most provinces, has a steadily decreasing EI trend. Its EI decreased from 276.4 kgce per thousand Yuan in 1995 to 122.9 in 2004 (1995 deflated value), a decrease of 55.6%.

Table 1- 1: Energy Intensity, 1995-2004 (Kgce per 1,000 Yuan GDP)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
National	163.25	160.74	138.44	123.21	115.31	108.54	98.30	98.38	104.35	115.42
Inner Mongolia	258.26	204.39	248.58	198.75	197.29	191.16	186.73	181.53	175.84	220.53
Liaoning	276.39	218.62	208.69	167.77	148.65	150.86	140.38	132.56	128.40	122.86
Ningxia	308.24	227.73	240.68	233.61	241.20	*	*	*	*	427.60

Note: *: data of energy consumption by sector unavailable from the sources below. Therefore the energy intensity cannot be calculated here. However, Polenske (2007) shows the energy intensity data of Ningxia for this period and indicates that Ningxia has a climbing curve of energy intensity over these 10 years.
Source: SSB&NDRC 1996-2005, SSB 1996-2005; edited by the author

The past decades have also witnessed China's development of renewable energy, which can be dated back to 1982 when the central government issued "Suggestions to reinforce the development of rural energy." (NREL, 2006) More efforts occurred since 1995 when the State Planning Commission, together with other commissions, issued the Outline on New and Renewable Energy Development in China (NREL, 2006). In 2001, the State

Economic and Trade Commission (SETC) proposed its Tenth Five-Year Plan for Sustainable Development, including the Tenth Five-Year Plan for New and Renewable Energy Commercialization Development. Five years later, in 2006, China passed its Renewable Energy Law with a firm objective of boosting the use of renewable energy capacity up to 10 percent of the country's total energy consumption by the year 2020 (compared to 3% in 2003). Totally, since the 1980s, China has issued more than 20 national policies or laws to promote renewable energy development and has achieved considerable progress (NREL 2004a&b, 2006). China's renewable energy development has also received attention from multiple aspects. National Renewable Energy Laboratory (NREL) under the U.S. Department of Energy keeps track of China's renewable energy policy. Some scholars, such as Wang (2005), conclude that renewable energy in China is still underutilized that it is even disregarded in official figures. Some reports also state that some provinces still rely on coal industries for economic growth (21 Century Economics 2005).

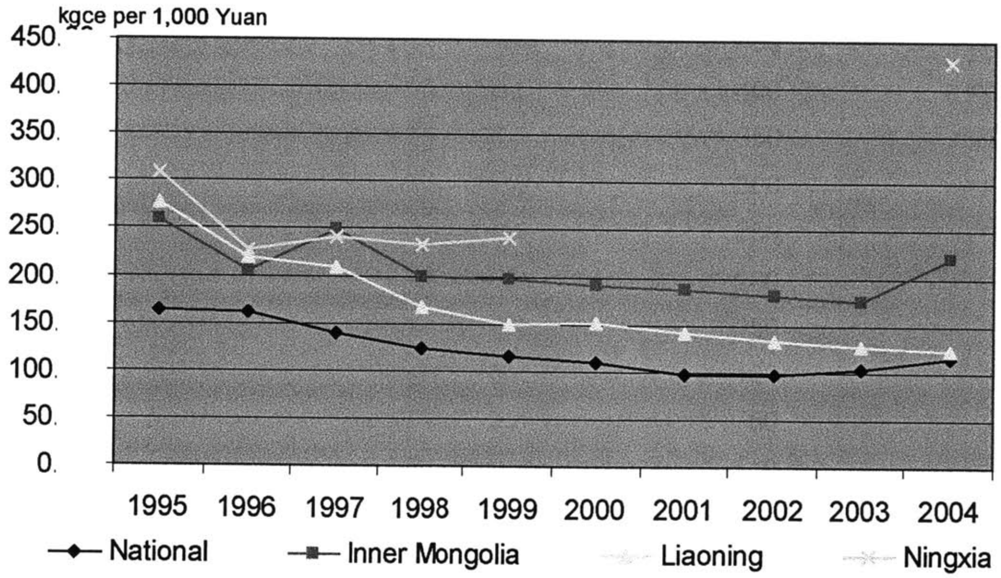

Figure 1- 1: China Energy Intensity from 1995 to 2004, National and Provincial
Source: Table 1-1

Renewable energy development, on the one hand, has a positive effect on the EI decrease. Martinot (2001a, 2001b) reviews the World Bank's renewable energy projects in China and finds that these projects contribute to energy efficiency or decreasing EI in China by promoting the awareness of energy conservation. On the other hand, renewable energy development is supposed to help decrease EI as it brings forth technology innovation of energy use (NREL 1999, Martinot 2001a&b, Gao et al. 2005). For example, coal gasification, an innovation introduced in this period in Inner Mongolia, not only decreases energy intensity but reduces carbon-dioxide emissions (Moniz & Deutch 2007, SEPA 2004).

Within this background, Inner Mongolia has achieved significant growth in its renewable energy, especially wind power and solar power. Inner Mongolia has the highest wind power potential in the country and the total wind power capacity by the end of 2005 was 166,000 kw, ranking 1st in China, with a projected capacity of 4,000,000kw by 2010 (North News 2006). Ningxia's solar industry dates back to the 1970s, and the government plans to build up its annual solar power capacity, which can substitute for 432,000 tons of coal equivalent, about 5% of its annual coal consumption in 2004 (San 2004). Liaoning, which has a heavy industry base, does not have much renewable energy capacity so far.

It becomes a puzzle that Ningxia and Inner Mongolia, with developed renewable energy industry and clean energy technology, have increasing or almost constant EI, while Liaoning, which has a heavy industry base and does not have much renewable energy capacity, experienced an EI decrease. In this analysis, I tackle this puzzle by exploring what drives the changes of energy intensity in Liaoning, Inner Mongolia, and Ningxia. I also probe what factors prevent renewable energy from playing a role in decreasing energy intensity. In this paper, I shed light on what factors account for EI changes in those regions and what factors hinder or reduce the effect of renewable energy.

2. Three Provinces

Inner Mongolia, Liaoning, and Ningxia are located in the north of China (Figure 1-2). Inner Mongolia has an area of 1.18 million kilometers (km) occupying about 12% of China's land area. In 2004, it had a population of about 24 million and its GDP was 271 billion Chinese Yuan (Yuan), which makes its GDP per capita rank 12th among all the provinces and municipalities in China. Its energy consumption occupied 3.9% of the national total, lower than Liaoning's but two times more than Ningxia's 2004 GDP. Liaoning has a larger population but smaller area than Inner Mongolia. Liaoning as of 2004 achieved a per capita GDP of 16,300 Yuan, almost double the national average of 9,649 Yuan. Accordingly, its energy consumption is higher, claiming 5.7% of the national total. Ningxia, the smallest province amongst the three, consumed about 1.3% of the national total energy in 2004 for its GDP of 46 billion Yuan. Ningxia's per capita 2004 GDP is about 81% of China's average, placing it as the 30th region (the second smallest in China, only higher than Tibet).

Inner Mongolia is famous for its abundance of coal and is an important coal base in north China (it also has other resources, such as cashmere, natural gas, and rare earth elements, and more deposits of naturally occurring niobium, zirconium and others). It planned to double its annual coal production, from 260 million tonnes in 2005 to 500 million tonnes per year by 2010 (PDO, 2005). Shenhua Group is the largest coal company in China (see the coming section), comparable to Peabody of the United States. Inner Mongolia develops its industry around coal, power generation, and so on. Six industries, energy, chemicals, metallurgy, equipment manufacturing, processing of farm produce, and hi-tech products, are stressed by the provincial government as competitive industries.

Liaoning is one of China's most important industrial bases, covering a wide range of industries, such as machinery, electronics, metal refining, petroleum, chemical industries, coal, and so on. It has the most iron, magnetite, diamond, and boron deposits among all province-level subdivisions of China. The history of being a base for heavy industry in China since the birth of the People's Republic of China and its abundance of iron and other resources make Liaoning a key producer of steel in China. It has several large steel corporations, such as Anshan Iron and Steel Group Corporation, and Benxi Steel Group Corporation. In 2006, Liaoning accounted for 1/6 of the total steel production in China.[1]

Ningxia is a relatively undeveloped region, by its GDP. Coal is its key resource and the coal industry has become a base industry in Ningxia. East Ningxia Coal Basin is one of the 13 main huge coal production areas in China, with a proven reserve of 27.34 billion tonnes and a potential reserve of 139.43 billion tonnes (SSB 2005). Developed by NingXia Coal Industry Corporation (merged with Shenhua Group from Inner Mongolia), this coal base will become an industrial park with mainly energy-intensive industries including coal mining, coke making, coal tar, and petroleum products. Ma Qizhi (2006), then the governor of Ningxia, stated that "The project of East Ningxia Coal Base is the key for ensuring our GDP growth of more than 10% per year until 2020."

Table 1- 2: Three Provinces, 2004

	Area (km^2)	Population (Persons)	GDP (Billion Yuan)	GDP per capita(Yuan)	Energy consumption (10,000 tonnes of standard coal equivalent)
Inner Mongolia	1,183,000	23,840,000	271	11,400	5,642
	(3rd)	(23rd)	(23rd)	(12th)	(3.9%)
Liaoning	145,900	42,170,000	687	16,300	8,180
	(21st)	(14th)	(8th)	(9th)	(5.7%)
Ningxia	66,000	5,880,000	46	7,830	1,844
	(27th)	(29th)	(30th)	(23rd)	(1.3%)
National	*9,600,000*	*1,295,330,000*	*12,496*	*9,649*	*144,227*

Source: SSB 2005, edited by the author.

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[1] See http://www.ln.stats.gov.cn/jrln/gy.htm

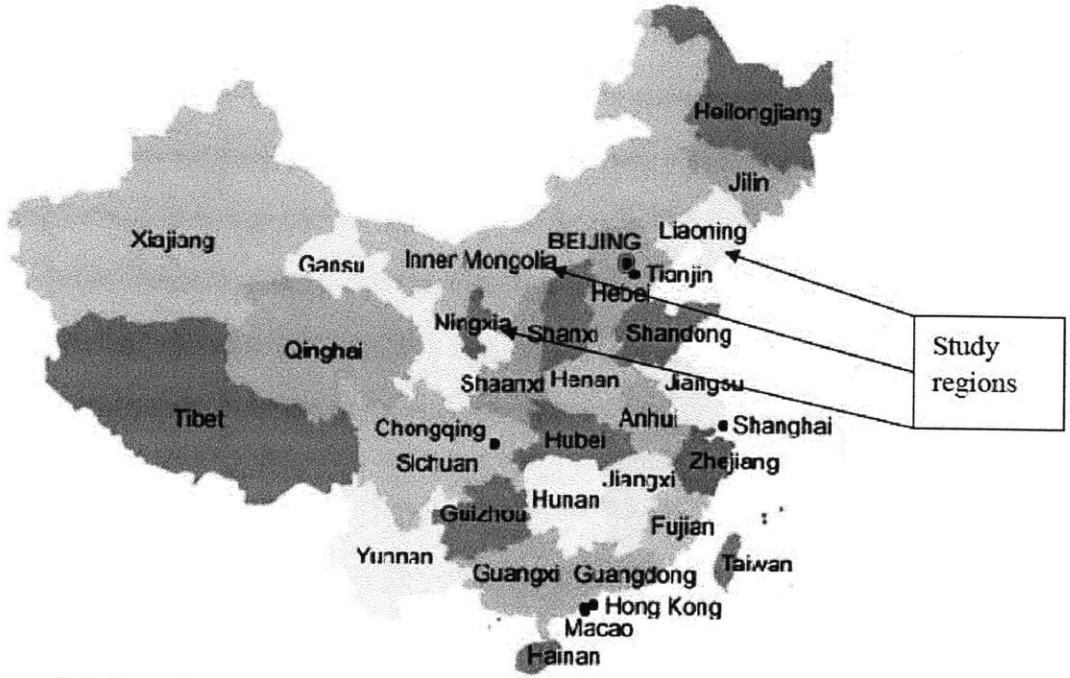

Figure 1- 2: Location of Three Provinces in China
Source: http://chinamash.com/wp-content/uploads/2006/08/china-map.jpg

3. Methodology

In this analysis, energy intensity is the amount of energy consumption per unit of gross domestic product (GDP) or gross regional product (GRP). Energy consumed is measured by 10,000 tonnes of standard coal equivalent (based on calorific value calculation). GDP is deflated into real GDP, based on 1995 value, and GRP is also converted into 1995 values via the current price index, which is calculated by the MIT research group led by Professor Polenske. Energy consumption and GDP/GRP data (1995 through 2004) come from the *China Energy Statistical Yearbook* and *China Statistical Yearbook.*

Shift-share analysis is a framework to explore energy intensity. Analysts use several different methods, but the Laspeyres method is used extensively (Zhang 2003). Park (1992) proposes this method, calculating changes in energy consumption with respect to a constant year. The change of energy consumption between two years, $\Delta E_{tot} = E_t - E_o$

is interpreted by three components: $\Delta E_{tot} = \Delta E_{out} + \Delta E_{str} + \Delta E_{\text{int}} + R$. ΔE_{out} is a change in aggregate production (output effect, the energy consumption of the second year based on the same energy intensity and industrial structure of the base year minus the energy consumption of the base year). ΔE_{str} represents a change of consumption due to changes in composition of aggregate production (structural effect), and ΔE_{int} is the intensity effect, which shows the changes result from the adoption of more efficient technologies and techniques (for detailed formulas about calculating these effects, see Zhang 2003, or Park 1992). R is the residual, which is not equal to zero, and it will grow generally if t increases, which leaves part of the observed change in energy consumption unexplained. This constitutes a shortcoming of the Laspeyres methods and some scholars, such as Zhang (2003), derive their own equations to eliminate this residual.

Therefore, I adopt the method developed by Polenske and Lin (1993). Their method clearly decomposes the energy consumption into three parts, each of which can be calculated and explained easily.

$$E_t = \underbrace{e_0 \cdot O_t}_{\text{(constant share)}} + \underbrace{\sum_i [(e_{i,0} - e_0) \cdot O_{i,t}]}_{\text{(industrial mix)}} + \underbrace{\sum_i [(e_{i,t} - e_{i,0}) \cdot O_{i,t}]}_{\text{(efficiency change)}} \quad \textbf{(1)}$$

where E_t is the total energy consumption in year t, O_t is the GRP (or GDP for the whole nation) in year t. $O_{i,t}$ is the GRP for each sector i in year t. e_0 is the energy intensity for the whole region in the base year, and accordingly, $e_{i,0}$ and $e_{i,t}$ are the energy intensity for industry i in the base year and year t.

The constant share indicates the energy consumption under the condition that the energy intensity in year t remains at the same level as that of the base year. The effect of industrial structure on energy use is illustrated by the industry-mix component. A negative industry mix means that the industrial structure has become less energy intensive compare with that in the base year, and vice versa. Efficiency change is similar to the intensity effect shown by the Laspeyres method, measuring the change of energy efficiency.

If we extend the items on the right-hand side of Equation (1) and add them, the sum is exactly equal to the item on the left-hand side, which makes no residual to appear in the equation. In other words, the energy intensity can be fully explained by the three effects defined on the right-hand side of the equation. Furthermore, by dividing both sides of Equation (1) by O_t, an equation describing the impacts on energy intensity can be obtained.

$$e_t = \underbrace{e_0}_{\text{(constant share)}} + \underbrace{\sum_i [(e_{i,0} - e_0)\cdot O_{i,t}]/O_t}_{\text{(industrial mix)}} + \underbrace{\sum_i [(e_{i,t} - e_{i,0})\cdot O_{i,t}]/O_t}_{\text{(efficiency change)}} \quad \textbf{(2)}$$

where $e_t = E_t / O_t$ is the energy intensity for the whole region in year t. e_t can be smaller or greater than e_0 depending on the simultaneous effects from the industry mix and efficiency change. Obviously the combined effect of industry mix and efficiency change determines the level of energy intensity in a given year.

Energy efficiency can be broadly defined as the introduction of new equipment, a new process, and/or new techniques, which can influence the amount of energy consumed per unit of output. A structural change reflects the shift in the industrial composition. Ideally, using a finer industrial classification can tell more about the shift and yield a more reasonable explanation, but data availability remains a challenge. Similar to Polenske and Lin (1993), I use China's classification of six material-production sectors: the Primary

Industry (Farming, Forestry, Animal Husbandry, Fishery & Water Conservancy); Industry; Construction, Transportation, Storage, Postal & Telecommunications Services; Wholesale, Retail Trade & Catering Service; and The Others. Using this classification is also determined by the data. The energy consumption data for different sectors is provided in the *China Energy Statistical Yearbook* which designates 7 sectors (the first five are the same as the above. The 6th and 7th sectors are Residential Consumption and Others, respectively). The GRP data are from the *China Statistical Yearbook,* which has data about more sectors but only the first five are same as those in the *China Energy Statistical Yearbook*. In this context, I adopt the first five sectors plus a sixth "the others" which includes all the other sectors.

4. Energy-intensity Changes

In this section, I present the results of shift-share analysis both for China and for the three provinces. As explained in Table 1-1, Ningxia Province energy consumption data by sector for 2000, 2001, and 2002 are not available, which leaves the 2000-2003 shift-share analysis blank. For the convenience of reading, I show only the results of the shift-share analysis. Readers can find tables about energy consumption by sector, and GDP/GRP by sector in the Appendix.

Table 1-3 shows the shift-share analysis for China's energy intensity in the past ten years (1995-2004). This country's energy intensity continues to decrease from 1995 to 2001/2002, from 163.25 to 98.3 kg of standard coal equivalent per 100 Yuan. I note that its EI shows an increasing trend in 2003 and 2004. In 2003 China's EI increases by 6 EI units, while in 2004 this increase is accelerated to be 11 EI units. Also note that the industrial-mix signs are all positive (except the value for 1998) in these ten years. This indicates that China's industrial structure in these ten years actually increases its energy intensity. This further might suggest that it is hard for China to reduce its energy intensity through changing its industrial structure. Note that the 1998 industrial-mix value is negative, -0.64. In 1998 China started its "laid off" employment reform by laying off many employees of state-owned companies and closing some old, inefficient, or unprofitable state-owned companies, which had great impacts on China's industrial structure. Efficiency shift played a role in decreasing energy intensity in most of those years except 2003 and 2004. During this period, changes in the efficiency shift account for the decrease of energy intensity, while changes in the industrial mix mostly increase the energy intensity of China.

Table 1- 3: Shift-share Analysis of Energy Intensity in China's Material Production Sector

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Constant share		163.25	160.74	138.44	123.21	115.31	108.54	98.30	98.38	104.35
Industrial mix		0.92	2.71	-0.64	0.95	2.39	0.34	0.34	1.10	0.29
Efficiency shift		-3.42	-25.02	-14.59	-8.85	-9.16	-10.58	-0.26	4.88	10.77
Total EI	163.25	160.74	138.44	123.21	115.31	108.54	98.30	98.38	104.35	115.42

Unit: Kilograms of standard coal equivalent per 1,000 Yuan of output
Source: calculated from the related tables in Appendix

In the case of Inner Mongolia, the effect of the efficiency shift is still significantly larger than that of industrial mix. Table 1-4 and Figure 1-2 show these two effects. In the past decade, the EI of Inner Mongolia has decreased and then increased, fluctuating about roughly 200 EI units. Industrial mix in general does not contribute to energy efficiency except in 1998 and 2000. In contrast, for most years, the efficiency shift is negative, decreasing energy intensity. This effect is noticeable especially in 1996 and 1998. In the early 2000s, the effect of the efficiency shift is relatively minute, and in 2004, this effect actually is positive on energy intensity. Figure 1-2 offers an explicit comparison between these two effects. Regardless of being negative or positive, the efficiency shift always has a larger influence on the total EI than the industrial mix does, which matches the trend at the national level discussed above.

Table 1- 4: Shift-share Analysis of Energy Intensity in Inner Mongolia's Material Production Sector

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Constant share		258.26	204.39	248.58	198.75	197.29	191.16	186.73	181.53	175.84
Industrial mix		10.06	6.77	-0.51	3	-2.36	2.06	1.13	1.62	12.50
Efficiency shift		-63.93	37.42	-49.32	-4.45	-3.78	-6.50	-6.33	-7.31	32.19
Total EI	258.26	204.39	248.58	198.75	197.29	191.16	186.73	181.53	175.84	220.53

Unit: Kilograms of standard coal equivalent per 1,000 Yuan of output
Source: calculated from the related tables in Appendix

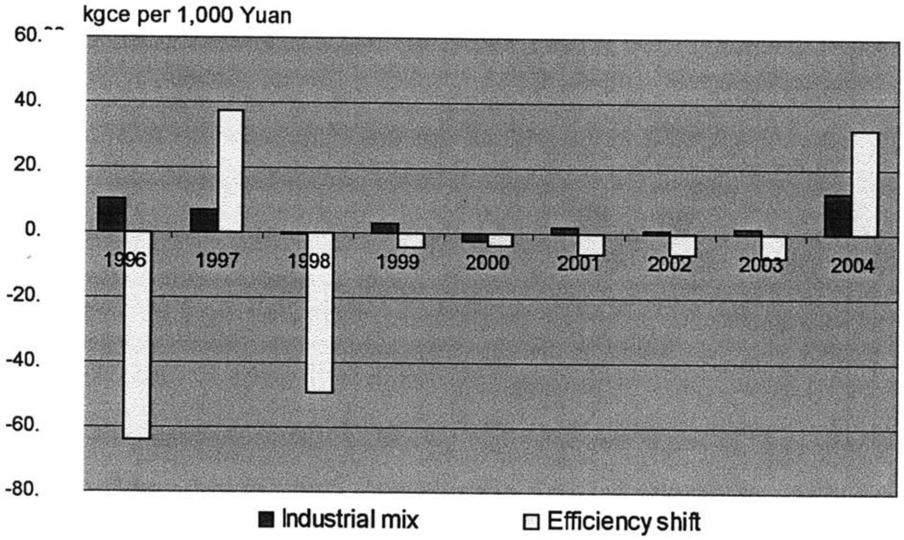

Figure 1- 3: Inner Mongolian Industrial Mix and Efficiency Shift
Source: Table 1-4

Liaoning shows a constant decrease of energy intensity except in the year 2000, which is slightly higher than the previous year and then returns to a lower level. This indicates that this province has made progress in improving its energy efficiency. Examining the effects of industrial mix and efficiency shift, we can easily find that its efficiency shift has been continuously negative, while the industry mix varies above and below zero. The efficiency-shift trend clearly shows that, Liaoning, in the past ten years, has introduced new energy technology or other techniques that improve energy efficiency and has made steady energy reductions. Different from Inner Mongolia, Liaoning also makes more progress in optimizing its industrial structure: in 5 out of the total 9 years the industrial mix is negative. Still, efficiency shift remains a main force in changing energy intensity. From both the table and the figure, we see that generally speaking the efficiency shift has higher values than the industrial mix.

Table 1- 5: Shift-share Analysis of Energy Intensity in Liaoning's Material Production Sector

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Constant share		276.39	218.62	208.69	167.77	148.65	150.86	140.38	132.56	128.40
Industrial mix		-6.76	3.72	-5.47	1.32	5.16	-3.09	-1.35	0.50	-2.53
Efficiency shift		-51.01	-13.65	-35.44	-20.44	-2.96	-7.39	-6.48	-4.66	-3.01
Total EI	276.39	218.62	208.69	167.77	148.65	150.86	140.38	132.56	128.40	122.86

Unit: Kilograms of standard coal equivalent per 1,000 Yuan of output
Source: calculated from the related tables in Appendix

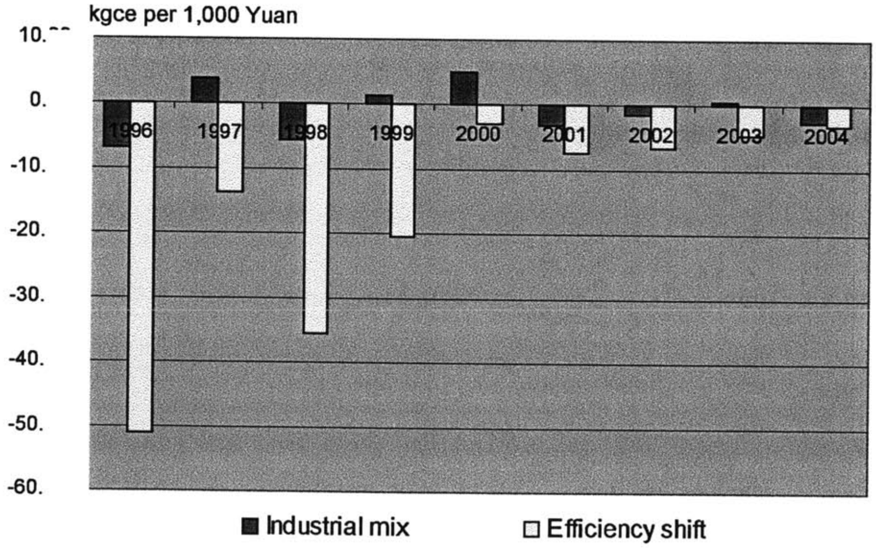

Figure 1- 4: Liaoning's Industrial Mix and Efficiency Shift
Source: Table 1-5

Due to data unavailability, we have only five years' data about shift and mix effects. Based on these results, we can see first that, as a whole Ningxia Province has increasing energy intensity in the period 1995 through 2004. Although its EI in 1996 decreases to

227.7 from 308.2 in 1995, the coming three years actually have increasing energy intensity. The 1997, 1998, and 1999 EI stays basically at the same level (around 240 EI units), and then in 2004, it soars to 427.6, almost doubling that of 1996. In addition, the efficiency shift does not stay constant, changing between positive and negative. The years of 1996 and 2004 witness a significant negative efficiency shift compared to other years but meanwhile the industrial mix also presents larger trade-offs, positive effect on energy intensity. To some degree, we can infer that, on the one hand, Ningxia, a relatively undeveloped region in China, has not improved its technology of utilizing energy significantly in the past ten years. On the other hand, its industrial structure still remains energy-intensive. We will explain this in detail in the coming section.

Table 1- 6: Shift-share Analysis of Energy Intensity in Ningxia's Material Production Sector

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Constant share		308.24	227.73	240.68	233.61					563.56
Industrial mix		10.06	0.48	-4.92	0.01					38.86
Efficiency shift		-90.57	12.47	-2.15	7.58					-74.83
Total EI	308.24	227.73	240.68	233.61	241.20					427.60

Unit: Kilograms of standard coal equivalent per 1,000 Yuan of output
Source: calculated from the related tables in Appendix

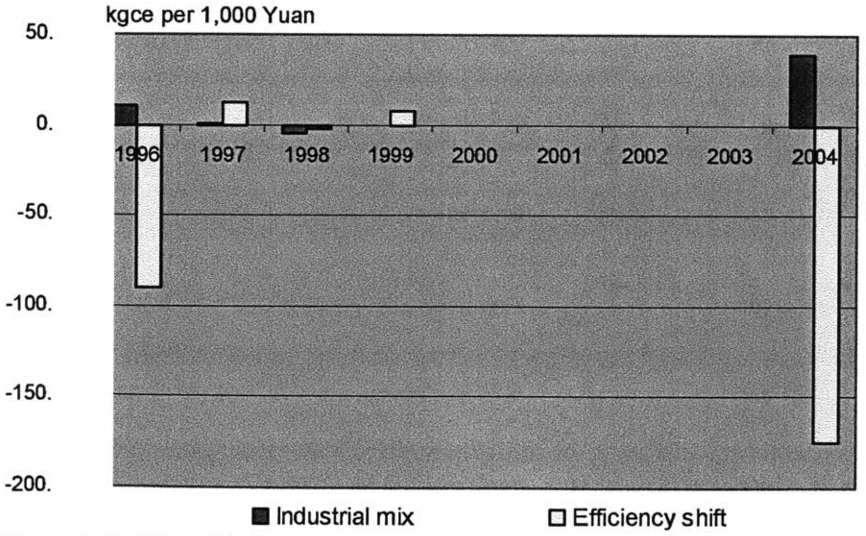

Figure 1- 5: Ningxia's Industrial Mix and Efficiency Shift
Source: Table 1-6

5. Energy investment, efficiency and renewable energy

In the previous section, we find that the energy-efficiency shift is the main factor explaining the change of energy intensity either in China as a whole or in each of the three provinces. As defined, we assume this efficiency effect is triggered by technology innovation. In this context, we explore the investment in energy technology in China and by examining the data from these provinces to understand the situation.

Table 1-7 describes the investment in technology improvements and transformation in the energy industry by region in China. On average, China's investment in technology has increased steadily in those years, from 0.441 Billion Yuan in 1991 to 3.549 Billion Yuan in 2002, an increase of 700% in 11 years. Compared to this national average, Both Inner Mongolia and Ningxia have underinvested. Ningxia's input remains roughly at the level of 400 Million Yuan during this period. Its investment in 2002 is only 367 Million Yuan, considering the factor of deflation, lower than that of 1995 which is 353 Million Yuan. Ningxia has experienced a long-term underinvestment in technology updates and transformation in energy industry. This underinvestment naturally cannot contribute to increasing energy efficiency and can cause the efficiency shift to be insignificant in decreasing energy intensity, which might well explain why this province, unlike many peers in China, has an increasing energy-intensity curve in the past ten years. Inner Mongolia, as shown in Figure 1-5, also experiences an underinvestment in this period. Since 1996, its investment has always been less than half of that of the average national level, and we can also find that from 1996 through 2000, Inner Mongolia invests about the same amount for technologies in the energy industry, around 700 Million Yuan (roughly 90 Million US Dollars). We have illustrated that Inner Mongolia's energy intensity basically has remained constant or only slightly decreased during 1996 through 2003, which can be matched by its investment profile.

Note that Liaoning, in contrast with the other two provinces, in general, has increased the technology investment annually. In 1991, Liaoning invested only 1,160 Million Yuan for the technology innovation in energy industry, but this number tripled to 3.75 Billion Yuan after four years. Then, from 1995, this investment continues to climb and reaches 9.2 Billion Yuan in 2002. The inputs of years around 1998 stay almost the same or only slightly decreased, which might be connected to the 1998 "laid-off" reform when many heavy industries or some other state-owned companies were shut down, which could lead to the non-increase in energy technology investment. Figure 1-5 well illustrates this trend. For each year, Liaoning's investment is more than double that of the provincial average. These large investments benefit Liaoning in decreasing its energy intensity remarkably. As discussed earlier, in 1995 Liaoning's energy intensity was 276.4 units almost double that of the national value (163.4 units), but in 2004, Liaoning had decreased this number to 122.86, very close to the national 115.42 EI units. This achievement, although we cannot show it strictly at this stage, can be reasonably attributed to the continuously increasing inputs in energy technology investment by Liaoning.

Table 1- 7: Investment in Technical Updates and Transformation in the Energy Industry

	1991	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
National (provincial average)*	*4.41*	*14.59*	*17.03*	*19.38*	*22.21*	*24.38*	*29.47*	*31.63*	*35.49*
Inner Mongolia	3.55	13.82	6.93	6.49	6.38	7.85	7.84	9.31	17.05
Liaoning	11.60	37.51	48.92	65.92	65.18	62.77	71.39	84.49	91.94
Ningxia	1.88	3.53	3.95	5.15	5.12	4.00	3.97	3.96	3.67

Unit: 100M Yuan, current price
*: the average of 31 China's provinces and municipalities (not including Hong Kong, Macau and Taiwan), calculated from the national total divided by 31.
Note: 1992/1993/1994, and 2003/2004 data unavailable.
Source: China Energy Statistics Yearbook (1992-2005)

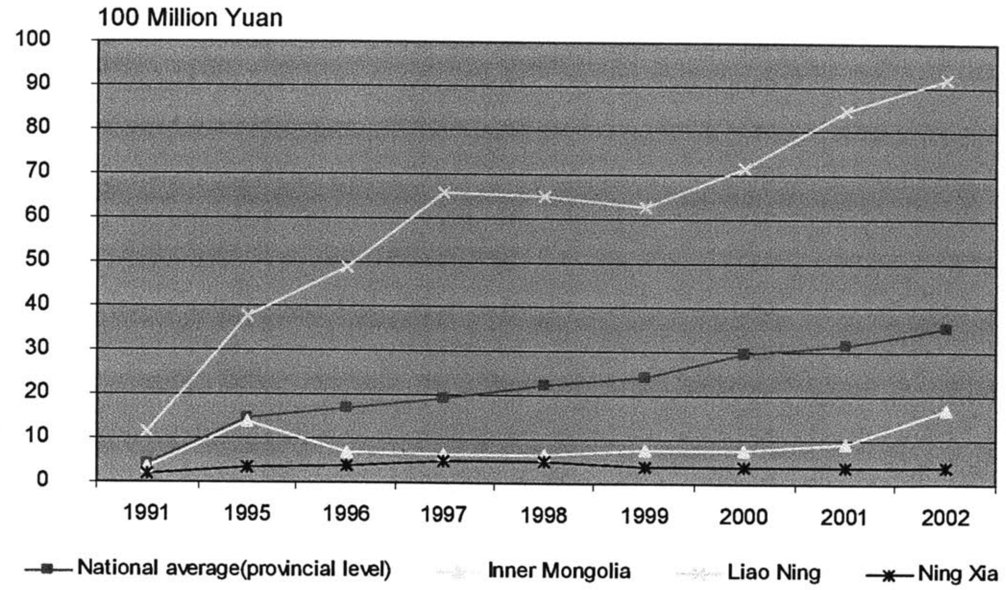

Figure 1- 6: Investment in Technical Updates & Transformation in the Energy Industry
Source: Table 1-7

However, these investments in the energy industry are not necessarily directed to renewable energy development. Due to China's long push and policy motivation for developing renewable energy, we believe that these provinces, more or less, have some renewable energy industries that might absorb some investment for energy technology innovation and then contribute some to energy efficiency. In the following, I discuss the development of renewable energy in these regions.

Unfortunately, due to the limitation of our data, we cannot analyze in detail the renewable energy development in those three provinces. But we can still give brief description about their status to yield some knowledge.

Ningxia province, given its geographic location, has a good potential for developing the solar industry. Its solar industry development can be dated back to the 1970s with technologies including solar stoves, solar water heaters, solar-powered houses, and household solar PV systems. Yinchuan, the capital of Ningxia, ranks the 3rd, after Lasha and Huhehaote, among all the 31 capital cities in China in terms of solar power potential capacity. San (2004) shows that the 2003-2010 planning of Ningxia solar power utilization will bring forth an annual reduction of energy consumption by 432,000 Tonnes of Coal Equivalent (TCE), about 5% of its 2004 coal consumption. However, the investment in the solar industry is still minimal: up to 2003, government investment for rural energy has accumulatively amounted only to 28 million RMB (about 3.7 Million US Dollars). Although having a relatively long history, the solar industry, the main renewable industry in Ningxia, remains still at an infant stage and its minimal scale prevents it from playing some noticeable role in bringing energy technology innovation or in reducing energy intensity.

Inner Mongolia has the largest wind power potential in China. Up to 2005, the total capacity of wind power was 166,000 kilowatt hours (kwh), the highest in China. However, only 1% of this potential has been developed so far. Up to 2004, there were 158,000 mini wind turbines, which supply 150,000 households with electricity. In 2010, this wind capacity will reach 4,000,000kwh, about 25 times that of 2005. However, even this planned amount, only accounts for 0.0075% of the electricity consumption by Inner Mongolia in 2004, which is 53.6 billion kwh. Similar to Ningxia, Inner Mongolia has a well-developed wind power industry, but it is still too little to decrease energy efficiency.

Due to data unavailability in Liaoning province, I cannot discuss more about its renewable energy industry. Renewable energy is less developed compared to the other two provinces. On the one hand, while the provincial government issues some policies or laws, these regulations mainly direct renewable energy development to the rural areas, which indicates that the scale is minimal. On the other hand, things are changing. In Liaoning, energy conservation and developing renewable energy have been on the provincial 11th 5-year planning agenda (Liaoning, 2006).

6. *Industrial Structure*

To play a role in decreasing energy efficiency, provincial authorities should promote the renewable energy industry much more than they do at present. The minimal scales of renewable energy in the three provinces explain why this industry cannot show the expected effect of improving energy efficiency. In contrast, investments in energy technology updates and transformation explain to a certain extent why there is difference of energy shift effect among the provinces. We also see that the industry mix usually has a minimal effect in changing energy intensity.

As mentioned before, the coal industries, energy-intensive sectors, are the main force driving the economy of Inner Mongolia and Ningxia, and in Liaoning, the steel industry plays a similar role, which is also an energy-intensive industry. Table 1-8 shows two supporting companies in Inner Mongolia and Ningxia: Shenhua and Ningxia Coal. Each of them is regarded as the main power fueling the GDP growth of its host province. As the economy relies on these energy-intensive industries for growth, it may face internal challenges of adjusting the industrial structure to a better level for decreasing energy intensity. Such a 'better' level is a structure at which companies can produce same outputs with less energy inputs. To understand the scale of such companies, for example, Shenhua Corporation, we can compare it with Peabody, the largest U.S. coal company, which made total revenue of 3.6 billion USD in 2004. Shenhua's 2004 revenue was 56.5 billion Yuan, about 7 billion USD, almost double that of Peabody.

Table 1- 8: Shenhua and Ningxia Coal

Rank	Corporation	Assets (Billion Yuan)	Proved Reserve (Billion tonnes)	Annual coal production (Million tonnes)	Province
1	Shenhua Corporation	188.8	> 223.6	121	Inner Mongolia
8	Ningxia Coal Corporation	25.1	24.1	33	Ningxia

Note: Ningxia Coal Corporation was merged by Shenhua in 2006.
Source: Companies' websites

7. Conclusion and Discussion

Through the shift-share analysis, I show that between 1995 and 2004, the energy efficiency shift plays a main role in changing the energy intensity of China, and three of its provinces, Inner Mongolia, Liaoning and Ningxia. Liaoning province, as a base of heavy industry, still decreases its energy intensity through those years. Inner Mongolia and Ningxia, although having a better developed renewable industry than Liaoning, have experienced flat or climbing curves of energy intensity. Renewable energy development, which is supposed to bring in new energy technology that can decrease energy intensity, has not shown this effect in Inner Mongolia and Ningxia. This can be explained by the minimal scale of this industry in both regions. The investment in the technology updates and transformations in energy industry can in some way explain the effect of efficiency shift in our three study provinces.

However, due to data limitations, I cannot further analyze the status of renewable energy development in China and in particular in these three provinces. This prevents me from examining what exactly renewable energy industry has brought to technology innovation. This remains a problem for future research.

Another puzzle occurs. The fact that the energy-intensive coal industry remains a base industry for both Inner Mongolia and Ningxia seems to explain why they cannot realize an energy-intensity decrease. But Shanxi, the largest coal production province in China, has successfully decreased its energy intensity in the past decades (Polenske 2007). Then why can Shanxi do this decrease while Inner Mongolia and Ningxia cannot? This can also be a question for future research. Both questions call for field trips in China to collect data, interview companies, and government, to find appropriate answers.

Appendix

Note 1.

All data come from *China Energy Statistics Yearbook 1996-2005*, and *China Statistics Yearbook 1996-2005*.

Note 2.

Energy consumption data are edited by the author from *China Energy Statistics Yearbook 1996-2005*. The total consumption is composed of the following ten sub-categories and is the sum of these ten after converting into standard coal equivalent via calorific value calculation: coal total, coke, coke oven gas, other gas, other coking products, petroleum products total, natural gas, heat, electricity, and other energy.

These data tables with sub-categories are not attached here but are available upon request from the author.

Note 3.

Sectors:

1. Farming,Forestry,Animal Husbandry,Fishery&Water Conservancy
2. Industry
3. Construction
4. Transportation, Storage, Postal, &Telecommunications Services
5. Wholesale, Retail Trade, & Catering Service
6. *Residential consumption*
7. *Others*

67. Sum of 6 and 7 to match the classification of GDP/GRP sectors

Table 1. Energy consumption in China's Material Production Sector (10,000 tonnes standard coal equivalent based on calorific value calculation)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	3,914.02	4,124.20	4,080.69	4,076.28	4,239.55	4,286.98	4331.86	4,593.60	4,754.12	5,818.18
2	69,930.63	74,726.76	69,823.12	66,687.98	64,390.11	64,735.67	62,488.43	68,161.68	80,398.58	98,384.39
3	897.41	978.75	842.26	1,091.69	1,599.52	1,736.29	1,090.17	1,203.09	1,316.25	2,741.89
4	5,159.18	5,245.47	6,550.95	7249.47	8,325.87	8,977.14	9,128.13	9,909.21	11,476.24	13,732.18
5	1,472.05	1,690.08	1,630.31	1738.9	1,975.12	1,993.65	2,048.23	2,219.21	2,612.87	3,098.56
67	16,765.29	19,160.07	16,296.37	14,385.74	14,935.93	15,378.63	15,379.76	16,379.92	18,216.19	20,452.03
Total	98,138.58	105,925.33	99,223.70	95,230.06	95,466.10	97,108.36	94,466.58	102,466.71	118,774.25	144,227.23

Source: SSB&NDRC, multiple years

Table 2. China's Real GDP/GRP (100M RMB, All the figures are in constant 1995 prices)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	12,328.80	13,438.94	13,678.95	14,356.88	14,599.82	14,628.20	15,219.34	15,962.03	16,591.76	18,960.57
2	25,410.41	28,231.27	31,198.16	32,939.31	35,397.10	39,047.30	41,845.43	45,532.28	51,538.72	57,348.07
3	3,926.55	4,397.88	4,630.43	5,161.11	5,518.92	5,888.00	6,295.78	6,937.51	7,941.81	8,739.00
4	3,140.23	3,391.72	3,654.98	4,065.93	4,499.69	5,408.60	5,893.77	6,358.45	6,519.01	7,024.54
5	5,070.40	5,397.53	5,928.90	6,490.71	6,971.33	7,316.00	7,819.91	8,395.04	8,967.67	9,219.59
67	10,239.09	11,040.08	12,582.32	14,278.64	15,805.47	17,180.00	19,025.31	20,973.77	22,260.62	23,671.30
Total	60,115.49	65,897.42	71,673.74	77,292.58	82,792.34	89,468.10	96,099.53	104,159.08	113,819.60	124,963.08

Source: SSB&NDRC, multiple years

Table 3. Energy consumption in Inner Mongolia's Material Production Sector (10,000 tonnes standard coal equivalent based on calorific value calculation)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	87.46	117.64	136.73	120.71	118.13	126.59	154.56	159.42	184.66	216.67
2	1,381.03	1,363.18	1,780.24	1,529.41	1,798.66	1,969.51	2,116.30	2,326.02	2,766.82	3,605.16
3	35.85	46.05	63.97	62.28	53.09	54.82	50.85	57.52	68.69	88.11
4	150.86	154.17	184.36	187.11	137.29	144.16	149.75	164.12	174.14	329.35
5	62.81	89.23	122.86	105.83	100.68	89.29	89.12	93.26	106.39	252.77
67	269.93	341.28	443.20	390.28	326.78	293.79	308.60	322.95	369.79	1,150.06
Total	1,987.95	2,111.54	2,731.36	2,395.63	2,534.62	2,678.16	2,869.18	3,123.29	3,670.48	5,642.12

Source: SSB&NDRC, multiple years

Table 4. Inner Mongolia's Real GDP/GRP (100M RMB, All data are in constant 1995 prices)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	235.39	328.17	323.78	345.37	347.37	350.80	356.75	371.71	407.79	477.40
2	232.51	338.36	375.80	403.80	433.90	455.21	503.67	568.74	700.44	958.11
3	63.00	67.94	71.44	80.99	88.26	101.07	119.07	153.81	244.96	298.86
4	60.46	87.52	98.43	107.21	118.16	142.59	161.82	186.59	210.41	229.19
5	54.35	74.62	80.59	96.54	104.33	133.45	147.30	162.82	175.49	191.84
67	124.04	136.49	148.75	171.46	192.67	217.89	247.97	276.86	348.31	403.01
Total	769.75	1,033.11	1,098.79	1,205.37	1,284.69	1,401.01	1,536.57	1,720.53	2,087.40	2,558.41

Source: SSB&NDRC, multiple years

Table 5. Energy consumption in Liaoning's Material Production Sector (10,000 tonnes standard coal equivalent based on calorific value calculation)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	128.50	147.32	145.53	144.88	148.41	143.18	148.09	145.83	144.75	151.08
2	5,938.14	5,454.32	5,540.41	5,011.22	4,759.76	5,483.66	5,251.18	5,411.11	5,837.28	6,005.13
3	45.86	40.98	68.96	64.79	64.19	65.67	68.13	68.75	73.53	77.91
4	245.12	195.10	304.37	290.10	289.98	442.32	653.91	637.74	594.25	635.94
5	61.41	67.15	49.53	51.00	54.92	58.61	62.95	66.77	69.47	99.96
67	984.55	1,056.68	1,015.11	852.90	877.94	850.21	881.23	985.58	943.30	1,140.78
Total	7,403.59	6,961.56	7,123.91	6,414.89	6,195.21	7,043.64	7,065.49	7,315.78	7,662.58	8,110.80

Source: SSB&NDRC, multiple years

Table 6. Liaoning's Real GDP/GRP (100M RMB, All data are in 1995 constant prices)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	347.05	478.09	474.76	523.50	520.28	503.44	544.44	596.76	612.24	739.57
2	1,207.67	1,390.71	1,533.26	1,639.11	1,793.91	2,114.89	2,190.12	2,357.89	2,542.04	2,721.37
3	162.31	159.95	172.45	188.31	205.56	229.51	250.43	280.99	340.09	428.33
4	174.31	196.20	219.13	267.88	314.17	350.46	394.50	430.14	492.81	588.88
5	312.95	394.55	428.72	525.16	575.20	631.64	696.51	768.72	798.57	860.70
67	474.38	564.84	585.37	679.60	758.39	839.12	957.08	1,084.43	1,182.10	1,263.03
Total	2,678.68	3,184.34	3,413.69	3,823.56	4,167.52	4,669.06	5,033.08	5,518.93	5,967.85	6,601.86

Source: SSB&NDRC, multiple years

Table 7. Energy consumption in Ningxia's Material Production Sector (10,000 tonnes standard coal equivalent based on calorific value calculation)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	23.64	19.55	21.19	20.06	21.15	*	*	*	9.83	9.73
2	307.17	321.19	359.34	380.11	428.40	*	*	*	1,851.69	1,365.95
3	2.65	1.41	3.14	2.83	3.04	*	*	*	2.68	7.33
4	39.41	31.92	35.72	34.52	27.86	*	*	*	113.82	37.33
5	0.75	0.68	0.36	5.79	12.46	*	*	*	15.86	18.58
67	76.40	75.18	79.29	79.06	87.24	*	*	*	120.51	409.26
Total	450.02	449.93	499.04	522.37	580.15	*	*	*	2,114.40	1,848.19

*: data unavailable

Source: SSB&NDRC, multiple years

Table 8. Ningxia's Real GDP/GRP (100M RMB, All data are in constant 1995 prices)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
1	32.62	44.12	44.06	47.86	47.82	45.95	48.79	52.32	54.04	61.15
2	50.01	69.02	71.94	74.78	80.38	93.00	100.62	113.67	139.53	174.92
3	10.78	12.35	14.22	17.64	21.89	27.04	31.63	36.00	47.41	49.87
4	6.69	11.93	14.09	15.84	17.96	19.31	22.59	25.33	27.11	28.07
5	12.77	17.38	18.17	18.71	20.44	21.60	23.08	25.04	27.22	29.81
67	33.13	42.78	44.87	48.78	52.04	58.67	66.97	73.68	79.88	88.40
Total	146.00	197.57	207.35	223.61	240.52	265.57	293.68	326.05	375.18	432.22

Source: SSB&NDRC, multiple years

References

Bendavid-Val, Avrom. 1991. The 4th Edition. *Regional and Local Economic Analysis for Practitioners*. New York, NY: Praeger Publishers. 67-85.

SSB & NDRC (State Statistical Bureau and National Development and Reform Commission of P.R. China). *China Energy Statistical Yearbook* (CESY) 1996-2005 (multiple years). China Statistics Press. Including:
CESY. 1995/1996.
CESY. 1997-1999.
CESY. 2000-2002.
CESY. 2003.
CESY. 2004.
CESY. 2005.

Fisher-Vanden, Karen, Jefferson Gray H., Liu Hongmei, and Tao Quan. 2004. What is driving China's decline in energy intensity? *Resource and Energy Economics* 26: 77-97.

Gao, Hu, Zhongying Wang and Yongqiang Zhao. 2005. Renewable Energy Options in improving the life of western rural poor population in China. Energy Research Institute of National Development and Reform Commission of China.

Garbaccio, R.F., Ho, M.S., Jorgenson, D.W., 1999. Why has the energy-output ratio fallen in China? *Energy Journal*. 20: 63–91.

Liaoning (Governmental Official Website). 2006. URL: http://www.ln.stats.gov.cn/jrln/gy.htm.

Lin, Xinnuan, and Karen R. Polenske. 1995. Input–output anatomy of China's energy use changes in the 1980s. *Economics System Research*. 7: 67–84.

Ma, Qizhi. 2006. URL: http://www.cctd.com.cn/detail/06/01/02/00055780/content.html.

Martinot, Eric. 2001a. Renewable energy investment by the World Bank. *Energy Policy*. 29: 689-699.

Martinot, Eric. 2001b. World Bank energy projects in China: influences on environmental protection. *Energy Policy*. 29: 581-594.

Moniz, Ernest J., and John Deutch. 2007. The Future of Coal. MIT Laboratory for Energy and the Environment. URL: http://web.mit.edu/coal

North News. 2006. Inner Mongolia ranks NO. 1 in the wind power in China. March 21st 2006. URL: http://www.newenergy.com.cn

NREL (National Renewable Energy Laboratory). 1999. Rneweable energy markets in China: an analysis of renewable energy markets in Guangdong, Jiangxi, Jilin, and Yunnan provinces with updated information from Beijing. URL: http://www.doe.gov/bridge

NREL. 2004a. Renewable Energy Policy in China: Review. URL: http://www.nrel.gov/China

NREL. 2004b. China's plan for renewable energy. URL: http://www.nrel.gov/China

NREL. 2006. Developing renewable energy in China. URL: http://www.nrel.gov/China

PDO (People's Daily Online). 2005. Inner Mongolia to double annual coal output by 2010. URL: http://english.people.com.cn/200512/27/eng20051227_231175.html.

Polenske, Karen R., and Xinnuan Lin. 1993. Conserving energy to reduce carbon-dioxide emissions in China. *Structural Change and Economic Dynamic*. 4(2): 249-265.

Polenske, Karen R., and Francis C. McMichael. 2002. A Chinese coke-making processing-flow model for energy and environmental analysis. *Energy policy* 30: 865-883.

Polenske, Karen R. 2007. Comparative and competitive energy strategies: Brazil and China. MIT SPURS/Humphrey Program Presentation, March 19 2007.

San, Jianren. 2004. The countermeasure analysis and exploration and utilization of solar energy in Ningxia. URL: http://www.newenergy.com.cn/html/2007-1/2007126_13040_1.html

SEPA (State Envirnonment Protection Administration of China). 2004. The green technology: coal gasification. URL: http://www.chinaeol.net/bell-green/xsyj/0402pdf/mqh.pdf

Sinton, J.E., Levine, M.D., 1994. Changing energy intensity in Chinese industry: the relative importance of structural shift and intensity change. *Energy Policy.* 22: 239–255.

Smil, V. 1990 China's Energy. Report Prepared for the U.S. Congress, Office of Technology Assessment, Washington, DC.

SSB (State Statistical Bureau), 1996. *China Statistical Yearbook.* China Statistical Publishing House, Beijing. URL: http://www.stats.gov.cn/english/statisticaldata/yearlydata/

SSB, 1997. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 1998. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 1999. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2000. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2001. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2002. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2003. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2004. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

SSB, 2005. *China Statistical Yearbook.* China Statistical Publishing House, Beijing.

Wang, Joy H. 2005. Wind power in China: social acceptability and development of a domestic manufacturing industry. Working paper, Michigan State University.

Zhang, Zhongxiang. 2003. Why did the energy intensity fall in China's industrial sector in the 1990s? *Energy Economics.* 25: 625-638.

21 Century Economics. 2005. The sample of Inner Mongolia: the energy-based pattern changes China's layout of regional economics. August 17th 2005.

Coal to Liquids: Why and How It Makes the Case in China

Abstract

In this study, I examine why and how coal liquefaction, or coal-to-liquids, makes its case in China. Different from Europe and the United States, China is actively developing coal-to-liquids technologies and projects. Different from conventional wisdom that in China the central government mandates and guides coal liquefaction to ensure energy security, I argue that the diversification strategy of state-owned coal companies is another key driver for coal-liquefaction development in China, in addition to the state interest and policy that initiated this move. Given current extensive conversation and debate on Chinese technology innovation capability, my research sheds light on the innovation system in China and provides implications for technology policy and investments.

Chinese energy resources and policy justify the development of coal liquefaction, and it was the economy and the coal industry development in the 1990s that made coal companies pursue business diversification into coal chemicals through coal liquefaction. I support this business-diversification argument with three cases of major coal companies developing coal-to-liquids projects. I also highlight the implications from this technology innovation in China: This bottom-up driving force for coal liquefaction indicates the capability of change and innovation in the Chinese system.

1. Introduction

The People's Republic of China (China) is actively developing coal-to-liquids (CtL) technologies. Meanwhile in Europe and the United States, these technologies have evolved to an unfavorable stage because of the intense capital investment and economic uncertainty caused by the volatility of crude oil prices, technological risks, and significant carbon-dioxide discharge (Vallentin 2008a, 2008b). CtL is a process of coal liquefaction with the action of a catalyst, and CtL includes two types of technologies: direct coal liquefaction, DCL, which turns coal directly into liquid products, and indirect coal liquefaction, ICL, or Fischer-Tropsch synthesis (FTS), which gasifies coal into syngas and then produces liquids from the syngas. Originated in Germany in the 1940s to meet urgent needs of liquid transportation fuels, CTL's peak production capacity reached 4.2 million metric tonnes per year (Mt/y) for DCL, and 0.6 Mt/y for FTS in Germany (Dadyburjor and Liu, 2004). Then the development of coal liquefaction was largely determined by the availability and price of petroleum. For example, in the 1950s due to the discovery of inexpensive oil in the Middle-East, the coal liquefaction development was essentially ceased in the world except in South Africa which lacked access to petroleum.

Currently in China there is one DCL project (the only one in the world) and five ICL projects being developed by state-owned major coal companies, with a total annual capacity of 2.6 million tonnes for the first stage. Developers all aim to expand production capacity after the success of the first-stage operation, and there are more CtL projects being planned or at the stage of feasibility studies.

Then why are CtL technologies being planned and developed with real investment and projects in China? One well-received explanation is the energy-security policy. China has a serious quest for energy security, especially oil for which over 50% of the consumption relies on imports, and CtL meets this demand through converting coal, the abundant fossil fuel in China, into oil (Sun et al. 2005; Zhang 2007; Wu 2009; Su et al. 2008; USCEC 2009). Also, unlike Europe and the United States, China gives low priority to carbon-dioxide (CO2) mitigation, a rather favorable policy framework for CtL, which makes CtL encounter many fewer barriers. In such an environment, CtL is advocated and developed with other favorable conditions, including economic advantages (low CtL capital costs), and strong CtL investors (large state-owned companies) (Vallentin and Stuttgart 2010).

However, this type of top-down argument, i.e., national policy implemented by SOEs, can only partially explain why CtL make its case in China: this did move CtL development at the beginning, but could not sustain the proactive pursuit of CtL by those major developers. A bottom-up force, for instance, from the coal companies, cannot be overlooked when examining the development of CtL in China. National energy-security policy, state ownership of coal majors, low capital costs, and priority of carbon regulation provide low entry barriers for CtL, but do not constitute sufficient incentives for companies to develop CtL projects, which demand investment of billions of Yuan and still carry technical or financial risks. If we only consider the national policy or the will of central government as the driver for CtL, then we miss the fact that in China, state-owned enterprises (SOEs) are transitioning into entities that also operate in the market economy and pursue business interests: CtL as an immature technology carries risks, unlikely to provide return on investment within just a few years. Government mandate or interest is not sufficiently convincing to explain the active pursuit of CtL by those SOE developers.

In this analysis, I hypothesize the following about CtL development in China: after being initiated by the central government, CtL development in China has been largely spurred from the bottom up: those coal majors' strategy of diversification and active pursuit for business opportunities. Exploring and testing this hypothesis can shed light on understanding why and how CtL can succeed in China. I also point out that, from the perspective of technology innovation, Chinese companies play a critical role in developing or upgrading CtL technologies. While developing CtL technologies and projects, the developers, mainly major coal companies, benefit from the knowledge spillovers of this advanced coal technology, and embrace the diversification into the coal-chemical industry. This would imply that the Chinese system is capable of innovation and change, unlike what some western analysts observed.[2] Another contribution of my research is to understand China's innovation system.

To test my hypothesis, in the following section, I introduce the CtL origin and development in China. Then, I analyze how CtL makes its case within the technological system intertwined with energy policy, technology innovation, and interests of parties involved in this development. Then, I elaborate why and how those state-owned major coal companies pursue CtL technologies as a diversification strategy in order to improve their business, within the background of China's economy, policy, and industries in the 1990s and later. Then I further support my hypothesis regarding business diversification with three case studies about the Shenhua Group, Yankuang Group, and Jinmei Group, three major coal companies and CtL developers in China. In the last section, I conclude this analysis.

2. CtL in China

Currently, South Africa and China are the only two countries developing commercial CtL technologies and plants, although the United States and Europe have some companies focusing on CtL research or small-scale demo plants. Since the 1950s, the South African Coal Oil and Gas Corporation (Sasol) has been operating two commercial indirect coal

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[2] See Steinfeld, Lester, and Cunningham (2009) for more description regarding this pessimistic stance.

liquefaction plants, producing about 30% (150,000 barrels per day) of South Africa's automotive fuels (Sasol 2009).

In China, CtL technology was initially charged with the mission of maturing into a strategic technology to enhance energy/oil security, and also breeding a new 'coal liquefaction industry', as reported in the 1990s in the 11th five-year plan for the coal industry.[3] In China, some major coal companies are CtL project developers, but the central government provided the initial and important support for research on CtL technologies, through the state high-tech "863" program. Governmental supports covered fundamental research topics of DCL technology, including process development, catalysts and kinetics, reaction engineering and reactor design and simulation, et al. (Liu, Shi, and Li 2009). In the 1990s, the State Council, after comparing three companies,[4] selected Shenhua Group, the largest coal company in the country, as the developer for the world's first modern DCL facility, with a support of a 11-billion-Yuan "Coal Replace Oil" fund. Since then Shenhua has been active in DCL technology research and development (R&D) and project development.

For the indirect liquefaction, or FTS technologies, China started the research in the 1970s through the Institute of Coal Chemistry (ICC) under the Chinese Academy of Science (CAS). ICC focused on iron catalysts and fixed-bed reactors in 1979-1987 and precipitated iron and fixed-bed reactors in 1986-1993. From 1995 to the early 2000s, ICC switched research to the slurry-phase technology and operated a 750 tonnes/year plant since then. In 2003, Yankuang Group, another major coal company in China built a 4,500 tonnes/year FTS facility using iron catalysts and a slurry reactor. ICC/CAS was the major

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[3] See the full-text document at http://www.china.com.cn/policy/txt/2007-01/22/content_7694688_3.htm; and http://info.chem.hc360.com/2007/08/03104919629-2.shtml

[4] These three were: (1) Shenhua Group based in Inner Mongolia, (2) Yilan Coal Group from Heilongjiang Province, and (3) Xianfeng Coal from Yunan Province.

carrier for fundamental FTS research. Still today, ICC remains as the major technology provider for ICL. Synfuels China, the ICL technology company I interviewed during my China trip, is a spin-off of the Shanxi Province ICC branch. In addition to ICC, Yankuang Group acts as another technology developer, through Yankuang Energy Technology Company headed by Dr. Qiwen Sun returning to China from Sasol. China Coal Research Institute (CCRI)[5] is the largest R&D institute for a broad spectrum of coal technologies. In terms of CtL technologies, CCRI built two 0.1 tonne/day bench scale DCL plants in the 1980s. Several leading coal chemical experts from CCRI were recruited by Shenhua or other companies to direct CtL development. CCRI still remains as the leading developer of coal technologies.

Currently in China, there are one DCL plant and four ICL plants that are constructed and have conducted some trial operations. The DCL plant is developed and owned by the Shenhua Group. Four ICL plants are also owned by major state-owned coal companies in China. The following table summarizes these CtL projects in China. Totally these plants account for a gross capacity of 2.6 million tonnes per year (Mt/Y). However, those coal companies all have plans for larger-capacity facilities. For instance, Shenhua Group is planning to invest 30 billion Yuan more to expand the Erdos DCL plant capacity to 3 Mt/Y in the coming few years. The CtL development is projected to have an investment of 400 to 500 billion Yuan by 2020, with total liquids production capacity of 50 Mt per year.[6]

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[5] See CCRI website, http://www.ccri.com.cn

[6] http://www.sxhgw.cn/html/5001/2008429/news_113671_9156.asp

Table 2-1: Major CtL Projects under Construction in China, December 2009

Type	Owner	Technology Developer	Capacity (Phase I, Mt/Y)	Location	Trial Operation
DCL	Shenhua Group	Shenhua Group	1	Erdos, Inner Mongolia	2008 & 2009
ICL	Shenhua Group	Synfuels China	0.18	Erdos, Inner Mongolia	2010e
	Yitai Group	Synfuels China	0.16	Erdos, Inner Mongolia	2009
	Lu'an Group	Synfuels China	0.16	Tunliu, Shanxi	2009
	Yankuang Group	Yankuang Group	1	Yulin, Shaanxi	2009
	Jincheng Coal	Exxon (MTG) *	0.1	Jincheng, Shanxi	2009

Note: 1. e, estimated; 2. each company has planning for larger capacity plants following the Phase I; 3. Shenhua, joined with Sasol, has two ICL projects in Ningxia and Shaanxi under planning. 4. There are some small-scale demo plants or being-planned plants, described by Liu, Shi, and Li (2009), that are not on the list for my interviews. *. Jincheng Coal Group joined with ICC (Shanxi) to modify Exxon's MTG technology to make it suitable for its high-ash coal.
Source: interviews and multiple sources, edited by the author.

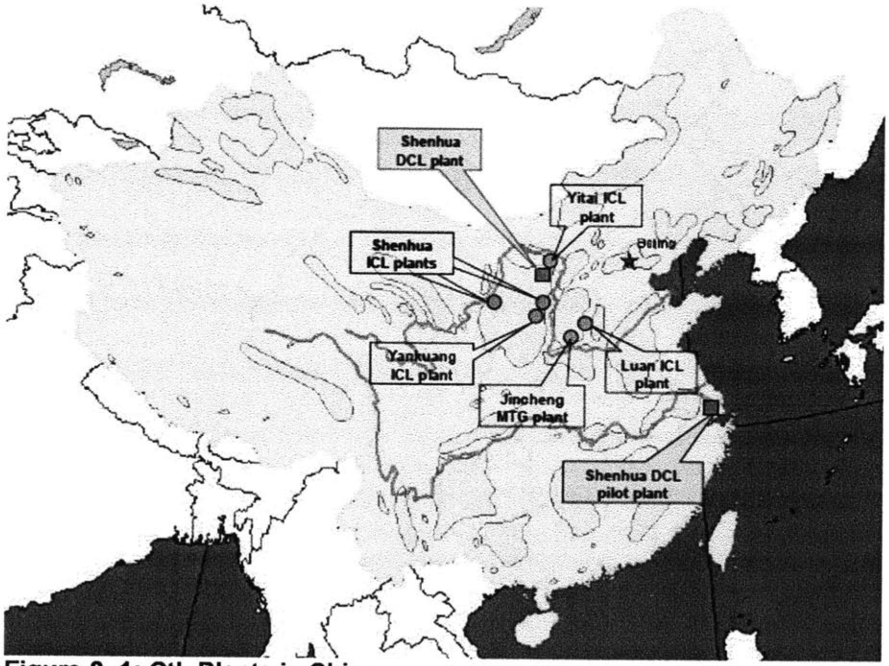

Figure 2- 1: CtL Plants in China
Source: US-China Energy Center (USCEC) 2009

3. Why and How CtL Develops: A Technological-systems View

I examine China's CtL development within the technological-systems framework, to shed light on why and how the government and SOEs in China develop CtL.

CtL is a complex system integrating the policy, technology, and business, which comprise a technological system. A technological system is a complex and dynamic one that consists not only of equipment, but also is shaped by social parameters, including political, economic, and interpersonal aspects (Rogers 2003). This framework is proposed by Hughes (1987), and Carlsson and Stankiewicz (1995), to understand the evolution of technologies and enterprises' competence. Under this framework, a technological system can be understood as a dynamic network of agents who interact within a particular institutional framework or set of infrastructure and natural resources and are involved in the generation, diffusion, and utilization of a specific technology. This technological system approach explores technology-diffusion processes by examining four major components: (1) energy resources that affect technology selection, (2) institutions, i.e., those policies or regulations and related synergies or conflicts, (3) innovation features of the technology, and (4) actors involved at this stage or in this process.

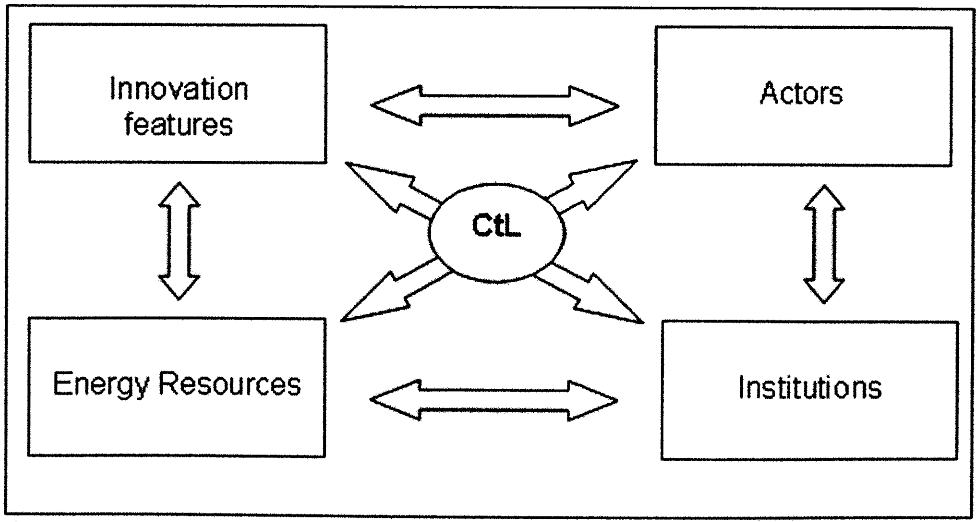

Figure 2- 2: Technological-systems Approach for China's CtL Development

3.1 Energy Resources

China's energy resources portfolio can explain why Chinese government initiated the pursuit of CtL technologies. The characteristics of the Chinese energy portfolio can be summarized as "dependent on coal, rich in coal, while short in oil." Coal remains as the dominant energy resource in China, accounting for around 70% of the primary energy consumption, and around 80% of the primary energy production (both in calorific value calculation) (NBS, 2007). Among the total proved energy reserves in China, coal occupies a major share of 87%, compared to that of oil at 3% (Ren 2006). China started importing oil since 1993, and the dependency on imported oil is around 50%, and it is projected to be 60% by 2020 (NBS 2007; Ren 2006). It is under this energy mix and with the concern of ensuring national energy security (especially oil) that the Chinese government views coal liquefaction as a strategic technology and vows to master this advanced coal technology as a type of "technology reserve," which can be used whenever necessary. The State Council followed this initiative with a special—Coal Replace Oil fund in 1981. During the late 1990s, the Chinese government compared several state-owned coal companies and selected Shenhua Group to pursue CTL development, which was the kick-off step for CtL development in China.

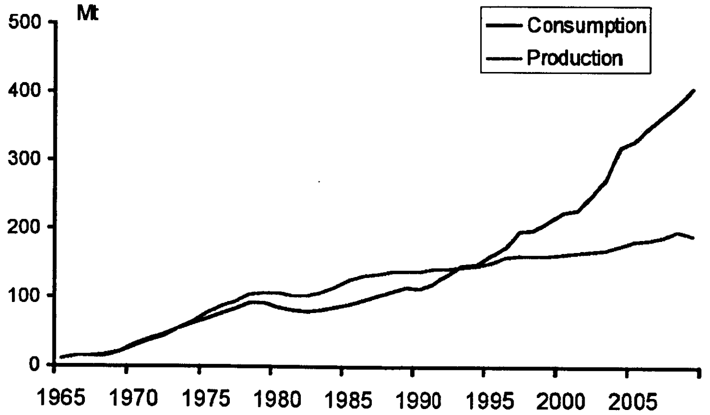

Figure 2- 3: China Oil Production and Consumption, 1965-2009
Source: Energy Information Administration (EIA), USCEC 2009

3.2 Institutions

Institutions refer to policies or regulations for CtL technologies in China. The Energy Bureau under the National Development and Reform Commission (NDRC) is the state unit charged with the power of approving or halting CtL projects, which usually incur an investment of billions of Chinese Yuan. Specifically, the Coal Division under the Energy Bureau has this power. It is worthwhile to note that the Energy Bureau, despite its enormous power of regulating the energy industry and policy in China, is a unit with only 112 staff.[7] The Coal Division is an office holding with three officers.[8]

Another governmental agency, the Ministry of Science and Technology (MOST) is also a key driving force. MOST exerts its impact through providing financial support to research projects under the 863 Program. MOST has an "863 Experts Committee" for Advanced Coal Technologies, composed of some well-known or authoritative domestic scientists who jointly determine the projects funding for CtL projects. These experts are not full-time employees for this Committee, and they meet several times each year to select projects to fund. In fact, some of them are the chief engineers or senior managers in the major coal companies who are developing CtL technologies and/or projects.[9]

Despite the fact that the Central Government initiated the development of CtL in China, as it moves on, the attitude of the central government gradually changed to "cautiously supportive". According to the "11th five-year (2006-2010) planning of the coal industry," China would gradually build CtL demo plants for coal conversion and coal liquefaction. Premier Wen Jiabao, when visiting Shenhua DCL plant in 2007, applauded this project as an 'important part for the national energy security strategy, and also a grand scientific

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[7] http://www.gov.cn/gzdt/2008-07/29/content_1058473.htm

[8] There is no publicly available data about this number. I estimate this number, from the population of three of an equivalent NDRC division I visited during this trip.

[9] For instance, Dr. REN Xiangkun, the chief of Shenhua DCL project, is in this committee. Dr. SUN Qiwen, the head of Yankuang ICL project, is also seated.

experiment,' but he also warned, 'it should be tried and developed gradually and cautiously, and should not be rushed with many projects together at one time'.[10] NDRC believes CtL in China is still at the experimental stage carrying technological and business risks. NDRC is regulating CtL development with caution: in September 2008[11] it halted all other CtL projects except the Shenhua DCL project.

Local governments are another regulatory force that actually supports CtL development. Ctl projects located in their territory have an investment of billions Yuan and are a significant driver of their GDP growth, a key performance indicator for the promotion of those officials. For instance, Shenhua's 10-billion-Yuan DCL investment in Inner Mongolia is estimated to increase this region's GDP by 60 billion Yuan, 10% of the 609 billion Yuan GDP in 2007 for Inner Mongolia (Wu and Polenske 2009). The city government of Erdos, Inner Mongolia, hosting Shenhua's DCL project and two ICL projects by Shenhua and Yitai, relies on the coal-chemical industry to sustain its high growth of GDP per capita, and vows to surpass Hong Kong by 2010 in GDP per capita.[12]

3.3 Innovation Features

These refer to techno-economic-environmental features of CtL with the successful example of Sasol ICL facilities, CTL developers or research institutes argue that ICL is a well-established technology, while DCL is relatively new and should be conducted cautiously with demo plants (Liu, 2001).

The economics of coal liquefaction remains uncertain. For DCL, Shenhua in 2005 claimed that the cost of its DCL liquids was less than $30/barrel in 2005 (Sun et al., 2005),

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[10] http://info.chem.hc360.com/2007/08/03104919629-2.shtml

[11] Xinhua New Agency, http://en.ce.cn/National/Politics/200809/05/t20080905_16717701.shtml. Then this ban was lifted sometime in early 2009. I will come to this later in this paper.

[12] http://www.zh818.com/Get/redian/2009127111870.Html

but most recently this estimate was elevated to $84-85/barrel.[13] Some experts in China also cast doubt on the threshold of $30 per barrel, by citing the much higher coal prices compared with several years ago. Some studies suggest that the net breakeven oil price (BEOP) for CtL would be Euro 49–57/BBL (Vallentin 2008a, 2008b). However, for ICL, the successful experience of Sasol seems to imply that indirect liquefaction is economic at the stage of commercial production. For example, Yankuang Group, a coal major and strong advocate for CtL, estimates their cost of ICL is 2,047 Yuan per tonne, equivalent to $27/barrel, based on 2006 data. If the coal price is 600 Yuan/tonne about the current level, then it would translate into $51/tonne for ICL liquid products, assuming other costs remain same. Such estimates can largely depend on the price: coal companies can adopt production costs instead of the market price of coal, thus the breakeven costs would be much lower, which makes CtL much more economic.

Table 2- 2: Yankuang ICL Costs Estimates

Materials	Unit input (tonne)	Unit price (Yuan)	Costs
Raw coal	4.1	150	615
Steam	2.5	120	300
Water	12	1.2	14
Depreciation			750
Others			368
Total			2,047

Source: SYWG Research and Consulting, 2006

The high discharge of carbon dioxide is another feature of CtL projects, as discussed previously. But Chinese developers are aware of this concern, and are working to capture the relatively high-concentration CO2 flow from CtL plants. For instance, Shenhua Group is conducting feasibility research with West Virginia University for the carbon capture and storage for its DCL plant in Erdos. For regular pollution other than CO2, Chinese developers believe it is not a major concern or there is not much pollution due to their

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[13] Dr. ZHANG Yuzhuo, CEO of Shenhua Group, see http://energy.people.com.cn/GB/11419714.html

environmental control measurements. When it comes to local environmental impact caused by facilities construction, some developers disagree with the conventional idea that their projects destroy the local environmental system. Instead, they believe they improve the local environment through providing funds for planting trees or improving the infrastructure[14].

CtL is also water-intensive. For example, Yitai project use 12 tonnes of water for each tonne of final liquid products[15]. China's CtL projects are currently all located in those water-scarce regions: Inner Mongolia, Shanxi, and Shaanxi. CtL developers I interviewed all acknowledge this issue, but they disagree with those critiques for three reasons: first and the most important, CtL water intensity is not higher compared with other chemical projects such as fertilizer projects which are not so intensively criticized; two, they pay close attention to water recycling and conservation to minimize the water consumption; and three, the water sources planning for current projects were conducted and all went through the approval process of governmental agencies.

3.4 Actors

Actors are those parties who participate in the CtL development in China. Current CtL developers are the main actors in this CtL movement. They are major state-owned coal companies, or CtL technologies providers, such as Shenhua, Lu'an, Yankuang (YETC), Jincheng Coal Group, and Synfuels China.

During developing CtL, these major players include a group of marginal players, such as Sosal and Shell who have some proposed joint-venture CtL projects with Chinese counterparties, and some other coal companies who are considering the entry into the

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[14] From interviews in November 2009.

[15] See http://energy.people.com.cn/GB/11419714.html

CtL playfield. These marginal players are watching the progress of current projects, and might enter the field when the technologies mature and the policies become clear.

CtL developers also include another group of institutions, such as a significant number of domestic or international, (1) universities or research institutes, including CCRI, CAS, chemical engineering departments or institutes in Tsinghua, Nanjing, and Zhejiang Universities and many others; (2) design, engineering, and manufacturing firms who work as suppliers to major CtL developers; and (3) oil companies from which CtL developers recruit refinery or chemical engineers for their CtL operation. These players are assembled by the major CtL developers throughout the projects, for technologies R&D, engineering construction, and facilities operation and management.

There is another group who objects or remains skeptical about the CtL development in China. These include, for example, scholars or scientists who are not convinced of the necessity and feasibility of CtL projects in China, and environmental organizations concerned about the pollution from CtL. Despite their different voices, they are not in fact a strong force halting the CtL development, given the supportive attitude from the central and local government, as well as the strong advocacy of SOE CtL developers.

As discussed above, the structure of energy supply, and the supportive attitude and efforts of the central government launched the CtL movement in China. The state interest of establishing a coal-liquefaction industry in the future, and no rigid regulatory carbon-emissions regulation make CtL development allowed and less challenged by regulation in this country. However, why do those major coal companies, i.e., those CtL developers in China, strongly support this CtL development? Is it only because as SOEs, they implement the national policy? I explore the incentives of these SOEs in the next section. The incentives of these SOEs to advocate for CtL are critical to understand why and how CtL makes its case in China.

4. Actors: Why and How SOEs Develop CtL

It is true that at the beginning some state-owned coal companies were encouraged or directed by the central government to develop CtL. For instance, The Chinese State Council provided 11 billion Yuan (about $1.3 billion US Dollars) from the "Coal-Replace-Oil" fund to Shenhua to initiate CTL development in January 1998. Since then, Shenhua has developed a business strategy, and it began CTL development in northwestern China's major coal production areas. However, the government did not allocate funding for other companies to develop capital-intensive CtL technologies and projects. Then, why did several other enterprises, together with Shenhua Group, become advocates for this CtL development? For example, these companies seek to lobby NDRC to approve their projects after the NDRC halted their development due to "technological and business risks" in 2008.[16]

I argue that it is the diversification strategy that motivated those coal companies in the late 1990s to develop CtL, which could extend their industrial chains into coal-chemicals, a significant profit growth source. To highlight the diversification strategy of coal companies, I start with reviewing the situation of the coal industry and the economy during that period. Under this economic situation, diversification became a viable business strategy for the coal industry.

4.1 Coal Producers in China: Decline During the 1990s

Before the 1980s, under the planned economy and priority strategy of heavy industries, coal output, a symbol of strength of a new communist nation, grew rapidly from 66 million

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[16] from personal interviews with Yankuang Group during the winter of 2009 in China

tonnes in 1952 to 636 million tonnes in 1979, an annual growth rate of 9% (Wang 2007). This significant output growth still could not meet the national demand. The central government decided to ease the entry for coal producers and encourage small mines: local government, collective, and private-owned coal mines were allowed and flourished. This policy effectively boosted coal output after 1980, until coal production became oversupplied toward the end of the 1980s (Figure 2-4 and 2-5).

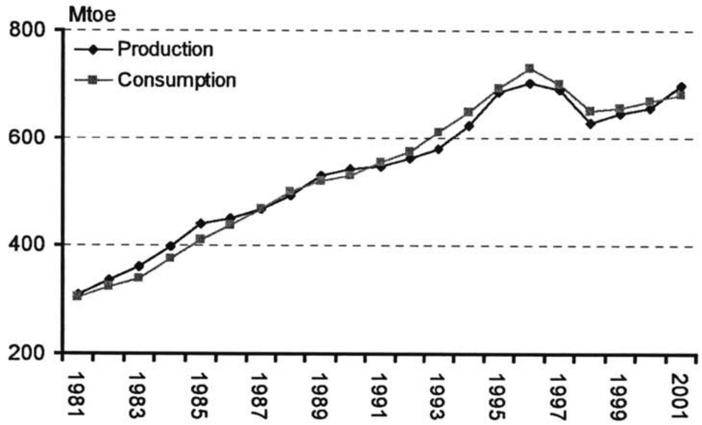

Figure 2- 4: Coal Production and Consumption in China, 1981-2001
Mtoe: million tonnes of oil equivalent
Source: BP Statistical Review of World Energy, 2010

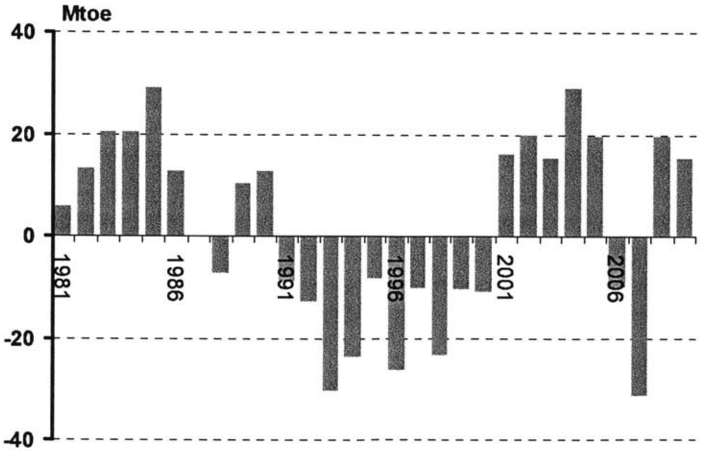

Figure 2- 5: Coal Production-consumption Gap in China, 1981-2009
Source: BP 2010

Then, in the 1990s, the output of coal declined. Coal was oversupplied and there was excessive competition among coal producers, which extended into the 1990s. The central government initiated the policy of "closing small mines, and limiting output" to bring down the coal production. China's economy was overheated in the early 1990s: GDP growth in 1992 reached a record high at 14.2%. The central government started a restrictive monetary and fiscal policy during 1993 and 1996 (Hu 2007). This macroeconomic control achieved the "soft-landing" for the economy: the consumer price index decreased from 24% in 1994 to 8.3% in 1996, and the GDP growth decelerated to 13.5% in 1993, and then to 9.6% in 1996. Coal demand also decreased after 1996, and hit the trough during the Asian Financial Crisis in 1998.

Coal producers also faced unfavorable low coal prices during the 1980s and 1990s. Although the dual-track pricing policy was introduced in 1985, which allowed a higher coal price for output above the given quota, the low-price for coal output within the given quota still reduced the sector's profitability. After 1994, the government decided to lift price controls, but also removed the subsidy, and the government also imposed a higher tax rate on coal producers, from a 3% sales tax to a 13% value-added tax[17]. Meanwhile, the restrictive macroeconomic policy also translated into a shrinking coal demand. Given these, and also due to low efficiency, overstaffing, high expenses for welfare, and a fierce competition from small mines, state-owned coal mines or companies had a significant loss for a long period through the late 1980s and 1990s (Table 2-3, Wang 2007).

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[17] Case study on Yankuang Group, see http://www.yygpzx.com/gzpd/jxzyg/dl/1/21/1/kzzl.htm

Figure 2- 6: China GDP Growth, 1994-2010
Source: TrandingEconomics, NBS

Figure 2- 7: China Inflation Rates, 1995-2010
Source: TrandingEconomics, NBS

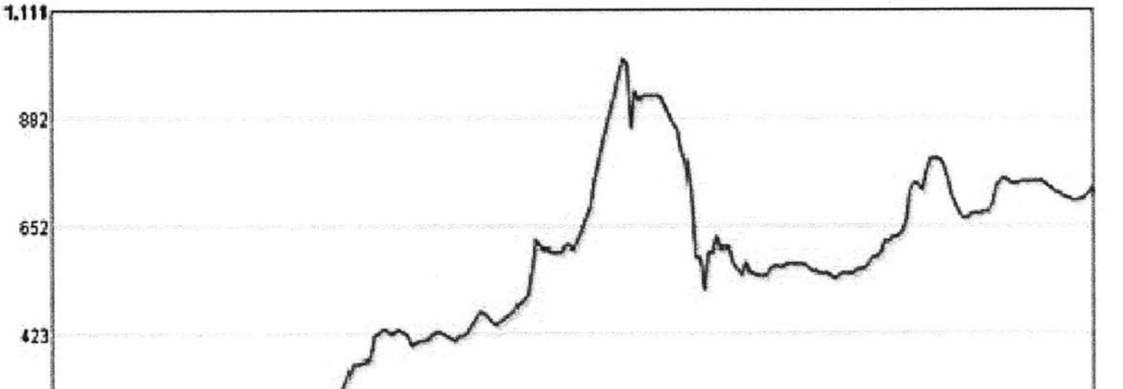

Figure 2- 8: Coal Price in China, 1998-2010
Note: based on 5500kcal/kg Shanxi coal, FOB price at Qinghuangdao Port; Unit: Yuan/tonne
Source: China Coal Resource Net, http://www.sxcoal.com

Table 2- 3: Comparison of Profits: Coal vs. Electricity

Year	Total profits (billion yuan)	
	Coal industry	Electricity industry
1980	1.033	5.341
1985	−3.652	6.624
1990	−6.146	7.341
1991	−6.216	8.739
1992	−5.336	10.793
1993	−1.376	13.064
1994	−0.542	18.357
1995	2.345	12.833
1996	2.293	21.804
1997	3.481	17.669
1998	−0.426	32.838
1999	−1.810	30.515
2000	0.05	45.716
2001	4.183	52.997
2002	5.388	50.825
2003	14.007	69.926
2004	30.692	70.817
2005	56.100	115.773

Source: Wang 2007; China Statistical Yearbook 1981-2006

4.2 Diversification Strategies in the Late 1990s

Although most coal producers reported a loss during the 1990s[18], some public coal companies witnessed a relatively strong performance by implementing a diversification strategy. For instance, the seven listed coal companies (Table 2-4) had positive earnings per share during 1999 despite some decrease in revenue due to the macroeconomic environment, and their average earnings per share (EPS) was 0.127 Yuan, above the average of Shenzhen and Shanghai Stock Exchanges. Hu and Hao (2000) examined this phenomenon and identified the strategy of diversification as the key driver for this strong performance. For example, Lanhua Kechuang acquired four fertilizer and chemical plants, and also invested in some biotech companies.

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[18] About 80% of coal companies had a loss during this period (Hu and Hao 2000)

Table 2- 4: Performance of Some Coal Companies, 1999

Company	Ticker	EPS (Chinese Yuan)	Revenue growth for main business, %	Profit growth for main business, %	Net profit growth, %
Shenhuo Limited	933	0.1339	12	13	32
Jinniu Energy	937	0.1329	-7	-6	7
Zhengzhou Coal&Electricity	600121	0.1399	16	19	19
Lanhua Kechuang	600123	0.12	20	-10	30
Yanzhou Coal	600188	0.13	-6	2	32
Tongbao Energy	600780	0.128	-20	21	22
Yitai Coal (B share)	900948	0.1018	-10	-71	-60

Source: Hu and Hao 2000

Table 2- 5: New Assets Invested during 1998-1999

Company	Coal	Coal-related assets	Assets non-related to coal
Shenhuo Limited	4 coal mines	1 power plant; retrofit a railway line	Alumium factory
Jinniu Energy	4 coal mines		
Zhengzhou Coal&Electricity	1 coal mine	Expanding a power plant	Machinery
Lanhua Kechuang	4 coal mines	4 fertilizer/chemical plants	Biotech companies
Yanzhou Coal	1 coal mine	Yanzhou-Shijiazhuang railway line	IT industry
Tongbao Energy		1 power plant	Airlines
Yitai Coal (B share)	1 coal mine	Highway	Hotel, shipping

Source: Hu and Hao 2000

During the 1990s when coal producers faced an unfavorable economic environment, diversification became a strategy which could improve or sustain their business. In line with this trend, the CtL developers also explored the opportunities to diversify their business. In the following section, I examine the CtL initiatives of three coal companies: Shenhua Group, Yankuang Group, and Jincheng Coal Group, based on interviews from my trips to China and literature.

4.3 Case Studies: CtL as A Diversification Strategy

To test my hypothesis about this bottom up driver for CtL in China, I interviewed Shenhua, Yankuang, and Jinmei, three major CtL developers in China. I have come to find that my findings support this hypothesis:

- Shenhua views DCL, which was originally a 'political' task assigned by the central government, as an opportunity of expanding into the coal chemical industry, and is also pursuing ICL development, to diversify into the coal chemical industry;
- Yankuang, stated explicitly their business strategy of CtL development, and moved with real project development;
- Jinmei, diversified into CtL amid the 1990's market, and based on their coal reserves portfolio.

In the following sections I explore in greater details how these coal majors started their CtL development and their related business strategies.

Shenhua Group

Shenhua Group is the only DCL project developer in China, and is also developing ICL project in Inner Mongolia. Originally picked and assigned by the central government with the charge of DLC development, Shenhua later viewed this development as an opportunity of diversifying and expanding its business and improve the company's performance. In this context, I argue that the business diversification strategy plays a key role in Shenhua's pursuit of coal liquefaction.

Shenhua was incorporated in 1995 during the "depressing" time for the coal industry, as the largest coal company in China, and also a key Central SOE, with integrated business of coal, power, railway, port, shipping, coal to liquids and coal to chemicals.[19] By the end of 2009, the Shenhua Group has a total of 37 wholly-owned and shareholding subsidiaries, with 163,745 employees and total assets of 530 billion Yuan. The Group's operation revenue reached 161.2 Billion Yuan with the top net income among the companies under the supervision of the Central Government. In 2010, Shenhua Group was ranked 356th in global Fortune 500. The following table summarizes Shenhua

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[19] Shenhua Group, http://www.shenhuagroup.com.cn/english/about0us/profile0of0shenhua/index.shtml

Group's operational performance for the first half of 2010 and organizational structure. China Shenhua Energy Company Limited (China Shenhua) is the listed subsidiary (listed in both Shanghai and Hong Kong Stock Exchanges) and the main body of Shenhua Group, with total revenue of 121 billion Yuan in 2009 (Table 2-6).

Table 2- 6: Shenhua Group Operational Performance

	January - June 2010	January - June 2009	Year-on-year growth
I			
Output of raw coal (Mt)	172.6	163.5	5.5%
Export of coal (Mt)	5.9	6.1	-3.1%
Raw coal productivity (ton/manshift)	23.5	21.9	7.3%
II			
Power output (billion kw/h)	76.4	49.7	53.6%
Power sales (billion kw/h)	71.3	46.0	55.0%
III			
Cargo turnover volume (Mt/km)	73,668.3	67,835.5	8.6%
IV			
Port throughput (Mt/km)	58.0	51.9	11.7%

Note: Mt, million tones; kw/h, kilo-watts per hour, Mt/km, million tones per kilometer
Source: Shenhua Group

Shenhua's diversification in the late 1990s was largely attributed to the political connection of its top leadership (Table 2-7), especially Mr. Qing Ye, with presidency from 1998 to 2003. Mr. Ye brought to Shenhua a fund of 20 billion Yuan, the "Coal Replace Oil" fund from the State Council when he took the presidency in 1998.[20] This fund was initially approved by then-Premier Peng Li in 1995 when Ye and Li discussed Shenhua's high debt rate: 87%. Mr. Ye used this fund for two purposes: buying four power plants (incorporated into Guohua Power Company, the flagship firm of Shenhua's electricity business), and developing DCL technologies. The former was to expand the market for coal during that coal depression – a vertical diversification, and the later was to

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[20] Shenhua Miracle: the story of YE Qing, see http://finance.sina.com.cn/leadership/crz/20050420/10201533998.shtml

implement the "assignment" from the State Council to enhance national energy security, and also generate another revenue source – also a strategy of diversification.

Table 2- 7: Shenhua Leaderships

President	Term	Prior position
Han Xiao	1995-1998	Vice Minister, Ministry of Coal Industry (not existing now)
Qing Ye	1998-2003	Deputy Director, State Planning Commission (former NDRC)
Biting Chen	2003-2008	Vice Governor, Jiangsu Province
Xiwu Zhang	2009-present	CEO, Shenhua Group

Source: Company website

The development of DCL technologies provided Shenhua with a unique opportunity to practice and improve advanced coal technology innovation and managerial and business experience. China Shenhua Coal to Liquid Company (CSCLC) is the subsidiary charged with CtL development and coal chemicals.[21] Currently, CSCLS is developing the DCL project in Erdos, Inner Mongolia and has twice put its 1Mt/Y DCL plant into successful trial operation at the end of 2008 and the middle of 2009. The DCL technology development took a long time. In early 2001, after finding the DCL technology licensed from HTI an US-based company, unsuitable to be scaled up, Shenhua adopted the design of HTI facilities, but started from scratch for key technology development, such as catalysts, engineering integration, and operation. They recruited top experts from CCRI who later led the whole DCL project in Inner Mongolia, they attracted talents from refineries in oil companies including PetroChina and SinoPec[22], and they assembled a team with technicians from industrial design institutes, engineering integration companies, and those coal chemical experts. CSCLC can send new employees for on-site training. Through developing their own DCL technology and catalyst, both of which are patented, and through assembling an R&D team, project design, engineering construction and managing teams from various industries and companies, Shenhua has established a

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[21] http://company.zhaopin.com/P9/CC1201/3278/CC120132783.htm

[22] PetroChina and SinoPec are two major state-owned oil and gas companies in China.

team for the whole DCL process, and, more importantly, they host a pool of top coal chemical scientists in the country. Shenhua is also planning a CCS demonstration project at the Erdos DCL Plant, which is a good example for spillovers from DCL development: benefiting CCS technology. By the end of 2009 the project feasibility study and the process simulation test were completed. Their short-term objective is to erect the CCS demonstration facility and accomplish an annual CO_2 storage capacity of 100,000 tons. The future development trend of DCL technology is to be combined with the CCS technology so as to accomplish near-zero emission of CO_2[23]. The Shenhua CCS study is conducted by West Virginia University under the support of a joint fund by the US Department of Energy (DOE) and NDRC.

Shenhua conducts CtL development as a business, not a political assignment. For instance, to hedge the risk from the project failure, in 2005 Shenhua Group purchased insurance with a compensation value of 7.5 billion Yuan for its 10-billion-Yuan Erdos DCL Project, from a consortium of four major properties' insurance companies in China.[24] Also, they are planning to sell this project to China Shenhua Energy Company Limited, the listed sister company under the Group, once the plant can be operated stably for commercial production.[25] This implies a way of recouping their investment costs and hedging the business and technological risks.

In addition to DCL, Shenhua also develops ICL projects, as described in Table 2-1. Shenhua contracted Synfuels China as ICL technology developer. Unlike in the case of DCL, Shenhua as a coal company considers herself as an ICL technology user, not a technology developer: they are interested in final products from ICL, not the technology

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[23] http://www.nae.edu/Programs/FOE/CAFOE/page200912230/InformationforAttendees/16084/16359.aspx
[24] http://www.imc.org.cn/Article/Catalog2/12749.html
[25] See CSEC 2008 annual report and press conference at http://www.csec.com/htmlen/investor/page_3_7_1.html

itself.[26] This further confirmed their interest of business diversification into coal chemical products and the market, through both practices in DCL and ICL.

Yangkuang Group

Yankuang Group Corporation, Ltd. has explicitly stated their business diversification strategy into coal liquefaction. Their recent moves and the information I received during the interviews with Yankuang's CtL arm confirmed this diversification strategy.

Yankuang is an SOE mainly engaged in coal mining and sales, coal chemical industry, power generation and aluminum production, and machinery manufacturing. It was restructured into a sole State-owned company in 1996, and further developed into Yankuang Group Co., Ltd. in 1999. In 2009, Yankuang was ranked 121st among China's Top 500 Enterprises, with total assets of 70 billion Yuan and 93,000 employees. The total revenue in 2009 was 40.8 billion Yuan, with 20% from coal chemicals, and 53% from coal mining and sales.[27] Its main subsidiary and listed arm, Yanzhou Coal Mining Company Limited, had total revenue of 26 billion Yuan in 2008, a 57% growth from 2007.[28]

Yankuang started to plan for diversification into non-coal industries or the third industry early in 1993, but not until 1999 Yankuang took the first step of diversification into coal chemicals by acquiring Lunan Fertilizer Factory.[29] Lunan Fertilizer has a 40-year history and kept a strong R&D force and technicians. Yankuang invested 200 million Yuan more after this acquisition for restructuring and achieved the successful turnaround in 2001. This factory then provided a group of technicians for Yankuang's ICL projects.

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[26] From my interview with Dr. REN Xiangkun, president of CSCLC, Shenhua, in November 2010.

[27] Caijing, http://www.caijing.com.cn/2010-08-26/110505978.html

[28] From the company annual report 2009

[29] Xinhua News Net, 2002

Yankuang develops CtL technologies and projects to enhance its strategy of diversification into the coal liquefaction industry, according to the Group's statement. Yankuang's pursuit of CtL started in the early 2000s when Dr. Qiwen Sun, a former Sasoal chief engineer joined the company and established Yankuang Energy Technology Company (YETC),[30] a technology R&D firm focusing on ICL technologies. YETC has another label "the State Key Laboratory for Coal Liquefaction and Coal Chemicals," which means it has high quality and is eligibile for receiving state funding and conducting technology research and development.[31] As a State Key Lab, YETC has priority of receiving R&D funding from the government under State High-tech Development Program (863 Program). The name of the State Key Lab also indicates a prestigious status as a R&D institute in China.

Dr. Sun is the technology leader and architect of Yankuang's coal-liquefaction initiative. With a contract with Sasol for not using Sasol technologies, especially catalysts for Yankuang, he assembled a team of 40 scientists, from top universities and local chemical institute branches under CAS in Shanghai and Nanjing, and developed their own ICL technologies from scratch in two years. He also relied on technicians from Lunan Fertilizer Factory who have operational experience of coal chemicals, and some of these people then became core technicians for ICL facilities. YETC is taking the advantage of the status of the state key laboratory to enhance their R&D capability, through undertaking R&D projects, both internally from Yankuang Group, and externally from MOST. Currently, Yankuang's ICL project has a capacity of 1MT/y and an investment of 10 billion Yuan,[32], much larger than other ICL projects developed by Synfuels China, of less than 0.2MT/Y, as shown in the table previously.

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[30] http://www.haoqiantu.cn/CJ783340.html

[31] Detailed information regarding funding seemed sensitive and I have no data.

[32] Since website, http://finance.sina.com.cn/chanjing/b/20080914/06245304328.shtml

This company retains an ambitious CtL development plan. In addition to the current ICL project in Yulin, Shaanxi Province, the company is also investigating the opportunity of coal liquefaction projects in Xinjiang Province. Similar to Shenhua projects, these CtL projects, according to the Yankuang Group, could be injected into their listed arm Yanzhou Coal, which just acquired Felix Resources an Australian coal company at a price of 3.5 billion Australian dollars.[33] This Felix deal was valued at 5.9 billion Yuan to acquire 100% of the stake of the target. According to Mr. WANG Xin, the President of Yankuang, "This deal is a key step for Yankuang's R&D for clean coal technologies", to expand into the downstream products, as Felix owns a patented "Super clean coal technology," which can improve the combustion efficiency of coal.

Yankuang's proactive move and ambition for CtL have made the company not a passive command-taken SOE or CtL developer, but a skillful lobbyist. In September 2008, NDRC halted some coal liquefaction projects including Yankuang's Yulin project. In addition mobilizing their Beijing Office to communicate with the Energy Bureau under NDRC, Yankuang organized workshops or conferences with attendance of CAS Academicians in the field of coal science who support CtL development,[34] and policy makers from the State Council: they aimed to exert the influence on policy makers through the voice of supportive experts. In addition, the Chairman of Board of the Group, Mr. Jiahuai Geng, is a representative of the People's Congress and also has the opportunity to lobby for his company. For example, in the 2010 People's Congress, he requested NDRC to approve Yankuang's 1Mt/year project in Yulin.[35]

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[33] http://www.chinaknowledge.com/Finance/StockChart.aspx?Type=Shanghai&StockCode=600188; Also see http://www.xuanmei5.com

[34] Academicians are CAS fellows who are regarded as authoritative experts in certain scientific fields.

[35] Yankuang news, http://www.ykjt.cn/xwsx/text/2010-03/08/content_247460.htm

Jinmei Group

Jincheng Anthracite Mining Group (Jinmei Group) is another CtL developer, in Shanxi Province. Jinmei's pursuit of CtL originated from their portfolio of coal reserves, and the company further enforced their plan of pursuing CtL amid the market in the 1990s. They have established their Methanol-to-gasoline (MTG) plant to convert coal into methanol and then gasoline, and have a plan of improving the capacity in the future.

Founded in 1958, Shanxi Jincheng is a state-owned enterprise with total assets of 100 billion Yuan (as of 2010), revenue of 62.3 billion Yuan, and over 110,000 employees. Jinmei is ranked as No. 9 out of the top 100 coal companies in China in 2010, and No. 106 out of the top 500 enterprises in China. Jinmei is comprised of six business segments: coal, coal-bed methane, electricity, coal chemicals, coal mechanicals, and miscellaneous operations.[36] Coal chemicals are an important industry where Jinmei has invested and achieved significant development. This segment is centered around the clean coal technologies utilizing high sulfur, high ash, and high ask-melting point (three Highs) coal, which is abundant in Jingmei's coal mines.

For the segment of coal chemicals, Jinmei has invested a total capital of over 1.2 billion Yuan, holding stakes in 10 chemical companies, with annual ammonia production about 4 million tonnes. In Jinmei's 12th five-year plan, in 2015, Jinmei will have annual production of 1 million tonnes of syn-fuel, and an ammonia production of 20 million tonnes. This goal indicates Jinmei's ambition in developing its coal chemical industry, including CtL (1 million tonnes of syn-fuel from coal by 2015).

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[36] The company website, http://www.jccoal.com

Jinmei initiated the move for coal chemicals as a business diversification strategy, based on their resource structure and the market situation in 1990s.[37] In the later 1990s when the coal price was low in a depressing market (as discussed previously), Jinmei management was considering strategies to improve their performance by diversifying into the coal chemicals. Jinmei, due to their resource base of anthracite coal, did not have an advantage in utilizing pulverized coal, thus they decided to explore the usage of anthracite. They also had a good connection with Shanxi Institute of Coal Chemistry (SICC) a branch of CAS, which had yet to test, but was interested, in testing their gasification technology with anthracite coal. Based on these, Jinmei's decision then was to move into the coal chemicals industry by taking advantage of the abundance of raw materials, No. 9 and 15 anthracite coal.

No. 9 and 15 anthracite coal are high in sulfur, ash, and has a high ask-melting point.[38] There are 4.2 billion tonnes of resource reserves of No. 15 anthracite in Jincheng metropolitan area. In addition to this abundance, this type of low-grade anthracite is well preserved deep underground, and the thickness of the coal bed (1.5~2.5 meters) is suitable for mining operations, and also suitable for immediate mining as the infrastructure already exists in those mining areas.

Jinmei adopted a two-stage way, different from Shenhua or Yankuang, to develop their CtL project: using coal-gasification technology from SICC to produce syngas which can be converted into methanol, then adopting MTG technology by licensing from Uhde Gmbh (one of the largest chemical engineering company in the world, in Germany) to produce liquids from methanol. Since 2003, Jinmei, set up a joint-venture company,

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[37] From interviewing Jinmei management, in charge of Ctl/MTG and coal chemicals business segment

[38] Sulfur content 2.4～3.6%, ash 22～35%, and melting point higher than 1500℃; in contrast, No.3 anthracite is a high grade coal and flagship coal product of Jinmei Group. Source: http://www.hgjob.com/resume/util/183967.html

Tianhe Co. Ltd., with SICC, to test SICC Pressured Ash Agglomerating Fluidized Bed Coal Gasification Technology (AFB), which is suitable for various types of coal and for being localized with its lower cost compared to gasification technologies by Shell and Chevron-Texaco.[39] In 2006, the coal-based syn-fuel project was erected with a target capacity of 100,000 tonnes/year, and was selected as a key project by the Eleventh Five-year Plan of Shanxi Province. Jinmei invested 2.3 billion Yuan in this project, adopting AFB and MTG technologies. In 2008, Tianxi Coal to Liquids Company was established from Jinmei Group to specialize in Jinmei's CtL development. According to the project description, this factory can produce 100,000 tonnes of Euro 3 standard gasoline, 13,000 tonnes of LPG, and 16,000 tonnes of sulfur. It can also be adjusted to produce 300,000 tonnes of high grade methanol (the interim product for the whole CtL chain). The annual revenue from products is estimated at 700 million Yuan.[40] This flexibility of products reflects the risk-hedging strategy Jinmei is using: their technology/facilities allow the switch to methanol production if the CtL production is not economical or technologically feasible.

Jinmei mobilized internal and external resources to ensure the progress of the CtL project. When SICC tested the AFB technology, Jinmei utilized the industrial boilers from its subsidiary, Jinshi Chemical Fertilizer Company for the interim experiments. Staff for this gasification process development came mainly from SICC and Jinmei internally. After Jinmei licensed MTG technology from Uhde, Uhde sent engineers to Jincheng City to direct the installation and set-ups. The design and construction were outsourced to the Third Design Institute of China Chemcial Engineering, a top institute in chemical engineering design and construction in China. Meanwhile, Jinmei solicited over 40 experienced engineers from Jinju Chemical Fertilizer Company in Zhejiang Provinces, a

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[39] See http://www.hgjob.com/resume/util/183967.html

[40] Introductory material by Tianxi CtL Company

subsidiary of Jinmei to be trained on spot in MTG facilities. These employees were assigned a three-year contract, and they became the core group of operating the MTG operation.

In summary, Jinmei determined to diversify into the coal chemical business through CtL, after analyzing the market situation and their resource portfolio, and since then they took efforts and succeeded in building their MTG project. Meanwhile, according to my interview, Jinmei management view Jinmei as a CtL technology user, instead of an technology owner. They adopted or licensed these technologies and put them into use for their CtL projects. Currently, the Jinmei CtL project is the only one in the world that uses MTG technology to produce oil liquids from coal. The project went through an experimental operation and was reported to be under 'stable' running in March 2010.[41]

4.4. Summary: CtL for Business Diversification

China's energy structure and the central government's policy initiated the CtL development in China. However, afterwards, it is the coal majors' proactive plans for business diversification that drove CtL projects in China. The Central government assigned financial resources to the Shenhua Group to develop the only DCL project; but Shenhua also pursued ICL projects with the intent to conduct business in coal chemicals. Jinmei's ambition in CtL was driven by the structure of their coal reserves: their large low-grade coal resources makes good economic sense for them to develop CtL projects in order to diversify into coal chemicals. Yankuang is also pursing CtLto expand into coal chemical business segment, as demonstrated in the three cases above.

Then, why do they choose CtL or coal chemicals instead of other business as a segment into which to diversify? CtL can grant them a competitive advantage over competitors,

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[41] See http://www.coalchina.org.cn/page/info.jsp?id=18262

and there is always enough market for CtL products, especially oil. The major coal companies, in addition to conventional coal production and sales, they can diversify into related sectors including power generation, transportation (railway and ports, for example), mining services, or miscellaneous sectors, such as real estates etc. However, these sectors are either already very competitive or are sectors in which they do not have a niche (for example power generation), or where almost any other company can enter without difficulty (real estate, mining services, etc.). CtL, due to its intensive capital costs and technology know-how, can only be pursued by companies who have sufficient financial, technical, and natural resources, such as the large state-owned coal companies. Given China's need for domestic oil and with over 50% of their oil being imported, CtL products can always be absorbed by the domestic market, if not by the international market. Therefore, for coal majors who own abundant coal reserves and believe in China's continuous surging demand for oil, expanding into CtL constitutes a meaningful business strategy.

As discussed in the cases above, these coal majors position themselves as users, instead of developers or owners, of these advanced CtL technologies (except Shenhua for DCL, which was "assigned" by the central government), although some of them do keep their CtL R&D force. In this context, although CtL is a complicated technological system, the technology has not constituted a serious barrier for the coal majors to develop CtL projects. For example, Jinmei Group joined forces or licensed external technologies and modified them to develop their CtL projects. The Shenhua Group (for their ICL project in Inner Mongolia) and the Lu'an Coal Group, another coal major in China, both contracted Synfuel China, a CtL technology company and a spin-off from SICC and headed by Dr. Yongwang Li another top CtL expert in China, to develop their ICL projects. Yankuang Group, different from Jinmei or Lu'an, does have their own R&D

force headed by Dr. Qiwen Sun, a former engineer with Sasol. However, Dr. Sun, based on his years' experience in Sasol, could assemble the team and establish the lab for Yankuang in a relatively short time, which as well did not pose a significant technological challenge for the company's venture into CtL. Thus, the complexity of the CtL technological system is not a barrier for these coal majors' development of CtL projects.

Being technology users does not mean that these coal majors can outsource CtL projects and get oil to foreign countries, which is not feasible. Outsourcing is not feasible in many ways, at least in the near term. First the energy-security concern determines that outsourcing whole CtL projects overseas is not politically viable. From the point of view of the Chinese government, CtL meets the energy security concern by its capability of supplying oil from within China: outsourcing those projects diverts from this strategy. Second, outsourcing such large-scale projects is unlikely to be economically feasible. CtL projects involve not only sophisticated technologies, intensive capital, infrastructure, and engineering issues, but also a sufficient and stable supply of coal as a raw material, as well as support from the local government. It would become extremely challenging or costly to meet these requirements in a foreign country. In other words, developing these projects within China is a more economical and politically feasible way than outsourcing projects to other countries. Instead, CtL technology developer, Synfuel China, in addition to developing domestic projects for Shenhua and other coal majors, is starting to explore business opportunities overseas to apply its technology. Dr. Yongwang Li, the CEO of Synfuel China, informed me in November 2010 that they were in talks with an Indian coal company that was seeking CtL projects in India through using Synfuel CtL technologies.

Therefore, those majors choose CtL to diversify their business, not because of any command from the central government, but because they viewed CtL as a business opportunity. Shenhua Group started their DCL project with the governmental funding, and continued with investment in ICL as they viewed these as business opportunities. Yankuang Group pursues CtL proactively as their diversification strategy. Jinmei Group, based on their resource portfolio, determined to enter the coal chemical industry through CtL development, and successfully built their MTG project. These three cases, therefore, support my hypothesis that CtL is driven from the bottom up. Meanwhile, during my interviews with these companies, I also find that these coal majors benefit from knowledge spillovers from these large- scale projects, for example, by expanding their industrial network and improving their managerial experience. Domestically, they collaborate with various companies or organizations to establish their projects. Internationally, these coal majors interact with companies and research institutes, in supplies, research, and joint ventures for companies in China. For instance, Shenhua Group has joint ventures with European companies who are also their suppliers for DCL projects.[42] Shenhua is also working extensively with West Virginia University on coal chemical research, carbon capture and storage, and economic analysis. Managing projects with an investment of billions of dollars involves significant organizational structure and helps build up the project management capability of those developers and improve their managerial experience.

5. Conclusion

China's energy structure, emphasis on energy security, and low priority for carbon regulation, make it feasible for the diffusion of CtL technologies. To explore the drivers for CtL in China, I proposed the hypothesis that, after being initiated by the central government, the key driver for CtL development in China is the business diversification strategy of major coal companies.

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[42] From the interview with Shenhua. But detailed information regarding what these joint-ventures are and how they operate were not disclosed.

I argue that, the low coal price, poor market performance, and reform of the coal and electricity sectors in the 1990s motivated coal companies to diversify in order to cope with competition and to improve their business performance. Coal companies perceive CtL as a value-adding business as they diversify into coal chemicals, given China's growing demand of oil and chemicals from rapid economic growth. Shenhua, Yankuang, and Jinmei, three coal majors in China, all decided to move into the CtL field, with the purposes of diversifying their business, as I demonstrated in the case studies.

Although these CtL developers view themselves as technology users, they still maintain internal technology R&D force, in order to master some industrial know-how, and keep some competitive advantage. Therefore, technology innovation is also an inherent part of this CtL development. Shenhua and Yankuang both have their technology focused on CtL in order to keep their competency in this industry. Shenhua, Yankuang and Jinmei, through CtL projects, have enhanced their R&D capability, extended their industrial chain and network, and improved managerial and business development experience. Chinese SOEs know how to innovate and change, and pursue their business interest. This indicates that the Chinese system is now capable of innovation and change, contrary to what some western observers thought.

References

Acs, Zoltan J., David B. Audretsch, Pontus Braunerhjelm and Bo Carlsson. 2005. The Knowledge Spillover theory of entrepreneurship. Discussion Paper. Center for Economic Policy Research.

Audretsch, David B. and Max Keilbach. 2007. The knowledge spillover theory of entrepreneurship and economic growth. Max Planck Institute of Economics.

Dadyburjor, D., Liu, Z., 2004. Coal liquefaction. In: Kirk-Othmer Encyclopedia of Chemical Technology. vol. 6, fifth ed., Wiley-Interscience, Wiley, Hoboken, New Jersey, pp. 832–869.

Feldman, M. P.. . Feller, J. E. L. Bercovitz, and R. M. Burton. (2002), University-technology transfer and the system of innovation, in M. P. Feldman and N. Massard, (eds.) *Institutions and Systems in the Geography of Innovation* (Kluwer Academic Publishers, Boston), 55-78.

Hu, Yanrong, 2007. Thoughts on China's macroeconomic control policy in 1990s. *Group Economy*, 241: 103-104

Hu, Yanrong, and Qingming Hao. 2000. The diversification development of public coal companies: experience for coal companies. *Coal Economics Research*, 8 (2000): 7-9.

Jacobs, Jane. 1969. *The Economy of Cities* (Random House, New York).

Jaffe, Adam B., Manuel Trajtenberg, Michael S. Fogarty. 2000. *The American Economic Review* Knowledge Spillovers and Patent Citations:Evidence from a Survey of Inventors. Vol. 90, No. 2, , pp. 215-218.

Liu, Zhengyu, Shidong Shi, and Yongwang Li. 2009. Coal liquefaction technologies: development in China and challenges in chemical raction engineering. *Chemical Engineering Science*. Doi: 10.1016/j.ces.2009.05.014.

Liu, Zhenyu. 2001. CCT – Coal Liquefaction, direct and indirect. Presentation at International Workshop of Energy, URL: http://www.interacademycouncil.net/Object.File/Draft/10/436/0.pdf.

Mansfield, E. (1995), Academic research underlying industrial innovations: sources, characteristics, and financing. *Review of Economics and Statistics* 77: 1:55-65.

Mansfield, E. (1998), Academic research and industrial innovation: an update of empirical finding,. *Research Policy* 26: 773-776.

National Statistics Bureau (NBS). 2007. *China Energy Statistical Yearbook*. Beijing: China Statistics Press.

Porter, Michael. 1990. *The Competitive Advantage of Nations. New York: The Free Press.*

Powell, W., K.W. Koput, & L. Smith-Doerr (1996), Interorganizational collaboration and the locus of innovation: networks of learning in biotechnology, *Administrative Science Quarterly* 42 (1): 116-145.

Prevenzer, M. (1997), The dynamics of industrial clustering in biotechnology, *Small Business Economics* 9(3): 255-271.

Sasol. 2009. Unlocking the potential wealth of coal. URL: http://www.sasol.com/sasol_internet/downloads/SSI_CTL_Brochure_1233579672375.pdf

Steinfeld, Edward, Richard Lester, and Edward Cunningham. 2009. Greener plants, greyer skies? A report from the front lines of China's energy sector. *Energy Policy.* 37: 1809-1824.

Su, Hui, Haixiao Huang, and Jerry Fletcher. 2008. Carbon Management of a Coal-to-Liquid Plant and its Implication for China. USAEE Conference 2008. New Orleans.

Sun, Qingyun, Jerald J. Fletcher, Yuzhuo Zhang and Xiangkun Ren. 2005. Comparative analysis of costs of alternative coal liquefaction processes. *Energy and Fuels*. 19: 1160-1164.

US-China Energy Center (USCEC). 2009. Carbon capture and sequestration options for the Shenhua direct coal liquefaction plant: final pre-feasibility study report. West Virginia University. (unpublished; for communication only)

Vallentin, Daniel. 2008a. Driving forces and barriers in the development and implementation of coal-to-liquid (CtL) technologies in Germany. *Energy Policy* (36): 2030-2043.

Vallentin, Daniel. 2008b. Policy drivers and barriers for coal-to-liquid (CtL) technologies in the United States. *Energy Policy* (36): 3198-3211.

Daniel Vallentin, ibidem Verlag, Stuttgart,2009. Coal-to-Liquids (CtL): Driving Forces and Barriers – Synergies and Conflicts from an Energy and Climate Policy Perspective, ISBN978-3-89821-998-3, h49.90, p.462

Wang, Bing. 2007. An imbalanced development of coal and electricity industries in China. *Energy Policy* 35: 4959-4968.

Wu, Ning. 2009. The input-output analysis of the economic impact of Shenhua DCL project on Inner Mongolia. Work paper, sponsored by US-China Energy Center at West Virginia University.

Wu, Ning, and Polenske Karen. 2009. The Economic Impact of DCL Project on Inner Mongolian Economy in China. Working paper, sponsored by Shenhua Group.

Zhang, Yuzhuo. 2007. Shenhua Coal Conversion Technology and Industry Development. URL: http://gcep.stanford.edu/pdfs/wR5MezrJ2SJ6NfFI5sb5Jg/16_china_zhangyuzhuo.pdf

The Impact of Future Carbon Prices on CCS Investment for PC and IGCC Power Plants in China

Abstract

In this study, I answer two related questions about the development of carbon capture and storage CCS and power generation technologies in China: (1) what is the breakeven carbon-dioxide price to justify CCS installation investment for Integrated Gasification Combined Cycle (IGCC) and pulverized coal (PC) power plants, and (2) what are the risks associated with investment for CCS. To answer these questions, I build a net present value model for IGCC and PC plants with capacity of 600MW, with assumptions best representing the current technologies in China. Then, I run a sensitivity analysis of capital costs and fuel costs to reveal their impact on the carbon price, and analyze the risk on investment return caused by the carbon price volatility. My study shows that in China, a breakeven carbon price of $61/tonne is required to justify investment on CCS for PC plants, and $72/tonne for IGCC plants. In this analysis, I also advise investors on the impact of capital and fuel costs on the carbon price and suggest optimal timing for CCS investment.

1. Introduction

Relying on coal-fueled power plants to meet the growing demand for electricity and facing the pressure of reducing carbon-dioxide (CO_2) emissions, the People's Republic of China (China) is actively pursuing advanced electricity generation technologies. In the National Action Plan for Climate Change, China vows to reduce CO_2 emissions by 1.5 billion tonnes by 2010, compared to the 2005 level and also proposes that developing countries take reasonable and suitable actions to reduce carbon emissions, although without solid obligation (CCD-NDRC, 2007). At the 2009 United Nations Climate Change Conference in Copenhagen, China proposed the goal of reducing carbon intensity by 40 to 45 percent from 2005 levels by 2020 (Finamore 2009). In China the coal-dominant power sector is a main source for CO_2 emissions, accounting for about 32% out of the total 7.6 billion tonnes of CO_2 emissions in 2007 (Wu 2009). To meet the soaring power demand in a more energy-efficient way, China is encouraging both the development of large-capacity (above 600 megawatt (MW)) supercritical (SC) or ultra-super critical (USC) pulverized coal (PC) for new generation units in the next decade, and research and development of the integrated gasification combined cycle (IGCC) and is extensively discussing carbon capture and storage (CCS) (Duan 2008; Chen and Xu 2009; Zhao et al. 2008). By adopting large-scale SC or USC units whose energy efficiency can be over 40%, together with shutting down small-scale and inefficient units, and improving the grids, China can reduce CO_2 emissions by 0.11 billion tonnes by 2010, about 7% of its target in the National Action Plan for Climate Change. The research and development of USC, SC, and IGCC technologies and equipments, as well as CCS technologies, are regarded as a key field to promote technology innovation and the capability of tackling the climate change (CCD-NDRC, 2007).

CCS in China is perceived as an important technology to reduce carbon emissions from power plants while meeting the growing energy demand, and there are extensive studies on this technology (MIT 2007, Liang and Wu 2009). In China, real CCS installation, designed and built with the power plants from the beginning, is being practiced by the only one IGCC+CCS demo project, GreenGen IGCC Project in Tianjin. This project is led by the Huaneng Group, the largest utility company in China, which joined forces with other major Chinese utilities and Peabody Energy. Shenhua Group, the largest coal company in China, is also considering the feasibility of CCS installation for its direct coal liquefaction facilities in Inner Mongolia. However, neither of these two projects has developed into the stage of construction for CCS. The technological risk remains as a barrier for China as well as many other countries to adopt CCS widely. Another obstacle can be the fact that in the near term, there is no indication of carbon-emission regulation (in the format of carbon tax or cap and trade, for instance) for China's power sector, thus there is no economic or regulatory incentive for utilities to adopt this expensive, but immature, technology for their generation units (Liang and Wu 2009).

Large-capacity PC or IGCC reduces carbon emissions through high energy efficiency, while CCS captures and injects CO_2 into underground geological formations. For example, a 1200MW-scale USC unit has net design energy efficiency of 42% (~295 gram coal equivalent per kilowatt hour, gce/KWh) and 200MW-scale IGCC's energy efficiency is high at 41%: a significant increase compared to the 33% average power plant efficiency in 2005 in China (Zhao et al., 2008; MIT 2007; NDRC 2007). This translates into a 27% energy-efficiency improvement: high-efficiency generation technology can reduce coal consumption by 27%, as well as lower CO_2 emissions by the same percentage, without carbon capture and storage. The saving of coal consumption alone can be a significant incentive for companies to pursue advanced generation technologies, such as USC PC or IGCC. CCS, can capture 90% of the total carbon emissions, and considering a 30% energy penalty (additional fuel consumption needed to maintain the same power output, due to CCS operation), this equals to about 86% of carbon reduction (MIT 2007). These technologies reduce carbon emissions in different ways and are not mandated to be combined together.

However, should there be some carbon regulation in China, power plants might choose to install CCS to control their carbon emissions, in order to reduce their payment for carbon charges. Wise investors or policy makers for the power industry in China should bear in mind the impact of future carbon regulation on their investment or policy decision. There has been growing awareness and demand for international or national efforts for combating global warming. China has already committed to reducing carbon intensity by 40~45% from its 2005 level by 2020, and U.S. Senators Kerry and Lieberman also proposed a new carbon legislation, the American Power Act. Although this America Power Act did not pass, it indicates the possibility of carbon regulation in the future. Thus, investors or policy makers in China should bear in mind how to make their investment decisions, if there is a carbon price and/or legislation in the future: to invest in PC or IGCC, with or without CCS. Without considering CCS and carbon prices, researchers expect IGCC to be more expensive than PC technologies (Zhao et al. 2008; MIT 2009). However, considering CCS and future carbon prices, according to an MIT study (2009), IGCC might have a cost advantage over PC. Therefore the carbon price plays a key role in this cost comparison. As for the case of China, costs of IGCC and PC are expected to be different from the United States or other countries. Therefore, two key questions arise: 1) What is the carbon price to justify the investment on CCS for IGCC and PC, should CO_2 emissions be charged in the future in China? 2) What is the risk caused by the CO_2 price variation for power plants' investment?

To answer these two questions, I explore the current cost structure for IGCC and PC in China and the cost of a CCS installation. Then, I build a net present value (NPV) model integrating carbon prices to identify the breakeven carbon price. Currently there have been few studies focusing on the cost comparison in China for IGCC and PC, integrating CCS or the future carbon pricing in China. My study fills this gap and provides implications for investors and policy makers in China for their decisions related to the power industry and climate change.

2. CCS and Electricity Generation Technologies in China

China has her own unique characteristics for power-plant investment. Reviewing the current development of IGCC, large-capacity PC, CCS, and potential carbon regulation, I identify the cost structures of these technologies in China and illustrate the development and economics of these technologies in China.

2. 1. IGCC and PC Development in China

Although IGCC technology is still in an experimental and demonstration stage (Zhao et al. 2008), China actually started research on IGCC in the 1970s and is attaching significant importance to this technology. In 1979, China decided to build its first experimental 10 megawatt (MW) IGCC plant for technical research, but it was stopped for several reasons (Pang, 2005). During the Eighth, Ninth, Tenth, and Eleventh Five-Year Plans, China supported research and development on the analysis and optimization of IGCC systems (Zhao and Gallagher, 2007). The 863 Program is a critical policy framework among many. The 863 Program or the State High-tech Development Plan, supervised by the Ministry of Science and Technology (MOST), sponsors advanced technology R&D in China including clean-coal technologies and IGCC. The 863 Program of the 11th Five-year Plan (2006-2010) was initiated in September 2006. MOST appropriated a budget of 3.5 billion

Chinese Yuan (CNY) for energy research, development, and demonstration, among which 21% was allocated for coal technologies. There is a budget of CNY 0.35 billion for developing coal gasification-based poly-production projects (*these plants produce syngas from gasification, and use syngas for both chemicals and power generation. This poly-generation is different from the electricity-oriented IGCC plants in this analysis: for the purpose of comparing technologies in-kind, we are studying electricity-oriented generation technologies, thus not discussing poly-generation power plants*). China is also actively seeking international cooperation for this advanced technology. During the Eleventh Five-Year Plan, several IGCC plants have been proposed or are under construction in China (Table 3-1). The annual workshops co-sponsored by Energy Technology Innovation Program of Harvard University and Chinese Academy of Sciences (CAS), are a powerhouse for exchanging ideas and research between the United States and China (Zhao, Xiao and Gallagher, 2009).

Table 3- 1: Active IGCC Projects in China

Active Projects	Location	Capacity MW	Fuel	Gasifier Vendor	CO_2 Capture
Dongguan IGCC Project (repowered)	Dongguan, Guangdong	2*60	coal	CAS	Study
Dongguan IGCC Project	Dongguan, Guangdong	4*200	coal	CAS	Study
Huadian Banshan IGCC Project	Hangzhou, Zhejiang	200	coal	ECUST	Study
Huaneng IGCC/GreenGen	Tianjin	250+400 **	coal	TPRI	Study
CPIC IGCC Project*	Langfang, Hebei	2*400	coal	N/A	Study, 8% EOR

*: ECUST, East China University of Science and Technology; CPIC, China Power Investment Corporation; **: capacities of two stages; EOR: enhanced oil recovery.
Source: Zhao, Xiao, and Gallagher, 2009; Xu 2008.

Pulverized coal, supercritical or ultra supercritical, is viewed in China as a key generation technology for new coal-fired power plants in the near future (Duan 2008; Chen and Xu 2009; Zhao et al. 2008). The government encourages USC PC and SC PC for new installed capacity, with 300MW circulating fluidized bed (CFB) as a supplement. Closing small-size power plants and building large-capacity PC plants, has contributed to the increase of the efficiency of power generation, and building large-capacity (over 600 MW) SC or USC for new electricity demand can further strengthen this contribution. The average coal intensity of China's power sector has decreased from 448 gram coal equivalent per kilowatt-hour (gce/kWh) in 1980 to 377 gce/kWh in 2005, and it is expected to drop to 320 gce/kWh in 2020 (NDRC, 2007). From 2004 to 2007 about 124 gigawatts (GW) of 600MW–level supercritical units were installed in China. Some analysts estimate that by 2020 there will be 30% of the total installed capacity in China that will be SC units (Chen and Xu 2009; Duan 2008). However, plants that install SC or USC PC units are not mandated to integrate CCS. CCS technology is still new and costly thus not suitable for deployment especially when there is no clear policy of carbon charges.

Given China's strong support for research and development (R&D) of advanced/clean coal technologies, there is a possibility that in the medium or long term, IGCC can join PC into the mainstream for the power plant fleet in China. This indicates that China's power industry planners should consider wise investment decisions with a long-term vision of both technologies instead of picking only one of them. CCS installed, the cost advantage between IGCC and PC would largely depends on the carbon price and the capital cost for CCS installation.

2. 2. Economics of PC and IGCC

Many analysts have examined the economics of coal power generation technologies in the United States and Europe, considering the option of carbon capture and storage (EPRI 2000, 2003; NETL 2002; National Coal Council 2004; Nsakala et al. 2003; Bohm et al. 2007; Sekar et al. 2007; MIT 2007, 2009). Sekar et al. (2007) establish a financial model comparing the cost of IGCC and PC and the break-even carbon price under the add-on of CCS after some years' operation of the plants, with data from several previous studies. Also, MIT has been giving considerable attention to coal-generation technologies research. The MIT (2007) study summarizes and compares a variety of analyses about performances and costs of PC and IGCC, with and without carbon capture and storage. MIT (2009), drawing from a symposium with participants from industry, academia, and governments, provides an analysis about performance of coal-generation technologies, as summarized in Table 3-2. However, the capital-cost estimates of power plants have significantly increased (in the case of the United States). Most recently, EIA (2010) released the updated estimates of power plants capital costs (Table 3-3). The key take-away from this EIA study is the significant increase of capital costs for power plants: about 50% higher than MIT (2009) results (Tables 3-2 and 3-3). Noticing this trend in the United States, I also update the capital costs of power plants in China with the most recent data, and reflect it in the modeling in the coming sections,

Table 3- 2: Performance of SC, USC, Oxy-fuel, and IGCC Plants

	SC		**USC**		**PC/Oxy**	**IGCC**	
CCS ->	**Without**	**With**	**Without**	**With**	**With**	**Without**	**With**
CO_2 emitted, g/KWh	830	109	738	94	104	824	101
Efficiency, % HHV	38.5	29.3	43.4	34.1	30.6	38.4	31.7
TCR $/KW	2,159	3,477	2,202	3,390	3,332	2,318	3,071
COE USD-cent/KWh	6.1	9.9	6.0	9.4	8.8	6.6	8.4

Note: 500 MW plant net output (noted by the author, from MIT (2007)); Oxy: oxy-combustion; TCR: total capital requirement; COE: cost of electricity; HHV: higher heating value. In 2010 US$ (original data in 2005US$, converted into 2010 US$ via CPI of 111.4 for 2010 (2005 as 100).
Source: MIT 2009.

Table 3- 3: Updated Capital Costs, 2010 (in 2010 US$)

	Capacity (MW)	**Heat Rate (BTU/KWH)**	**Overnight Capital Cost (2010$/KW)**	**Fixed O&M Cost (2010$/KW)**	**Variable O&M Cost (2010$/KW)**
Single unit advanced PC	650	8,800	**3,167**	35.97	4.25
With CCS	650	12,000	**5,099**	76.62	9.05
Dual unit adv. PC	1,300	8,800	**2,844**	29.67	4.25
With CCS	1,300	12,000	**4,579**	63.21	9.05
Single unit IGCC	600	8,700	**3,565**	59.23	6.87
With CCS	520	10,700	**5,348**	69.30	8.04

O&M: Operation and Maintenance
Source: EIA 2010

Studies about IGCC economics in China mainly focus on the cost comparison between IGCC and PC without considering carbon prices and the cost of CCS. For example, Zhao and Gallagher (2007) introduced research and development (R&D) and demonstration projects and policies for advanced coal technologies in China. Chen and Xu (2009) describe coal's role in China's energy system and discuss the development and policies for IGCC and carbon capture and storage (CCS) with no cost data provided. Some institutes, including Tsinghua University (Tsinghua 2008), the Institute of Thermal Physics in the CAS (Zhao et al. 2008), and the Thermal Physics Research Institute (TPRI) study the economics of IGCC in China. Among these, Zhao et al. (2008) reveal performance and economics of PC and IGCC power plants based on data of the design studies for 12 power plants including two IGCC plants with capacities of 228 MW and 251 MW. Zhao's (2008) case studies, drawing upon projects in China provide the following results for PC and IGCC technology options (Table 3-3). GreenGen, the largest IGCC development project in China considers CCS in their IGCC design for Stage II (2010-2012) and Stage III (2013-2015), but these CCS data are preliminary in the design stage and are confidential. Therefore, these studies provide only limited data regarding the cost of CCS on PC or IGCC plants.

To overcome the limitation of current data in revealing the investment costs in China, I collected more data from my trips to China and utility companies' annual reports. The capital costs are increasing, but not at a dramatic pace, and basically fluctuate around the level of CNY 4,000/KW. As shown in Table 3-4, Zhao et al. (2008) identified that PC power plant capital costs are in the range of CNY 4,277 to 5,192 per KW (2010 currency value). I also draw upon capital costs data from annual reports of Huaneng Group, the largest utility company in China. Most of Huaneng's new assets are supercritical plants. As shown in Table 3-5, average capital cost is CNY 3,602 per KW in 2008 and then CNY

3,812 in 2009, a modest increase of 6%. The most recent estimates by Dave, et al. (2011) show the average capital cost of CNY 4,569/KW for all types of power plants in China (Table 3-5). The costs in China are significantly lower than those in the United States, as summarized in Table 3-7. However, as EIA (2010) estimates, power-plant capital costs have experienced a significant increase in the past two years (Tables 3-2 and 3-3, 64% increase for PC and 71% for IGCC, benchmarked by MIT (2009) study). Considering this, (and also bearing in mind that 2008 and 2009 are years with an economic slowdown and lower commodity prices), I believe the capitals costs for PC plants in 2010 and 2011 should also be increased noticeably. Therefore, in the model, I adopt the same percentage increase as EIA projected, based on the most recent estimate CNY 4,569/KW or $674/KW, to $1,106/KW (Table 3-7).

For IGCC plants, Zhao et al. (2008) estimate the capital costs of two plants (based on data of design studies) at CNY 7,433 and 8,842 per KW (Table 3-4). Other sources show that the unit costs for different IGCC plants vary in a range from CNY 7,625 to CNY 11,250, averaging at CNY 10,097 (2010 currency value) or $1,490/KW (Table 3-6). As these studies were conducted a few years ago, costs might actually have increased since then, as EIA (2010) projects. Therefore, I adopt the increase percentage of 71% from EIA (2010) for IGCC capital costs, which gives $2,548/KW (Table 3-7).

Table 3- 4: Performance of PC and IGCC Plants in China

Performance	PC 1200MW	IGCC 251MW	IGCC 228MW
Coal consumption rate (gce/kWh)	290.8 - 311.4	303.9	298.5
Net design efficiency (LHV)	39.5 - 42.3	40.5	41.2
TCR (Yuan/kW)	4,277 - 5,192	8,450	9,720
COE(Chinese cent/KWh), exclusive of pollution charges	29.7 - 31.7	40.9	43.9
COE(Chinese cent/KWh), including pollution charges	29.9 - 31.7	40.9	43.9

Note: Currency values: 2010 CNY (converted from 2006 CNY by CPI of 113.7 of 2010 vs. 100 of 2006). PC plants include 1200MW-scale subcritical, supercritical, and ultra-supercritical units. All plants are designed without considering CCS. gce = gram standard coal equivalent; LHV = Lower heating value; MW = Mega-watt;
Source: Zhao et al. 2008.

Table 3- 5: PC Power Plants Economics, China Huaneng Group

Power Plant	Investment Billion CNY	Capacity MW	Technology	Operation	Construction months	TCR CNY/KW
Shang'an Phase III	4.55	2*600	Supercritical	2008	24	3,794
Rizhao Phase II	4.00	2*680	Supercritical	2008	19	2,945
Yuhuang Plant	15.60	4*1,000	Ultra-supercritical	2008	41	3,900
Luohuang, Phase III	4.50	2*600	Subcritical	2006	27	3,750
Yingkou, Phase III	4.58	2*600	Ultra-supercritical	2007	29	3,817
Hegang, Phase II	1.98	1*600	Supercritical	2007	32	3,300
Yangluo, Phase III	4.45	2*600	Supercritical	2007	27	3,708
					Average (2008)	*3,602*
Fuzhou, Phase III	5.3	2*600	USC	2010	16	4,417
Yueyang, Phase III	4.3	2*600	USC	2010	22	3,583
Pingliang, Phase II	4.4	2*600	SC	2010	n.a	3,667
Weihai PP, Phase III	4.7	2*600	USC	n.a	n.a	3,917
Haimen PP,	7.2	2*1036	USC	2009	24	3,475
					Average (2009)	*3,812*
					*Dave, etc (2011)**	*4,569*

*: 4,569 CNY/KWh, 2010 currency value, from overall PC plants, estimated by Dr. Shisen Xu, the chief technology officer from TPRI.

Source: 2008, 2009 Annual Reports, China Huaneng Group; for each power plant project, I also searched related news on the Internet to check the consistency.

Table 3- 6: Some IGCC Plant Designs in China

Power Plant	Developer	Budget, Billion CNY	Capacity MW	TCR CNY/KW
1. Shenyang IGCC*	Datang	18.6	4*400	11,610
2. GreenGen, Phase I	Huaneng and others	2.3	1*250	9,082
GreenGen, Phase II*	Huaneng and others	5.4	400	13,416
3. Dongguan IGCC	Dongguan Electricity and Chemical Inc.	6.3	4*200	7,869
4. Banshan IGCC*	Huadian	2.1	200	10,310
5. Langfang IGCC	China Power Investment International	6.6	2*400	8,295
		Average of IGCC TCR		**10,097**

Note: numbers from design studies; *, planned or proposed; otherwise under construction as of May 2010; GreenGen Phase II, including CCS. The currency values are in 2010 CNY (converted from 2009 thought CPI increase of 3.2% in 2010).

Source: Utility companies news and Internet reports, including:

1. http://www.cecm.net.cn/news/Elec/2008/06/3527.html,
2. Phase I at http://www.chng.com.cn/n16/n26536/n26584/100382.html, and phase II at http://www.cecm.net.cn/news/Region/2007/04/1552.html
3. http://www.cecm.net.cn/news/Region/2007/06/1786.html
4. http://www.cftn.cn/news/cftn_1/20/2007122810545371_1153.html, and http://power.nengyuan.net/2008/0112/5280.html
5. http://zdt.cpnn.com.cn/template/WebRootj/xianshi.jsp?nid=09031313324925925265

Table 3- 7: Power Plants Capital Costs Comparison

	PC	IGCC
China (CNY)	**4,569**	**10,097**
Nominal exchange rate: 6.78, 2010	674	1,490
Cost hiked as EIA projected (1.64 PC, 1.71 IGCC)*	**1,106**	**2,548**
Purchasing power parity exchange rate, 3.92, 2010	1,166	2,576
USA, by EIA 2010	**3,167**	**3,565**

Note:
2010 US$ otherwise noted; *1.64 or 1.71 are benchmarked with PC and IGCC cost data from MIT (2009) study, of the similar currency of those Chinese power plants data; these costs are adopted in modeling; 2010 nominal exchange rate from IRS, URL: http://www.irs.gov/businesses/small/international/article/0,,id=206089,00.html
2010 PPP exchange rate from http://en.wikipedia.org/wiki/Renminbi#Purchasing_power_parity
Source: Table 3-2, 3-3, 3-5, and 3-6.

As seen from the above tables, and also expected by many analysts, Chinese power plants have much lower cost or capital investment compared to the United States (Zhao, Xiao and Gallagher 2009). Benchmarked by the market exchange rate, the capital costs for PC in the United States is $3,167/KW for SC and $3,565/KW IGCC according to the most recent estimates by EIA (2010), while in China the numbers are 674 and 1,490 (benchmarked by the market exchange rate), less than half those of the USA. Even if I assume that during the past two years, power plants capital costs have increased significantly (EIA, 2010), China's power plants' costs are still only $1,106/KWh for PC and $2,548/KWh for IGCC. Figure 3-1 shows this comparison.

However, what is the cost comparison if benchmarked to the real exchange rate, purchasing power parity (PPP) exchange rate? Given the long-lasting debate about the under-valuation of the Chinese Yuan, this PPP-based comparison might yield different results – this is not the focus of this paper, but it can provide another perspective for the readers to understand the costs of power plant investment in China. The PPP exchange rate is deduced by finding goods available for purchase in both currencies and comparing the total cost for those goods in each currency – thus a 'real' exchange rate. China's IGCC plants costs, if benchmarked by the PPP exchange rate of 3.92 in 2010, would be more expensive, but still lower than the United States. As shown in Figure 3-2, the total capital requirement for PC in China is $1,166/KW, and IGCC's cost estimates in China now becomes as high as $2,567/KW: still much less expensive than in the United States Although currently there is no more recent data available (e.g., 2010 power plants costs), I am inclined to the view that the costs should also be significantly higher compared to a couple years ago when the global economy was in a recession, as EIA (2010) estimates. Therefore, in this analysis, I adopt the 'increased' cost estimates, i.e., $1,106/KW for PC, and $2,548/KW for IGCC, as the base scenario in modeling.

Given the above cost estimates, an analyst might wonder why power plants in China are much cheaper to construct than in the United States. This can be another interesting question to explore. However, given the limited time and resources, I will leave this question, which is not the purpose of this study, for future research.

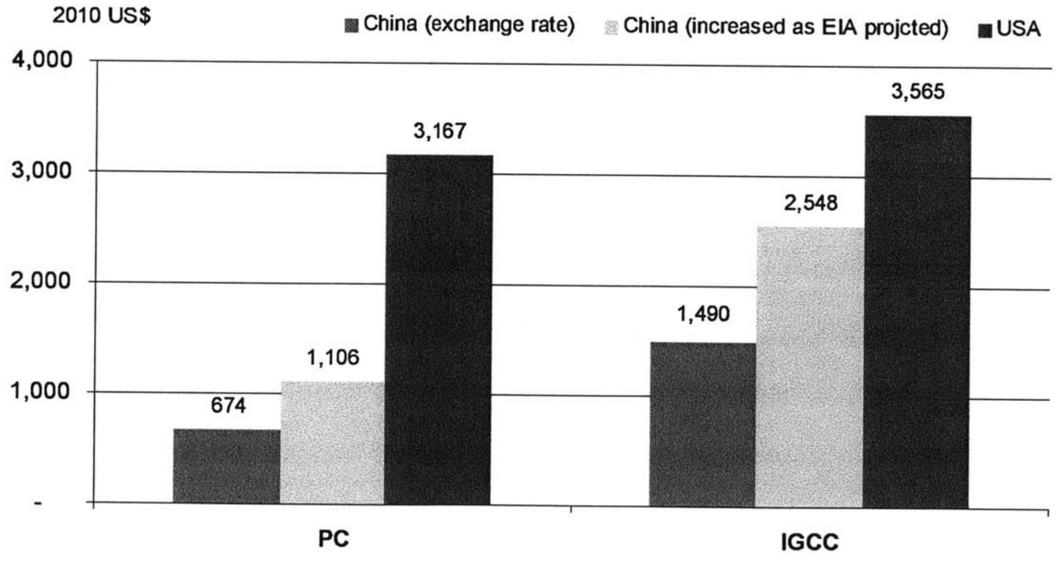

Figure 3- 1: Market Exchange Rate Based Costs Comparison: China vs. USA
Note: Costs are total cost requirement, TCR.

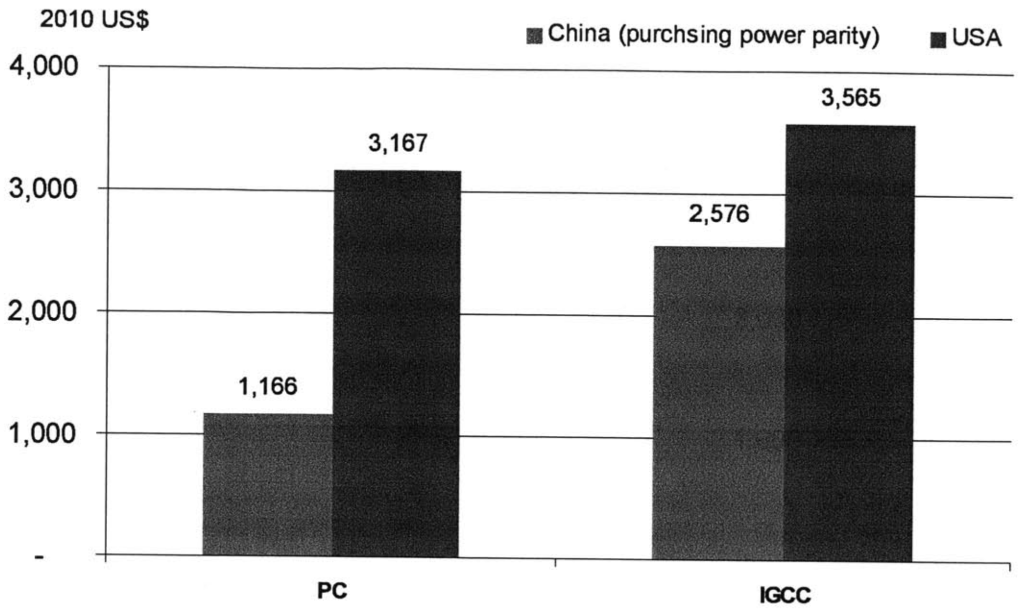

Figure 3- 2: PPP Exchange Rate Based Costs Comparison: China vs. USA
Note: Costs are total cost requirement, TCR.

2. 3. Carbon prices and CCS

Currently, there is no legislation on CO_2 emissions in China, but there is a goal of carbon-intensity reduction by 40 to 45 percent from 2005 levels by 2020, and also a near-term target of 1.5 billion tonnes of CO_2 emissions reduction by 2010 as stated by the NDRC. Therefore, China relies on increasing energy efficiency, developing renewable energy, developing advanced coal-fired generation technologies, and other measures. The 1.5 billion tonnes CO_2 reduction by 2010 means that about 20% of China's 2007 total CO_2 emissions must be captured. Although China does not set any explicit regulation for the CO_2 emissions, her current efforts might imply a possibility of carbon regulation in the future.

To reduce CO_2 emissions from the power sector, in addition to encouraging those large-capacity and high-efficiency generation units, Chinese policy makers perceive CCS as a critical (although currently unsuitable for commercialization) technology. However, each stage of CCS, capture, transport, and storage, is capital and energy intensive, and will impact the cost of electricity or other industrial commodities as materials for CCS equipments (McCoy 2008). In China, although many experts agree that CCS should be considered a method for combating climate change because of the increase of coal consumption and the compatibility with current coal-dominant energy system, they hold that currently CCS is far from being deployable on a commercial scale due to high cost and technological uncertainties, and other reasons (Liang and Wu 2009).

In China CCS research focuses on the capture stage. There are a few enhanced oil recovery (EOR) and enhanced coal bed methane projects, but China lacks the integrated technology for transportation, injection, monitoring, and risk control (Liang and Wu 2009).

In terms of the cost of CCS, a literature review shows a range of \$30-\$70 per tonne, based on studies conducted some years ago. For instance, MIT (2007) estimates that the cost of CO_2 capture and pressurization is about \$25/tonne, and the transportation and storage cost is about \$5/tonne, which requires a carbon-dioxide price of \$30/tonne to make CCS economically viable. Similarly, the Boston Consulting Group (2008) estimates that then-current CCS implementation cost would be 45 Euro per tonne, and by 2030 it can be decreased to 30 Euro per tonne if 500 billion euro investment from government subsidies and company during this period. Al-Juaied and Whitmore (2009) estimate a range of 35 to 70 US dollars per tonne (2008\$) for carbon-capture costs. In China, laboratory data shows that the cost of CO_2 capture is 0.19-0.25 Yuan/KWh, or \$38-50/tonne CO_2, assuming 0.6 tonnes CO_2/MWh captured (Sekar et al. 2008) and an exchange rate of 7 for USD/CNY. However CO_2 transportation and storage cost is less studied and known in China's case (Liang and Wu 2009). Currently there are no data available to reveal incremental capital investment for CCS installation in China. GreenGen, the IGCC+CCS demo project in China, shows a gross unit cost of CNY

13,000 for the second stage 400MW IGCC plus CCS. But GreenGen is still at the designing stage, and no specific data are available for CCS. Even TPRI (Thermal Power Research Institute), the leading power generation technology institute that is developing IGCC for the GreenGen Project in China, had to cite the U.S. CCS cost data in their presentation about the GreenGen (IGCC+CCS) project (Xu, 2006, 2008).

Therefore to overcome the limitation of data availability, I identify CCS cost from the incremental capital investment to power plants. I devise a CCS Incremental Index, as summarized in the following table. The average incremental cost percentages of several studies are 66% for PC and 34% for IGCC. I separate EIA data as they are the most recent estimates, different from other studies in this summary in considering the likely augmented capital costs. Given that EIA numbers are in line or not significantly different from the average, i.e., 61% vs. 66%, and 50% vs. 34%, I adopt the EIA numbers for modeling, in order to reflect the most recent cost structure.

Table 3- 8: CCS Incremental Capital Costs Index

	PC	IGCC
1. Hamilton (2009)	61%	51%
	80%	16%
	82%	32%
	39%	40%
		35%
2. Sekar (2007)	73%	30%
3. MIT (2009)	57%	32%
Average	**66%**	**34%**
EIA (2010)	**61%**	**50%**

Note: The incremental capital cost resulted from CCS related to the capital cost of the power plant
Source: 1. Hamilton (2009) summarizes costs data from various sources including CERA, NETL, EPRI, AEP, and others. 2. PC data from MIT (2009) are the average of SC and USC technologies.

3. Methodology and Data

To calculate the costs and identify the optimal investment decision under carbon prices, I adopt the net present value (NPV) methodology. Appropriate assumptions for China's case are critical to build this NPV model, but it is also challenging given the limitation of current data and literature. Through communicating with scholars, engineers, and government officers during my field trips in China, combined with data from the literature review, I made assumptions which best represent the situation in China.

The power plants of question have the following characteristics, for both PC and IGCC:

- installed capacity, 600MW,
- annual operation hours, 6000, according to Zhao et al. (2008) design data[43],
- operational life, 40 years,
- energy penalty with CCS, 28% for PC, and 17% for IGCC (Table 3-9)
- tax rate, 40%,
- depreciation, linear, 6.3% per year for 15 years, then 5% salvage value remains,
- discount rate of 6%, and
- thermal coal price, CNY 700/tonne, equal to $5.2/MMBTU.

Table 3- 9: Energy Penalty

PC	IGCC	Source
31%	16%	Rubin, Chen and Rao, 2007 (Carnegie Mellon)
21-24%	19%	MIT 2009
28%	14%	Herzog and Golomb, 2004 (MIT)
-	20%	NETL 2010
30-40%	-	IPCC 2005
28%	**17%**	**Aggregated average**

Source: listed in the table

More performance parameters are summarized and explained in Table 3-11. Based on an extensive literature review and survey in China, I believe the following assumptions adequately represent the performance of typical power plants in China.

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[43] In 2010, average operation hours of thermal power plants are 5,329, 5% of increase from 2009, according to China Power International, one of the major utilities in China. CPI also projects 2011 operation hours will stay the same as 2010. See http://www.chinapower.hk/gb/ir/faq.htm. Therefore, 6,000 is not a low number, as power plants usually need days for maintenance, etc.

Table 3- 10: China CPI

Year	CPI (2006=100)
2000	92.4
2001	92.8
2002	92.1
2003	93.2
2004	96.8
2005	98.6
2006	**100.0**
2007	104.8
2008	110.9
2009	110.2
2010*	113.7

Note: CPI, Consumer price index

Source: NBS, Measuringworth. URL: http://www.measuringworth.com, and http://www.chinamining.org/News/2010-01-21/1264055685d33624.html.

Table 3- 11: Power Plants Assumptions

Performances and Assumptions	Without CCS		With CCS	
	PC	IGCC	PC	IGCC
1. Capital cost (Million $)	663	1,529	1,068	2,293
Capital cost ($/KW)	1,106	2,548	1,780	3,822
2. Net heat rate (BTU/KWH)	8,441	8,361	11,724	10,074
3. Fuel input (Annual, Million MMBTU)	30.4	30.1	42.2	36.3
4. Fuel costs($Million)	157.8	156.3	219.1	188.3
5. O&M costs ($Million)	16.6	53.5	42.2	95.6
6. CO_2 emissions (Tonne/MWH)	0.669	0.663	0.086	0.078
7. CO_2 emissions (Million tonnes/year)	2.41	2.39	0.31	0.28

Note: based on 600 MW capacity power plants.

1. Based on TCR data from Table 3-7, US$ 1,106/KW for PC and US$ 2,548/KW for IGCC. CCS installation increases the capital costs by 61% for PC, and 50% for IGCC, based on EIA (2010) estimates. Total capital costs (Million $) = Unit cost ($/KW) * 600/1000

2. The coal rates are 304.1gCoe/KWh and 301.2gCoe/KWh for PC and IGCC (Zhao et al. 2008), without CCS. Multiplying 27.76Btu/gCoe, to get the net heat rates. For with CCS, considering 28% energy penalty for PC and 17% for IGCC, i.e., fuel = net heat rates / (1-energy penalty).

3. Fuel input = net heat rate * Annual operation hours * capacity factor * capacity * unit conversion

4. Fuel costs = fuel input * coal price. The coal price is assumed to be CNY 700/Metric Tonnes of raw coal at 2010 prices (thus, CNY 980/Metric Tonnes of standard coal), equals to $5.2/MMBtu, considering a heat content of 27.76MMBTU/Metric tonnes of standard coal.

5. Assuming 2.5% and 3.5% of Capex for annual O&M Costs for PC and IGCC (from Zhao et al. (2008) design studies data). With CCS, the O&M costs include $5/tonne for all the CO_2 emissions. e.g., for IGCC with CCS, O&M = 3.5%*Capex + $5 * CO_2 emissions /(1-energy penalty) * capture rate.

6. Without CCS, assuming 60% carbon content and 27.76 MMBTU per tonne for standard coal. CO_2 emissions per MWH = net heat rate/1000/27.76 * 60% * 44/12; with CCS, consider energy penalty and 90% capture rate, i.e., =emissions * (1+ penalty) * 10%.

7. Annual CO_2 emission = CO_2 emissions / MWH * capacity * annual operation hours * capacity factor.

For the NPV model, the breakeven CO_2 price is the price that makes the saving of carbon charge from installing CCS on par with the incremental investment for CCS. With CCS installation, a power plant would have a higher capital expense, higher fuel costs and O&M costs due to the energy penalty and operating the CCS unit, and also different cash-flow elements including depreciation, taxes, tax shields, and others. But the savings from paying a lower carbon charge can offset this additional cost. I attach the NPV models in the Appendix, and the spreadsheets are also attached separately for readers' reference.

4. Results and Discussion

A carbon price of $61/tonne is necessary to justify the CCS investment for PC plants, while for IGCC plants, the breakeven price is higher, at $72/tonne. The price gap between the two technologies is mainly caused by the difference in capital costs. As shown in Table 3-11, without CCS, the IGCC capital requirement is $2,548 per KW, and PC is $1,106 per KW: IGCC is 130% more expensive than PC. With CCS installation, IGCC is 110% more expensive than PC. IGCC, with gasification technologies, is more complicated than PC plants, thus more expensive. Higher capital costs explain the bulk of this difference of breakeven carbon prices.

The estimates of carbon prices are slightly above the range of estimates by other analysts. For example, costs for CCS are estimated at $35-70/tonne by Harvard (Al-Juaied & Whitmore 2009), and Euro 45/tonne in the near term and Euro 30/tonne by 2030 (BCG 2008), and or $30/tonne by MIT (2007). Sekar et al. (2008) identified the breakeven price at $21/tonne for PC while $45/tonne for IGCC, for retrofit for CCS after 4 years' operation. Given the cost increases during the past years as EIA (2010) estimates, the results about carbon prices are basically in line with this upward trend and can reasonably reflect the situation in China. However, the prices from our analysis are significantly higher than the recent international carbon price, for instance, the CER price of 16 Euro per tonne (Future price of December 2012 Certified Emission Reduction, CER, in European Climate Exchange priced at EUR 16/tonne, September 2010, according to Bloomberg). This high CO_2 price threshold, then, indicates a potential financial barrier to make CCS investment in China in the near term, as the lower carbon price would be insufficient to justify investment for CCS if the carbon charge savings are the main profit source for CCS installation.

The breakeven carbon prices are subject to the impacts of several parameters. Volatility of each parameter would introduce the variation of breakeven carbon prices, thus, different profit or loss scenario for investors. It is worthy to explore how some key parameters impact the carbon prices, in order to highlight the risks for investment and provide implications for investors.

4.1 Capital Costs

Power plants' capital costs are a key factor that affects the carbon price. As shown in the following table, for PC plants, if the unit capital cost decreases by 20% to $885/KW, the breakeven carbon price becomes lower by about $5, or 8%, which translates into an elasticity of 0.4. In the case of IGCC, a 20% lower Capex introduces a carbon price of $10, about 14%, an elasticity of roughly 0.7. IGCC, which incurs higher capital costs, is more sensitive to the change in capital costs. When the capital cost is low, for example, 40% less than the base scenario, the breakeven carbon prices for PC and IGCC are approximately similar: $51 and $52. The lower the capital costs are, the narrower the carbon prices between PC and IGCC. Whereas, IGCC requires a higher carbon price to justify CCS installation when the capital costs are larger, as shown in Figure 3-3.

Table 3- 12: Capital Costs and CO_2 Prices

TCR, $/KW	PC, $/KW	CO_2 Price, for PC	Elasticity	IGCC, $/KW	CO_2 price, for IGCC	Elasticity
-60%	442	46.3		1,019	42.3	
-40%	663	51.2		1,529	52.3	
-20%	885	56.1		2,038	62.2	
Base	**1,106**	**61.0**	0.4	**2,548**	**72.2**	0.7
+20%	1,327	65.8		3,057	82.1	

Note: other assumptions remain unchanged while conducting this sensitivity analysis.

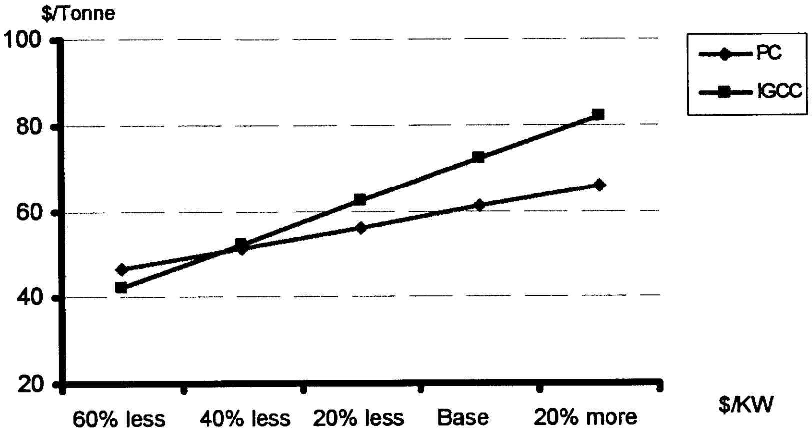

Figure 3- 3: Capital Costs and CO_2 Price

4.2 Fuel Cost

Another key factor is the fuel cost, or the price of coal. Steam Coal is the main fuel for power plants in China, thus accounting for a significant portion of operating costs. Thus, variation in the price of coal also determines the volatility of carbon price needed to justify CCS investment. If the coal price increases by 20% to $6.2/MMBTU, the breakeven carbon price increases by about $6 for PC (10%), and $3 for IGCC (4%). This implies an elasticity of coal price at 0.5 for the breakeven carbon price for PC, while 0.2 for IGCC: IGCC is less sensitive to coal price volatility than PC, due to the fact that it has a bit higher energy efficiency (net heat rate of 8,361 BTU/KWh vs. 8,441 BTU/KWh) and its lower energy penalty (17% vs. 28%), both of which cushions some of the coal-price volatility shock, compared to PC. If the coal price keeps increasing, as shown in Figure 3-4, we would expect IGCC to demand a lower breakeven carbon price than PC. For example, if the price is doubled to CNY1,400 per tonne, or \$10.4/MMBTU, IGCC requires \$87.4/tonne CO_2 price to justify its CCS investment, while PC needs \$90. In general, when the fuel cost increases, IGCC is catching up with PC in the economy for CCS installation.

Table 3- 13: Fuel Costs and CO_2 Prices

Price scenarios	Coal Price (\$/MMBTU)	CO_2 Price for PC	CO_2 price for IGCC
-50%	2.596	46.3	64.6
-20%	4.153	55.1	69.1
Base	**5.192**	**61.0**	**72.2**
+20%	6.230	66.8	75.2
+50%	7.787	75.6	79.8
+100%	10.383	90.2	87.4

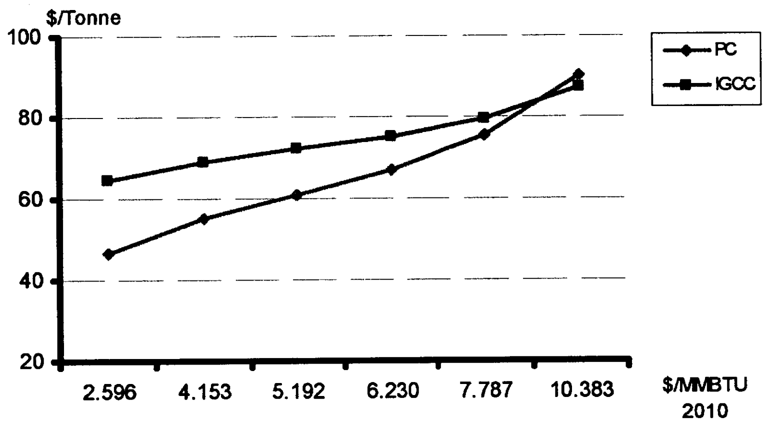

Figure 3- 4: Coal and CO_2 Prices

The coal price in China has been high for the past couple years, above CNY 700/tonne. Bohai-rim steam coal price index (BSPI), China's first government-backed coal price index to reflect the coal prices for major ports around the Bohai-rim in China, for 2010 and early 2011 is fluctuating between CNY 700 and 800 per tonne, as shown in the following graph. Given the growing demand due to economic development and increasing net coal imports since 2008, there is a good chance that this 'high' price is unlikely to tumble in the near future. Feng Ping, an official from National Energy Administration under NDRC, expects that "in 2011 [the coal price] is expected to stay around the level registered at the end of 2010" (HSN, 2011). NDRC in December 2010 ordered "the price of the country's 2011 major coal-supplying contracts to remain unchanged from 2010" and "no excuse for a price increase" would be allowed (Chen, 2010), which also reflects the pressure from soaring coal prices.

Therefore, bear in mind that a coal price of $5.2/MMBTU, equal to CNY 700/Tonne of raw coal in China, is still a modest coal-price assumption for China. If the coal price continues to augment in the future, the breakeven CO_2 price will also increase with this trend, whereas IGCC might be gaining an advantage for CCS investment due to its saving in coal consumption.

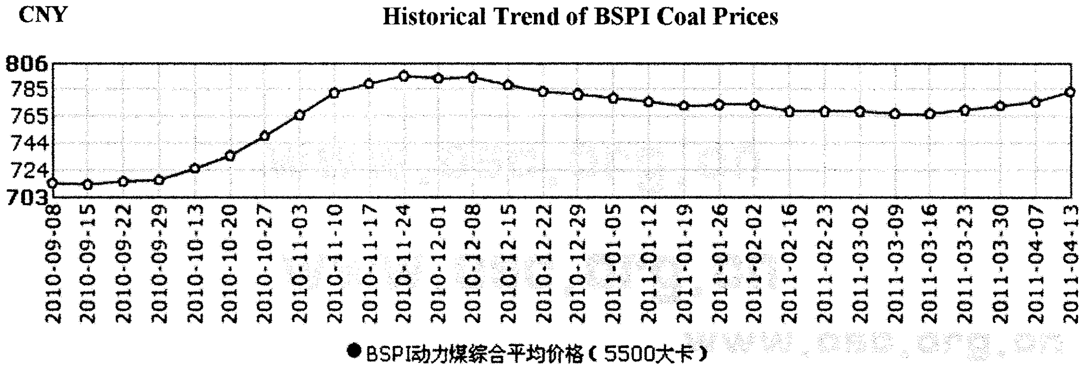

Figure 3- 5: BSPI Weekly Average Price
Note: BSPI, Bohai-Rim Steam-coal Price Index; Prices for 5500Kcal/kg steam coal.
Source: http://www.osc.org.cn/CoalIndex/chs/new/index.html#bohai_1

4.3 Investment Return

In addition to capital costs and fuel prices, investors might also need to understand how their investment return is affected under different carbon price scenarios. PC and IGCC plants call for different breakeven carbon prices to justify CCS investments, which indicate that, under one carbon price, PC and IGCC plants might have different investment returns. As shown in Table 3-14, under the low carbon price scenarios, e.g., $40, or $50 per tonne, both PC and IGCC would have losses, and IGCC has a larger exposure to this loss due to its higher capital investment for both power plants and CCS installation. As the carbon price increases, both types of power plants gain improving returns, but PC still gains a more resilient profit or loss profile than IGCC. A carbon price at $70/Tonne would generate a total return of $171 million for a PC plant,, which is still insufficient to make IGCC plus CCS installation profitable. This trend delivers a signal that if investing for CCS, only based on carbon prices, and all other factors being equal, investors might prefer PC plants to IGCC, as the former carries a better investment return from the carbon-charge savings.

Table 3- 14: CO_2 Price and CCS Investment Return

CO_2 Price $/Tonne	Profit for CCS Investment, PC, $Mn	Profit for CCS Investment, IGCC, $Mn
40	(397)	(612)
50	(208)	(421)
60	(18)	(231)
70	**171**	**(41)**
80	361	149
90	551	339
100	740	529

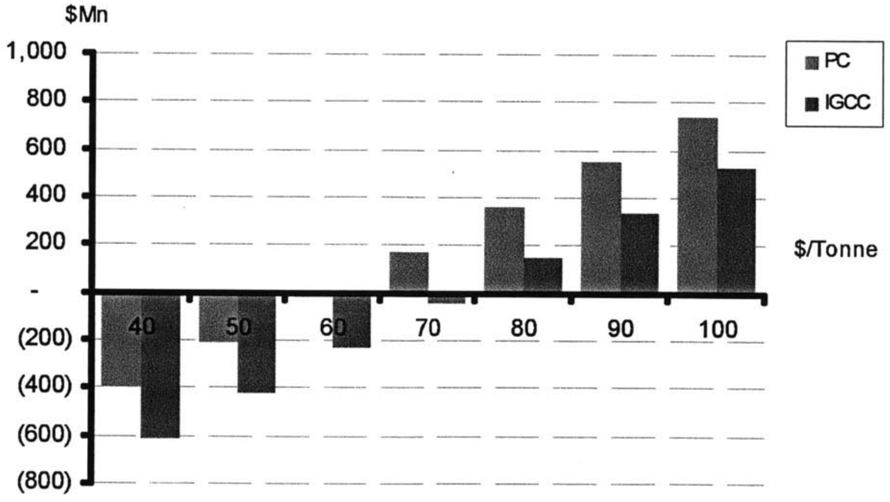

Figure 3- 6: CO_2 Price and CCS Investment Return

5. When to Invest in CCS?

For investors, it is critical to acknowledge when would be an appropriate entry time to invest for CCS. There are two important factors to bear in mind for CCS investment: the technology innovation, which can reduce the capital expense, and the carbon price, which can be affected by international or national efforts for combating climate change. Investment for CCS for coal-fueled power plants can become cheaper as more technology innovation is achieved. Also, the debut of international climate change protocol or the US climate change legislation, if any, can be a bullish driver for international carbon prices. For example, the American Power Act proposed by US Senators John Kerry and Joe Lieberman in May 2010 suggested a price collar for carbon charges of $12 and $25/T in the first year (2013), with annual escalations according to CPI at a rate of 3% and 5% for the floor and ceiling, respectively. This indicates the carbon price can be as high as $43 in 2020 and $93 by 2030, assuming a 3% increase in the CPI.

To answer the question when to invest in CCS, I conduct a scenario simulation based on the following assumptions:

- an annual 10% decrease for unit capital costs due to technology innovation[44],
- an annual 4% decrease for breakeven carbon price for PC at the elasticity of 0.4 discussed previously, and 7% for IGCC at the elasticity of 0.7.
- international carbon prices in line with the medium of the price scenarios suggested by Kerry-Lieberman.

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[44] 10% annually might be an aggressive assumption. But this is just an example of how capital costs affect the entry time of investment. Also, we are simulating for China, where many power plants are being built each year, and a significant amount of investment is made for energy technology innovation. In this context, 10% is not a greatly unrealistic assumption.

There are a couple takeaways from this simulation. First, the required breakeven CO_2 price decreases accordingly when the capital costs is decreased due to technology innovation, and in 2015, IGCC turns as competitive as PC in investing for CCS installation as they have a very close CO_2 breakeven price at about $50 per tonne. Second, by 2024, the international carbon price can be sufficient to justify the CCS investment for IGCC power plants, but not yet PC plants. Then, four years later, in 2028, the carbon price rises to about $31/tonne, and becomes high enough to ensure a positive investment return for PC plants. Still, from this point on, investing in CCS for IGCC plants yields a higher return.

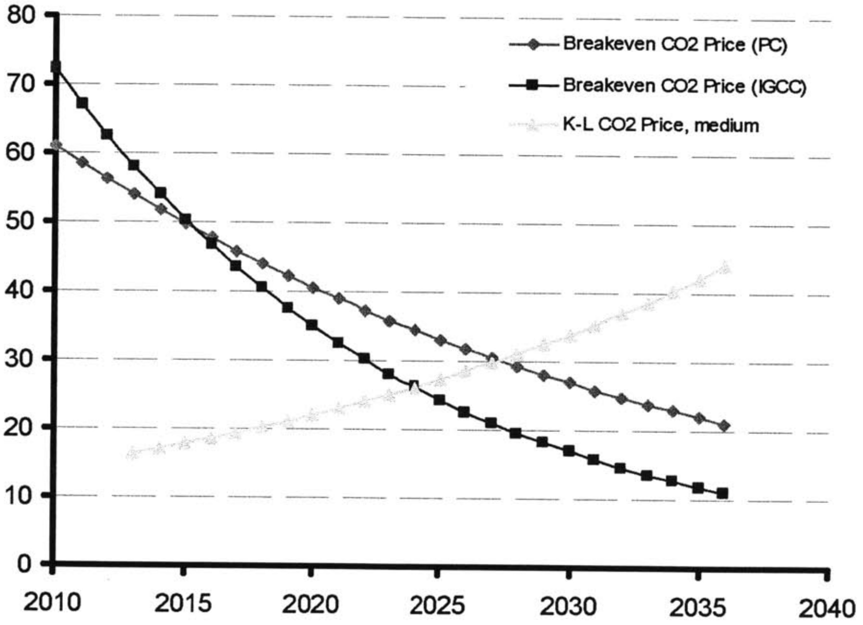

Figure 3- 7: When to Invest for CCS

Table 3- 15: Technology Innovation and Carbon Pricing

Year	PC		IGCC		K-L Price		
	Cost, $/KW	Breakeven C CO_2 Price, $/Tonne	Cost, $/KW	Breakeven CO_2 Price, $/Tonne	Medium, $/Tonne	Floor, $/Tonne	Ceiling, $/Tonne
2010	1,106	61.0	2,548	72.2			
2011	995	58.5	2,293	67.1			
2012	896	56.2	2,064	62.4			
2013	806	53.9	1,857	58.0	16.3	11.0	21.6
2014	725	51.8	1,672	54.0	17.0	11.3	22.7
2015	**653**	**49.7**	**1,505**	**50.2**	**17.7**	**11.7**	**23.8**
2016	588	47.7	1,354	46.7	18.5	12.0	25.0
2017	529	45.8	1,219	43.4	19.3	12.4	26.3
2018	476	44.0	1,097	40.4	20.1	12.7	27.6
2019	428	42.2	987	37.6	21.0	13.1	28.9
2020	386	40.5	888	34.9	21.9	13.5	30.4
2021	347	38.9	800	32.5	22.9	13.9	31.9
2022	312	37.3	720	30.2	23.9	14.3	33.5
2023	281	35.9	648	28.1	25.0	14.8	35.2
2024	**253**	**34.4**	**583**	**26.1**	**26.1**	**15.2**	**36.9**
2025	228	33.0	525	24.3	27.2	15.7	38.8
2026	205	31.7	472	22.6	28.4	16.1	40.7
2027	184	30.5	425	21.0	29.7	16.6	42.8
2028	**166**	**29.2**	**382**	**19.5**	**31.0**	**17.1**	**44.9**
2029	149	28.1	344	18.2	32.4	17.6	47.1
2030	134	26.9	310	16.9	33.8	18.2	49.5
2031	121	25.9	279	15.7	35.3	18.7	52.0
2032	109	24.8	251	14.6	36.9	19.3	54.6
2033	98	23.8	226	13.6	38.6	19.8	57.3
2034	88	22.9	203	12.6	40.3	20.4	60.2
2035	79	22.0	183	11.8	42.1	21.0	63.2
2036	71	21.1	165	10.9	44.0	21.7	66.3

Note: Power plants costs and CO_2prices are all at 2010 value. K-L prices start in 2013 with then-current value of $12 and $25 for floor and ceiling, benchmarked to 2010 by annual CPI of 3%, then the flooring and ceiling grow at 3% and 5%, respectively, according to the CPI. The medium price is the average of the floor and the ceiling prices.

6. Conclusion

This study shows that, given the current technology and costs, a carbon price of $61/tonne is required to justify the investment on CCS for a typical PC plant in China, and a higher price of $72/tonne is necessary to make the similar investment for an IGCC plant feasible. With the same CO_2 price, PC shows a better investment return than IGCC for CCS investment in China.

Both capital costs and coal prices affect the breakeven CO_2 prices significantly. A decrease of 20% in the unit capital cost of power plants will lower the breakeven CO_2 price by 8% for a PC plant, and by 14% for an IGCC plant. Currently China's coal price is at $5.2/MMBTU or higher, and will likely be at this level for the near future or longer. If the coal price fluctuates by 20%, the breakeven CO_2 price will decrease by about 10% for PC and 5% for IGCC. For IGCC, the breakeven CO_2 price is less sensitive to coal price volatility due to IGCC's higher energy efficiency.

I also conduct a simulation to determine the investors' entry time for CCS investment. IGCC begins earlier than PC to become feasible for CCS investment: by 2024, the international carbon price can be sufficient to justify the CCS investment for IGCC power plants. Then in 2028, the carbon price hikes to about $31/tonne, and can ensure a positive investment return for PC plants as well.

In this study, I have laid a foundation to understand the breakeven carbon price for CCS investment in China. This research can be advanced with data from real projects in China as they become available. Currently the GreenGen project is being built in China, and China, Europe, and the United States are building or planning more "power plants + CCS" projects: more data based on these real projects can help improve the study of the breakeven CO_2 price and make it more valuable for investment decisions and policy making. I also note that power plants costs are significantly lower in China than in the United States: why this is the case can be a topic for future research.

Appendix: the NPV Model

A.1 Evaluation of a typical PC plant in China, w/ and w/o CCS

	0	1	2	3	4	5	6	7	38	39	40
PV of costs exclusive of carbon charge ($ million)											
Without Capture											
1 Capital investment	-663										
2 Depreciation		-41.8	-41.8	-41.8	-41.8	-41.8	-41.8	-41.8	0.0	0.0	0.0
3 Insurance and property taxes		-11.8	-11.8	-11.8	-11.8	-11.8	-11.8	-11.8	-11.8	-11.8	-11.8
4 Fuel cost		-157.8	-157.8	-157.8	-157.8	-157.8	-157.8	-157.8	-157.8	-157.8	-157.8
5 O&M cost		-16.6	-16.6	-16.6	-16.6	-16.6	-16.6	-16.6	-16.6	-16.6	-16.6
6 Tax shield at 40%		91.2	91.2	91.2	91.2	91.2	91.2	91.2	74.5	74.5	74.5
7 Total cash flow	-663	-95.0	-95.0	-95.0	-95.0	-95.0	-95.0	-95.0	-111.7	-111.7	-111.7
8 Present Value at 6%	-663	-89.6	-84.5	-79.7	-75.2	-71.0	-67.0	-63.2	-12.2	-11.5	-10.9
9 NPV, 40 years	-2182										
With Capture											
10 Capital investment	-1068				*0*						
11 Depreciation		-67.3	-67.3	-67.3	-67.3	-67.3	-67.3	-67.3	0.0	0.0	0.0
12 Insurance and property taxes		-19.0	-19.0	-19.0	-19.0	-19.0	-19.0	-19.0	-19.0	-19.0	-19.0
13 Fuel cost		-219.1	-219.1	-219.1	-219.1	-219.1	-219.1	-219.1	-219.1	-219.1	-219.1
14 O&M cost (incl. CO2 trans & Strg.)		-42.2	-42.2	-42.2	-42.2	-42.2	-42.2	-42.2	-42.2	-42.2	-42.2
15 Tax shield at 40%		139.0	139.0	139.0	139.0	139.0	139.0	139.0	112.1	112.1	112.1
16 Total cash flow	-1068	-141.3	-141.3	-141.3	-141.3	-141.3	-141.3	-141.3	-168.2	-168.2	-168.2
17 Present Value at 6%	-1068	-133.3	-125.7	-118.6	-111.9	-105.6	-99.6	-94.0	-18.4	-17.3	-16.4
18 NPV through 40 years	-3337										
19 PV incremental cost of capture	-1156										
PV of carbon charge at a certain prices, $1/tCO2, ($ mil)											
without capture											
20 cash flow per $1/t CO2 carbon tax		-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4
21 after tax		-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
22 Present Value at 6%		-1.4	-1.3	-1.2	-1.1	-1.1	-1.0	-1.0	-0.2	-0.1	-0.1
23 NPV, through 40 years	-22										
w/ carbon capture from the first operation year											
24 cash flow per $1/t CO2 carbon tax		-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
25 after tax		-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
26 Present Value		-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0
27 NPV through year 40	-3										
28 PV savings from capture per $1/t charge	19										
29 Carbon price required to warrant CCS	61.0										

Note:

2	Linear depreciation, 6.3% per year until Year 15, then 5% salvage value without depreciation (Zhao et al. 2008)
3	1.78% of initial capital investment (1.78% adopted from Sekar. et al (2007); our interview with Banshan Power Plant showed a rate from 0.65% ~ 3.7%
4	from assumptions
5	from assumptions
6	=40% * sum (Row 2:5)
7	=sum (Row 3 : 6)
8	=Row 7/(1+discount rate)^# of years
9	sum of all the present values at Row 8
11-18	similar to the above 2- 9
19	= Row 18 - Row 9
20	=$1/t * annual CO2 emission from assumptions
21	=(1-40%)*Row 20
22	=Row 21 / (1+discount rate)^# of years
23	=sum of values in Row 22
24-27	similar to the above 20-23
28	=Row 27- Row 23
29	=Row 19/Row 28

A.2 Evaluation of a typical IGCC plant in China, w/ and w/o CCS

	0	1	2	3	4	5	6	7	38	39	40
PV of costs exclusive of carbon charge ($ million)											
Without Capture											
1 Capital investment	-1529										
2 Depreciation		-96.3	-96.3	-96.3	-96.3	-96.3	-96.3	-96.3	0.0	0.0	0.0
3 Insurance and property taxes		-27.2	-27.2	-27.2	-27.2	-27.2	-27.2	-27.2	-27.2	-27.2	27.2
4 Fuel cost		-156.3	-156.3	-156.3	-156.3	-156.3	-156.3	-156.3	-156.3	-156.3	-156.3
5 O&M cost		-53.506	-53.51	-53.5059	-53.506	-53.5059	-53.51	-53.51	-53.51	-53.51	-53.51
6 Tax shield at 40%		133.3	133.3	133.3	133.3	133.3	133.3	133.3	94.8	94.8	73.0
7 Total cash flow	-1529	-103.7	-103.7	-103.7	-103.7	-103.7	-103.7	-103.7	-142.2	-142.2	-109.5
8 Present Value at 6%	-1529	-97.8	-92.3	-87.0	-82.1	-77.5	-73.1	-68.9	-15.5	-14.7	-10.6
9 NPV, 40 years	-3291										
With Capture											
10 Capital investment	-2293										
11 Depreciation		-144.5	-144.5	-144.5	-144.5	-144.5	-144.5	-144.5	0.0	0.0	0.0
12 Insurance and property taxes		-40.8	-40.8	-40.8	-40.8	-40.8	-40.8	-40.8	-40.8	-40.8	-40.8
13 Fuel cost		-188.3	-188.3	-188.3	-188.3	-188.3	-188.3	-188.3	-188.3	-188.3	-188.3
14 O&M cost (incl. CO2 trans & Strg.)		-95.6	-95.6	-95.6	-95.6	-95.6	-95.6	-95.6	-95.6	-95.6	-95.6
15 Tax shield at 40%		187.7	187.7	187.7	187.7	187.7	187.7	187.7	129.9	129.9	129.9
16 Total cash flow	-2293	-137.0	-137.0	-137.0	-137.0	-137.0	-137.0	-137.0	-194.8	-194.8	-194.8
17 Present Value at 6%	-2293	-129.3	-122.0	-115.1	-108.5	-102.4	-96.6	-91.1	-21.3	-20.1	-18.9
18 NPV through 40 years	-4663										
19 PV incremental cost of capture	-1372										
PV of carbon charge at a certain prices, $1/tCO2, ($ mil)											
without capture											
20 cash flow per $1/t CO2 carbon tax		-2.39	-2.39	-2.39	-2.39	-2.39	-2.39	-2.39	-2.39	-2.39	-2.39
21 after tax		-1.43	-1.43	-1.43	-1.43	-1.43	-1.43	-1.43	-1.43	-1.43	-1.43
22 Present Value at 6%		-1.35	-1.27	-1.20	-1.13	-1.07	-1.01	-0.95	-0.16	-0.15	-0.14
23 NPV, through 40 years	-22										
w/ carbon capture from the first operation year											
24 cash flow per $1/t CO2 carbon tax		-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28
25 after tax		-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
26 Present Value		-0.16	-0.15	-0.14	-0.13	-0.13	-0.12	-0.11	-0.02	-0.02	-0.02
27 NPV through year 40	-3										
28 PV savings from capture per $1/t charge	19										
29 Carbon price required to warrant CCS	72.2										

Note:

2	Linear depreciation, 6.3% per year until Year 15, then 5% salvage value without depreciation (Zhao et al 2008)
3	1.78% of initial capital investment (1.78% adopted from Sekar. et al (2007); our interview with Banshan Power Plant showed a rate from 0.65% ~ 3.7%
4	from assumptions
5	from assumptions
6	=40% * sum (Row 2:5)
7	=sum (Row 3 : 6)
8	=Row 7/(1+discount rate)^# of years
9	sum of all the present values at Row 8
11-18	similar to the above 2- 9
19	= Row 18 - Row 9
20	=$1/t * annual CO2 emission from assumptions
21	=(1-40%)*Row 20
22	=Row 21 / (1+discount rate)^# of years
23	=sum of values in Row 22
24-27	similar to the above 20-23
28	=Row 27- Row 23
29	=Row 19/Row 28

References

Al-Juaied, Mohammed and Adam Whitmore. 2009. Realistic cost of carbon capture. Discussion paper, Belfer Center for Science and International Affairs, Harvard University.

Bohm, Mark C., Howard J. Herzog, John E. Parsons, Ram C. Sekar. 2007. Capture-ready coal plants – options, technologies, and economics. *International Journal of Greenhouse Gas Control* (1): 113-120.

Climate Change Department, National Development and Reform Commission (CCD-NDRC). National Action Plan for Climate Change. 2007. URL: http://qhs.ndrc.gov.cn/.

Center for Global Development (CGD). 2008. Carbon Monitoring for Action (CARMA), global power plants and carbon emissions database. URL: http://carma.org/

Chen, Wenying, and Ruina Xu. 2009. Clean coal technology development in China. *Energy Policy* (2009), doi:10.1016/j.enpol.2009.06.003.

Chen, Man-nong, and staff reporter. 2010. China freezes coal prices for 2011 contracts. Want Chinatimes, URL: http://www.wantchinatimes.com/news-subclass-cnt.aspx?cid=1102&MainCatID=&id=20101211000098.

Duan, Liqiang. 2008. Pulverized coal power generation in China. Working paper, for discussion, North China Electric Power University, China.

Energy Information Administration (EIA), 2010. Updated capital costs estimates for electricity generation plants.

EPRI, 2000. Evaluation of innovative fossil fuel power plants with CO_2 removal. Report 1000316, Palo Alto, CA.

EPRI, 2003. Phased Construction of IGCC Plants for CO_2 Capture - Effect of Pre-Investment: Low Cost IGCC Plant Design for CO_2 Capture. Report 1004537, Palo Alto, CA, December.

Finamore, Barbara. 2009. China's Carbon Intensity Target. NRDC Switchboard, URL: http://switchboard.nrdc.org/blogs/bfinamore/chinas_carbon_intensity_target.html

Harvard Energy Technology Innovation Program (ETIP). 2009. US-China IGCC Workshop. The Kennedy School of Government, Harvard University.

Hamilton, Michael. 2009. Analysis of Policies to Support Deployment and Cost Reduction of Carbon Capture and Sequestration Technology in the United States. Thesis for Masters Degree at Technology and Policy, MIT.

Hellenic Shipping News (HSN), 2011. China expects domestic coal prices in 2011 to stay around end-2010 level. URL: http://www.hellenicshippingnews.com/index.php?option=com_content&view=article&id=5438:china-expects-domestic-coal-prices-in-2011-to-stay-around-end-2010-level&catid=44:latest-news&Itemid=64.

Henderson, C., 2007. G8 case studies by the IEA Clean Coal Centre. Third International Conference on Clean Coal Technologies for our Future, London, May 15–17, 2007.

Herzog, Howard and Daniel Golomb. 2004. Carbon Capture and Storage from Fossil Fuel Use. *Encyclopedia of Energy*.

IPCC, 2005, IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)].

Kerry, John, and Joseph Lieberman. 2010. American Power Act. US Senate Bill, URL: http://kerry.senate.gov/americanpoweract/pdf/APAbill.pdf

Liang, Dapeng, and Weiwei Wu. 2009. Barriers and incentives of CCS deployment in China: results from semi-structural interviews. *Energy Policy* (37): 2421-2432.

Liu, Hengwei, Weidou Ni, Zheng Li, and Linwei Ma. 2008. Strategic thinking on IGCC in China. *Energy Policy* (36): 1-11.

Massachusetts Institute of Technology (MIT), 2007. The Future of Coal. http://web.mit.edu/coal/.

Massachusetts Institute of Technology (MIT), 2009. Retrofitting of coal-fired power plants for CO_2 emissions reductions. MIT Energy Initiative Symposium, March 2009.

McCoy, Sean. 2008. The economics of CO_2 transport by pipeline and storage in saline aquifers and oil reservoirs. Carnegie Mellon University, Dissertation.

Morse, Richard, and Gang He. 2010. The World's greatest coal arbitrage: China's coal import behavior and implications for the global coal market. Working paper. Program on Energy and Sustainable Development, Stanford University.

National Development and Reform Commission (NDRC). 2007. Special Plan for Mid- and Long-term Energy Conservation. Beijing.

Nsakala, N., Liljedahl, G.N., Marion, J.L., Bozzuto, C.R., Andrus, H.E.,Chamberland, R.P., 2003. Greenhouse gas emissions control by oxygen firing in circulating fluidized bed boilers. Presented at the Second Annual National Conference on Carbon Sequestration. Alexandria, VA, USA, May 5 - 8.

NETL (National Energy Technology Laboratory), 2002. Advanced fossil power systems comparison study. U.S. Department of Energy, December.

NETL, 2010. DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update.

Rubin, Edward, Chao Chen, and B. Rao. 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy* (35): 4444-4454.

Sekar, Ram, John Parsons, Howard Herzog, Henry Jacoby. 2007. Future carbon regulations and current investments in alternative coal-fired power plant technologies. *Energy Policy* (35): 2064-2074.

SEPA (State Environmental Protection Agency of China, now Ministry of Environmental Protection), 2005. Report on the state of the environment in China in 2005, Beijing.

Tsinghua University (Tsinghua). 2008. Promotion of the IGCC technology in China for power and fuel production. Tsinghua-BP Clean Energy Research and Education Center. Project report for Energy Foundation, G-0610-08595.

Wu, Ning, 2009. Spatial imbalance of China's coal and power sector: market concentration, coal transportation and CO_2 emissions. Working paper, MIT.

Xu, Shisen, 2008. GreenGen in China. URL: http://www.netl.doe.gov/publications/proceedings/08/CO2E/PDF/session%204/xushishen.pdf

Xu, Shisen, Shiwang Gao. 2006. Near zero emission coal based power generation in China GreenGen project. Clean Coal Day in Japan, 2006.

Zhao, Lifeng, and Kelly Sims Gallapher. 2007. Research, development, demonstration, and early deployment policies for advanced-coal technology in China. *Energy Policy* (35): 6467-6477.

Zhao, Lifeng, Yunhan Xiao, Kelly Sims Gallapher. 2009. Summary on the joint workshop on promoting the development and deployment of IGCC/Co-production/CCS technologies in China and the United States. URL: http://enews.belfercenter.org/ct.html?rtr=on&s=lj1i,go6p,7oo,jifu,c028,lzv,58kk.

Zhao, Lifeng, Yunhan Xiao, Kelly Sims Gallapher, Bo Wang, Xiang Xu. 2008. Technical, environmental, and economic assessment of deploying advanced coal power technologies in the Chinese context. *Energy Policy* (36): 2709-2718.

Zhao, J., M. Zhao, and Q.Y. Xie, 2006. General situations of IGCC worldwide and China's construction conditions. Gas Turbine Power Generation Technology 8 (3), 5–10 (in Chinese).