nzec
carbon capture & storage

WP2 – Future Energy Technology Perspectives

2.2 Energy Intensive Sectors Technology Assessment

Kejun Jiang
Energy System Analysis and Market Analysis Division
Energy Research Institute, China

Table of contents

1 Introduction

Industry accounted for nearly one-third of the world’s primary energy use and approximately 22% of the world’s energy and process CO_2 emissions in 2005. Total CO_2 emissions from industry were 9.9 Gt in 2005, equivalent to 37% of total global CO_2 emissions (IEA 2008). As the world’s largest producer of steel, aluminium and cement, fossil fuel use in the energy intensive sectors is even more significant in China than in OECD countries. In 2005, total CO_2 emissions from Chinese industry were around 3.75 Gt accounting for 73% of total emission from energy combustion (Jiang et al, 2009).

This report provides a preliminary review of the key CO_2 producing energy intensive sectors. Each section reviews the current technological status of the sector in China and sources of CO_2 emissions. It then considers the opportunities for reducing CO_2 emissions including, where information is available, the potential for application of CO_2 Capture.

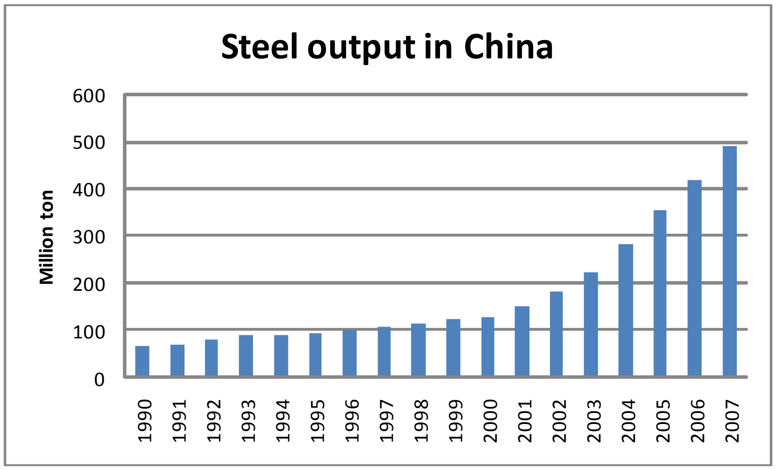
2 Iron & steel

2.1 Current status of Iron and Steel Industry in China

The 2005 global production of iron and steel was 785 and 1129 Mt per year respectively. Of the 9.9 Gt CO_2 direct and indirect emissions from industry, the iron and steel sector accounted for 27% or 2.6 Gt (equivalent to 10% of worldwide total CO_2 emissions).

Today the Chinese crude steel output accounts for 34% of the world's total, which compares to an output of 29% in Europe, and 14.5% on the American continent. While output is increasing in China, production in Europe and the US is falling. As shown in Figure 1, China's output of crude steel in 2007 was 493 million tonnes.

Figure 1 Steel output in China



There are more than 290 steel producers in China. Contrary to developed countries, China's small and medium size enterprises still account for a large amount of production. The breakdown of key enterprises is shown below and in Table 1. Examples of large enterprises include Anben Group, Baoshan Steel Corporation, Tangshan Iron & Steel Group, Sha Gang, Wuhan Steel Corporation, Ji Gang, Maanshan Iron & Steel Company Limited, Laigang, Beijing Steel Corporation.

Energy consumption and energy efficiency

In 2004, China's total energy consumption was 1,970 million tce with the iron and steel industry consuming 299 million tce (including mine, ferroalloy, coking, refractory materials), which accounts for 15.2% of the total energy consumption. In 2004, coal accounted for 69.9% of final energy consumption in the steel and iron industry while electric power accounted for 26.4% with 3.7% coming from other sources. In 2007, the total energy consumption in the iron and steel sector accounted for 14.7% of the national total energy consumption, making it the largest industrial sector in terms of final energy consumption in China.

Table 1 Chinese steel enterprises in China: size and unit energy consumption

Enterprise situation	Share of market, %	Energy consumption index, kgce/t
Large enterprise (>10 million tonnes capacity)	30	700
Medium enterprise (5-10million tonnes capacity)	40	750
Small enterprise (<5 million tonnes capacity)	30	800

Considering the blast furnace, the consumption of coke in developed countries is less than 300kg/t while fuel consumption is less than 500kg/t. In China, on the other hand, the use of Coke amounts to 426kg/t in the most advanced iron and steel enterprises and 488kg/t in other enterprises with fuel use reaching approximately 560kg/t. So it is seen that, compared to the rest of the world, China's blast furnace craft energy consumption is 50~100kg/t higher. The majority of advanced iron and steel enterprise in developed countries have reached what can be described as "the negative energy steel-making" in convertor process, which can produce more energy than energy used by using gas recovery. In China, only the Baoshan Steel Corporation, Wuhan Steel Corporation, Anshan Steel Company, Magang Company and Laigang Company have realized "the negative energy steel-making" in the convertor process. Energy consumption in the convertor process in Japan's Junjin Steel company is -6.27kgce /t, while the typical energy consumption in China's convertor process can still be as high as 23.56kgce /t.

In 2005, the energy consumption of key large and middle scale iron and steel enterprise in China was 0.741 tce/t and the comparable unit energy consumption was 0.7141 tce/t. The comparable energy consumption worldwide is 0.650kgce/t. In steel production, the iron-smelting system (coking, agglutination and iron-smelting) energy consumption accounts for 78% in the steel production total energy consumption. Table 2 shows the energy consumption relative proportion of the key working procedures within China steel production in 2005. As can be seen, the blast furnace iron smelting is responsible for 59% of total energy consumption and so will be given further attention below.

Blast furnace Technology development

During the past ten years, there has been rapid development in the Chinese steel and iron industry particularly with respect to smelting technology. The large-scale blast furnace is the main feature of modern iron-smelting technology. As of 2006, there were 1250 blast furnace in China, with 124 blast furnaces above 1000m^3. Energy consumption within the iron-making process has reached

456kgce/tonne with consumption for coke making reaching 142kgce/tonne and that for sintering reaching 64kgce/tonne.

Table 2: Energy consumption in the key steel production processes unit:Kgce/t

	Agglutination	Pellet	Coking	Iron-smelting	Converter	Electric stove	Rolling	Other
2005 national average	64.83	142.21	39.62	456.79	36.34	201.02	88.82	
Share in total energy consumption in steel industry(%)	12.13	6.45	1.03	59.26	3.58	2.33	10.22	5

Source: Steel Industry Yearbook 2005

Coal injection technology in blast furnaces has also developed rapidly. Coal injection technology is an important indicator of technological advancement of iron-making. The 1960s saw the first use of this technology in China at the Beijing Steel Corporation and Anshan Steel Company, who were world leaders in developing and deploying this technology. After the 1990s, the blast furnace coal injection technology was included in the National Science and Technology plan. Currently, nearly all of the large and medium-scale blast furnaces are using this technology.

There has been relatively good implementation of concentrated feed technology. The concentrated feed is the important material base of blast furnace production with high quality production and low consumption. Since the volume of imported iron ore has increased, the ore grade, which enters the stove increased from 54.9% in 1995 to nearly 59% in 2006, with the ore status of some iron and steel enterprise achieving 60%.

In recent years, the domestic molten iron pretreatment has been rapidly promoted. In 2005, the volume of molten iron pretreatment exceeded 68.9 million tonnes. The Baoshan Steel Corporation has realized desulphurization pretreatment of all of the molten iron. Wuhan Steel Corporation, Panzhihua steel company, Anshan Steel Company, the Baotou Steel company's molten iron desulphurization pretreatment proportion has surpassed 50% of iron manufactured.

The converter is the major steel-making process in China. The steel output from convertor accounts for more than 80% of the national steel output. In 2006, it surpassed 300 million tonnes/year.

The continuous casting technological development is rapid and catching up with international developments. In 1995, the international continuous casting proportion was only 46.4% while the Chinese continuous casting ratio reached 96.0% in 2004. In 2005, more than 50 enterprises in China's

Steel Industry Association maintained all continuous casting production. The level of continuous casting technology in China is already close to that of other major steel producing nations. In 2004, the continuous casting ratios in Japan, South Korea, and the US were 97.8%, 98.5%, and 97.1% respectively. By the end of 2005, China's conticaster production equipments reached 677 sets, with an annual production capacity of 410 million tonnes.

2.2 CO_2 emissions from the iron and steel making process

The steel and iron industry consumed 15.4% of national total energy in 2007. And the coal consumption accounted for 72% of total energy consumption in steel production. Based on literature review (Bai Bing, 2006; Wang Ke, 2006), in blast furnace, CO_2 emission is 2.5 tCO_2/tonne steel, 0.5 tCO_2/tonne steel by electric furnace. But with the progress in energy efficiency, the unit CO_2 emission dropped gradually. At present the unit steel CO_2 emission factor is estimated at about 1.6tCO_2/tonne steel. In 2007 China's steel output was 489 million tonnes, accounting for 36% of global output. From this we can estimate CO_2 emission of around 825 million tonnes/year.

Table 3 CO_2 emission in steel industry (unit:Mt-CO2)

Year	1990	1994	1996	1998	2004	2007
Steel output Mt	6 3	8 7	9 6	110	27 2	489
Carbon emission	204	258	269	277	499	826
Unit steel carbon emission, t-C/tonnes	0.88	0.81	0.76	0.68	0.50	0.46

2.3 CO_2 emission reduction options for iron and steel production in China

At present, to reduce CO_2 emission in the steel industry, the first choice is to reduce the unit steel energy consumption through the enhancement of energy efficiency and energy conservation in industry process. Promising options for reducing CO_2 emissions from Chinese steel industry include:

1. Using non-carbon based reducing agent. Currently, the hydrogen based reducing technology had important developments. But because of lack of cheap hydrogen supply, the hydrogen based reducing technology has not been able to realize production on an industrial scale. Replacing

coke by hydrogen in blast furnace is currently the hot topic, which the scientists have been discussing for a long time. In addition to reducing CO_2 emissions, using hydrogen in blast furnace will have other benefits including improving the blast furnace productivity and reducing energy consumption. However, it is not clear that this will lead to a massive decrease in overall CO_2 emissions when you consider the CO_2 emitted by the H_2 production process. A most important factor to limit massive hydrogen using in blast furnace is how to guarantee safe transportation of hydrogen under the hot conditions.

2. The electrolytic process has been widely applied in the nonferrous industry (for example, aluminium, copper, zinc and so on). Although not yet widespread application in iron and steel industry, but the electrolytic process can also be used in the iron and steel industry, which has potential to use near zero emission power generation, which is the key requirement for reduction in CO_2 emissions across the whole system; the key is the different electrolytes' choice. It is possible to use HCl to get the Fe^{3+} solution by processing iron ore or the scrap steel.

3. Along with biological science's fast development, in recent year the biological metallurgy has received attention. The rare metal smelting industry commonly used bacterium carriers to process the ore. This method had not been applied in the steel-making industry, but research discovered that bacterium may turn Fe^{3+} into Fe^{2+}, but cannot completely transform Fe^{2+} as the metal iron.

China's national development targets are to realize industrialization by 2020 and obtain economic level of a medium-sized developed country by 2050. In order to support this development, the following projection for China's steel sector may be envisaged:

- From the present to 2010, the steel industry will continue with rapid development (although current economic recession has slowed recent growth).
- From 2010 to 2030, the steel and iron demand will likely enter the saturation period with steel output reaching a peak.
- After 2030, along with the complete industrialization and on-going urbanization, the steel products consumption intensity and the total output will have reduced, although overall levels will remain relatively high to support continued growth.

According to a study from the Beijing Steel Corporation research institute, China is now at the heavy chemical industry stage. This is based on developed country steel and iron industrial development experience that suggests the average per person steel annual output will achieve 4600 kg per capita when industrialization is achieved. In 2020, assuming a population of 1.5 billion steel annual output peak value is likely to amount to about 600 million tonnes. Some other studies show the peak will be around 700-800 million tonnes. For example the NZEC WP2 Future Energy Service demand report, based on the analysis of other studies and historical trends within OECD countries concludes steel production in China to peak at 750 million tonnes in 2035. Therefore we may expect China steel production output in 2020 to 200 million tonnes higher than current levels.

Based on the mitigation analysis for China's steel industry (Jiang et al, 2009), over the next 20 years the main energy conservation and reduction technology in steel and iron industry mainly include:

- Enhances the use of coal injection in blast furnace
- More advanced CCM
- More advanced blast furnace with TRT excess pressure power technology
- Dry Coke Quenching technology
- More advanced coke oven
- Iron steel ratio adjustment
- More advanced sintering machine, sintering cooling waste heat recovery
- The rolling mill equipment is continuous Promotes the converter vanguard technology, enhances the converter coal gas recycling use
- Uses the smelting reduction iron-making process
- Advanced electric furnace
- Coal humidifying treatment technology

2.4 Application of CO_2 capture to the iron and steel sector

Most of the CO_2 generated by the steel industry comes from the chemical interaction between carbon and iron ore in a blast furnace. This process is called iron reduction. In the most advanced facilities the iron reduction process has already undergone efficiency improvements reaching a level of maturity where the process operates close to thermodynamic limits therefore further reduction in CO_2 emissions will be next to impossible.

The global steel industry is committed to help reduce global greenhouse gas emissions[1].
Commitments include:

- Expanding the use of current efficient technologies, widely used in modern steel making sites, to minimise the generation of CO_2
- Undertaking research and development for new technology solutions to radically reduce the level of CO_2 emissions into the atmosphere for each tonne of steel produced

There is a clear CO_2 capture potential in the core steel making process, it produces 75% of total CO_2 emissions while the other 25% is accounted for in non-core process. The focus should therefore be on capture from the core process while capturing the remaining non-core CO_2 could only be achieved at a considerably higher, prohibitive, cost.

There are three approaches to CO_2 capture from blast furnaces, articulated in the IEA 2008 report:

- Oxyfueling to generate a pure CO_2 off-gas; CCS, used together with oxygen injection, could result in a reduction of 85% to 95% of the CO_2 emissions attributable to the core production processes.

---

[1] http://www.worldsteel.org/climatechange/?page=2&subpage=3

- Chemical absorption capture of CO_2, using waste heat for regeneration;
- Substituting coke and coal with hydrogen or electricity.

According to the IEA (2008) post-combustion capture using chemical absorbents is not suitable for CO_2 capture in the iron and steel industry as insufficient waste heat is available. Only about half of the necessary heat could be recovered from coke ovens, sinter plants, blast furnace slag, and converter slag and slabs, and separate combined heat and power (CHP) units would be needed to achieve this. Integrated oxyfueling, the IEA suggest, is therefore the preferred method of capture in the steel industry.

One chemical absorption method being investigated in Japan uses alkaline solvent for absorbing CO_2. This technology has a high recovery rate of CO_2, applicable to a large amount of flue gas at normal pressures, but not suitable for gas containing high-level impurities. In order to lower the cost to reasonable levels for commercialisation, the high energy-consumption for CO_2 recovery and high cost of solvents need to be reduced. Using waste heat at plants is one possibility (Tenaka, 2005).

Another option, investigated by Ryozo Tanaka on Carbon Capture Technologies in Japan, includes membrane separation using polymeric and ceramic porous membranes to selectively separate CO_2 in gas. Although the system for membrane separation is quite simple compared with other methods for carbon capture such as chemical absorption, there are a number of challenges such as high cost of membranes, low CO2 recovery rate, high-pressure requirement and necessity of impurity removal before the treatment. One of the possible applications is blast furnace gas, where CO_2 concentration is at high levels. This method is being investigated by organisations such as Kansai Electric Power Co., Inc. (KEPCO), Tokyo Electric Power Co., Inc. (TEPCO), Mitsubishi Heavy Industries, Ltd. (MHI) (Tenaka, 2005).

The cost of CCS for blast furnaces is uncertain. Capture costs are estimated at EUR 20/t CO_2 to EUR 25/t CO_2, although changes in furnace productivity can have a significant impact on the process economics (Borlée, 2007).

There is a multitude of research going on into various different steel and iron production processes, R&D is relatively advanced in relation to the status in other energy intensive sectors. Some initiatives include:

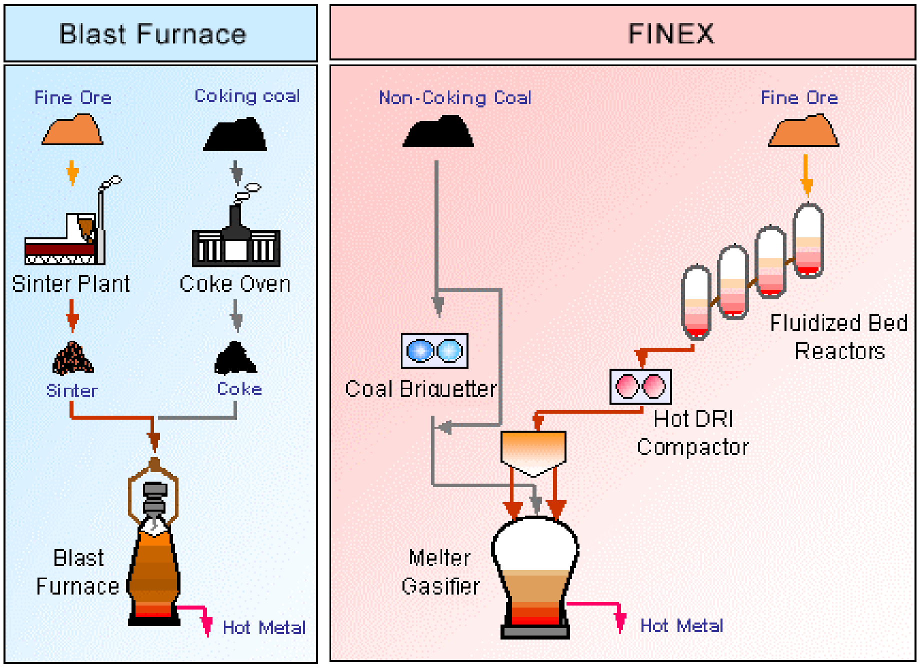
- The International Iron and Steel Institute's (IISI) initiative the CO_2 Breakthrough Programme: international collaboration agreement of IISI members to address the issues and set a challenging goal to reduce, eliminate or capture emissions.
- The European Union (EU)-funded and Arcelor-led Ultra-Low CO_2 Steelmaking (ULCOS) programme: Gas based Direct-reduced iron (DRI) production. This technology although currently far more expensive than the conventional blast furnace method has potential and will remove the need for coke ovens. ULCOS project development is under way to reduce natural

gas consumption needed to produce DRI. On top of this in the new layout there will be a single source of CO_2. This CO_2 will be sufficiently clean for geological storage.

- The FINEX technology

The incorporation of carbon capture inevitably brings with it an energy penalty, however some technological suggestions e.g. the FINEX technology with some process redesign, could capture all CO_2 with a reduced energy penalty. This technology developed by Siemens and POSCO, a Korean steel making company, is currently being tested in a 1.5 Mt demonstration plant in Korea. This technology Finex eliminates the first step in the steelmaking process of sintering and coking and allows the direct use of low-cost ore fines and coal, bringing overall plant installation and operational costs down as well as producing less air pollutants than traditional methods.

Figure 2: FINEX Technology Diagram



from http://posco-india.com/website/project/technology.htm

Overall, CCS in iron and steel production could save around 0.5 Gt CO_2 to 1.5 Gt CO_2 per year by 2050, which is 10% to 15% of total reduction attributable to CCS in the IEA scenarios. However, this will not only depend on technology development, but also on a global level playing field, for example an approach based on sectoral agreements.

2.5 Possible future application of CO_2 Capture specific in China

Reviewing domestic and international reports about the steel industry CO_2 emission in China, provides the following analysis of the CO_2 capture potential in the steel industry. The review undertaken by Bai Bing (2006) considered the main industrial large point sources and collecting production data for thermal power, steel and iron, cement, petroleum, ethylene, synthetic ammonia, oxirane, hydrogen making. The CO_2 emissions for these sectors were calculated using the IPCC method. Based on this research the steel industries' CO_2 emissions factor (Mg/t) is 1.270, in 2007 the steel industries' CO_2 emissions was 2833Mt (steel and iron).

The China International Engineering Consulting Corporation (CIECC) undertook research of the large and middle scale Iron and steel enterprise's energy consumption. In 2005, unit comparable energy consumption of steel is 0.714 tce/t steel, while unit synthesis energy consumption is 0.741 (0.747 CHINAISA[2] data) tce/t steel. This suggested that the energy consumption of the iron-making procedure accounts for 70% of total steel industry energy consumption, with blast furnace iron-making accounts for 46.4%. However according to the most recent energy consumption data issued by CHINAISA (Table 2), the blast furnace iron-making will account for 59% with the estimate value in the future of about 50%.

Recently, researchers (Wang Ke, 2006) have developed a LEAP-China model, based on the LEAP (Long-range Energy Alternatives Planning system) software that contains energy demand, energy cost, CO_2 emission and so on. Wang Ke constructed the Leap-China model for China's steel and iron industry from 2000-2030 with CO_2 emissions scenarios as shown in Table 4.

Table 4 CO_2 emission per unit steel in different scenario unit: tonne/tonne

	2000	2010	2020	2030
Benchmark scenario	2. 68	2. 19	1. 97	1. 83
Carry out current policy scenario	2. 68	1. 96	1. 80	1. 63
Strengthen energy saving technology policy scenario	2. 68	1. 71	1. 58	1. 48

Source: Wang Ke (2006)

Future CCS technology's utilization will mainly capture CO_2 produced by the blast furnace procedure. The energy consumption proportion and the large-scale blast furnace equipment's scale proportion which is possible to utilize the CCS technology, only accounts for a part of total steel industry CO_2 emissions.

---

[2] China Iron and Steel Association

In order to analyse the potential of CCS, here we made a simple assumption due to lack of information. By assuming CCS could be utilized only with large size blast furnace with capacity above 1500m^3, and 100% CO_2 could be captured, the potential of capture CO_2 in the blast furnace iron-smelting is around 340 million tonnes per year in 2030 (see table 5).

Table 5 the future potential of capture CO_2 in iron and steel industry in China

	2005	2010	2020	2030
a) Steel output/100Mt	3.56	4.8	5.5	6.0
b) Unit steel CO2 emission intensity/t/t	1.7	1. 51	1. 38	1. 28
c) Proportion of blast furnace energy consumption in total energy consumption /%	59	50	50	50
d) Large blast furnace share/%	70	80	85	90
e) Steel industry CO_2 emission/100Mt		7.2	7.6	7.6
f) Potential of capture CO_2 by CCS /100Mt		2.8	3.2	3.4

Note items 1-4 are estimated. The units steel CO_2 emission intensity /t/t come from the literature (Bai Bing, 2006, Steel Industry Yearbook, 2007)

3 Cement

In 2005 around 2.3 Gt of cement was produced worldwide. China accounted for more than 46% of this. Cement production accounts for about 22% (1.5 Gt in 2005) of the industry sector's total direct CO_2 emissions. Two thirds of this (0.94 Gt per year in 2005) is generated by the decomposition of limestone into cement clinker and CO_2. The remaining one third is from fuel combustion.[3]

3.1 Current status of cement industry in China

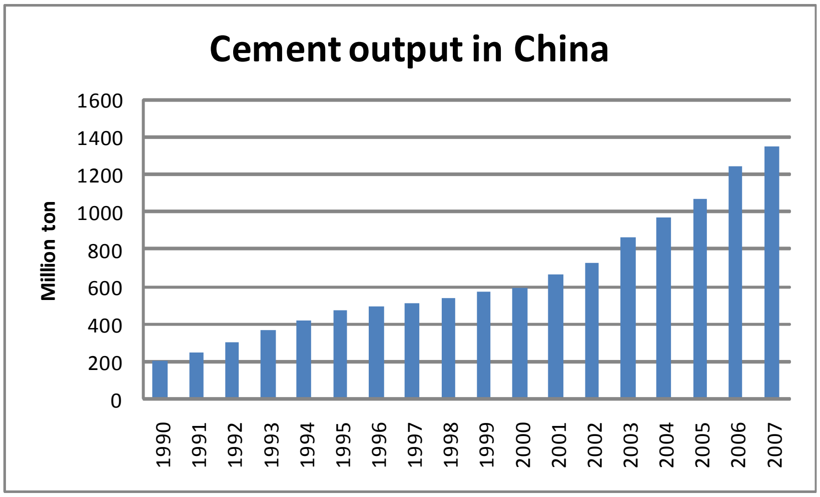
In 1978, China's cement production was 65.2 million tonnes. Since 1985, China's has ranked first in the world's cement production for 23 years. In 2007, China's cement production reached 1.35 billion tonnes, accounting for half of the world production (see Figure 3). The rapid growth of cement in China has generally fulfilled the needs of rapid economy development and large-scale infrastructure construction. In terms of cement production capacities, 55% still belong to out-dated shaft kiln and small-scaled hollow dry process rotary kiln. The concrete labelling standard in China is comparatively lower than some of the western countries, resulting in a larger percentage of low-end products. The 32.5 Portland Cement makes up 85% of the total production, while the 42.5 Portland Cement and above (high-end products) only makes up 12%, and the rest belongs to special cement.

In 1970s, the new efficient New Suspension Preheater (NSP) facilities started to develop. With the promotion of national policies, China has been experiencing a rapid change in cement production structure. In 1995, NSP based cement production was 28.53 million tonnes, accounting for only 6% of national production. By 2000, the number had increased to 71.88 million tonnes, 12% of national production. In 2005, NSP cement reached 473 million tonnes, or 45% of total production. Currently, NSP cement represents more than half of the Chinese cement market and its future growth looks promising. It receives great support from government, big demands from the market, and pursued by plants, which are all greatly contributing to the structural adjustment of cement sector.

---

[3] IEA (2008, p. 69)

Figure 3 China’s cement production in the past years



Structure of China’s cement industry

There are presently more than 5000 cement plants with revenues of 5 million Yuan or above. The number of cement plants in China surpasses the sum of number of plants in the rest of the world. Before 2002, the average production capacity in China was only 220,000 tonnes, much lower than the world’s average level. Small cement plants make up the main part of China’s cement sector, accounting for more than 80% of total cement productions. There are a lot of small and medium-sized plants with a large percentage of cement still produced by out-dated production facilities. The production concentration level meanwhile is still low and the structural contradictions are big. In recent years, Chinese government has enhanced the policies to adjust cement production structures and has achieved remarkable progress. By 2008 the more efficient New Suspension Pre-heated Dry Process (NSP) is producing more than half of China’s cement. A group of big enterprises are having rapidly growing production capacities, which contribute to the increase of concentration level. The production from the largest 10 cement plants in China accounts for 18% of the national production. The overall energy consumption per unit of cement production is tending to decrease year on year.

3.2 Energy consumption of cement sector

The Cement sector is one of the most important components in the energy-intensive buildings materials sectors in China. Energy consumption in the cement sector makes up more than 7% of national energy consumption. Table 6 shows the amount of energy consumed by China’s cement sector in recent years. The main kinds of energy consumed by cement making are coal and electricity, among which coal accounts for more than 70%.

Table 6 Energy consumption of China’s cement sector

Year		1995	2000	2001	2002	2003	2004	2005	2006	2007
Cement production (billion tonnes)		0.476	0.597	0.661	0.725	0.862	0.97	1.06	1.26	1.35
Energy consumption (million tce)		83.31	100.30	104.33	117.74	137.23	151.32	160.43		
Among which:	Coal/t	6331	7582	7875	8845	10258	11252	11865		
	Electricity /kWh	495	606	633	725	858	960	1034		
Comprehensive energy consumption	kgce/t	175	168.0	165.6	162.4	159.2	156.0	152.7	142	138

Source: CIECC, 2006

In 2000, most Chinese cement plants were of a small scale and using old production techniques, with a large percentage of cement production using facilities such as shaft kilns. Compared to NSP, shaft kilns and wet kilns require higher in energy consumption, which is responsible for the higher level of overall energy consumption in China’s cement sector. In the last 10 years, overall energy consumption per tonne of cement in China has been decreasing. In addition to the influence of scaling up of cement plants and technology upgrades, production techniques improvements, change of cement products structure as well as the methodology change to convert electricity to standard coal equivalent are also contributing. According to NDRC (NDRC, 2006), at the end of 1990s, the comprehensive energy consumption per tonne of cement from large and medium-sized cement plants was around 170 kgce; and the electricity consumption was around 100 kWh. However in 2006, the same values in big cement plants (with production capacity of over 3 million tonnes) had decreased to 94 kgce/tonne cement and 83 kWh/tonne cement respectively.

Table 7 Comparison of average heat consumption of different cement kilns in China (NDRC, 2006)

Type of kiln	New dry kiln	Mechanic shaft kiln	Wet kiln	Hollow dry kiln
Average heat consumption per tonne of clinker (kgce)	115	160	208	243
Heat consumption index	100	139	181	211

3.3 CO_2 emissions from the Cement Sector

Cement making has complex production processes, including raw material extraction and delivery, crude cement and fuel preparation, clinker calcining, waste heat regeneration, cement making and transmission, cement making auxiliary process, transportation outside and inside the plants and production management. All these processes consume energy, which results in the CO_2 emissions from each industrial process.

According to the analysis by the China Building Materials Science Research Institute (CBMSRI), the direct and indirect CO_2 emissions by China's cement sector account for 20% of China's CO_2 emissions. A study by this institute shows that the main sources of CO_2 emissions in cement making are carbonate decomposition, fuel combustion and the electricity consumption. CO_2 emission from carbonate decomposition is relatively easier. It could be analyzed and calculated by the amount of raw materials being used and the carbonate content in the raw materials, and could also be analysed by the weight of clinker and the percentage of CaO and MgO in clinker. CBMSRI has undertaken some analysis based on the amount of crude cement and calculated the emission from carbonate decomposition.

The CO_2 emissions from fuel combustion are comparatively more complex. The fuels consumed in cement making process include several kinds of coal, alternative fuels and oil. When calculating CO_2 emissions from this part, it is necessary to know the amount of each fuel type, and assign the appropriate emission factor. The emission factor is dependent on the carbon content and heat value of the specific fuel. In the following we carry out the CO_2 emission analysis during the cement making process.

1. Direct emissions calculation

a) Emissions from carbonate decomposition

- CO_2 emissions from $CaCO_3$ decomposition: according to the domestic average level, CaO content in ordinary Portland clinker is around 65%. By chemical formula $CaCO_3=CaO+CO_2$, producing one unit of CaO will produce 0.7857 unit of CO_2. Therefore, producing one tonne of clinker will have 1t×65%×0.7857=0.5107t of CO_2 emitted from $CaCO_3$ decomposition.
- CO_2 emissions from $MgCO_3$ decomposition: according to the domestic average level, MgO content in ordinary Portland clinker is around 1.5%. By chemical formula $MgCO_3=MgO+CO_2$, producing one unit of MgO will produce 1.1 unit of CO_2. Therefore, producing one tonne of clinker will have 1t×1.5%×1.1=0.0165t of CO_2 emitted from $MgCO_3$ decomposition. Therefore, the total amount of CO_2 emitted from $CaCO_3$ and $MgCO_3$ decomposition is 0.5107t+0.0165t=0.5272t-CO2/tonne clinker.

b) Kiln dust calcining in kiln system: Kiln dusts from kiln system are mainly the materials collected from kiln-end filters and conditioning tower. Currently in China, kiln dusts are directly fed into cement or calcined again as the crude cement. Dust emission factor from cement kiln is estimated to be 0.0362. In rotary kiln system, kiln dust usually takes up 25% (20%~30%) of clinker weight.

Therefore, producing one tonne of clinker will have 1t×25%×0.0362=0.009t CO_2 emitted from calcining kiln dust.

c) Combustion of organic carbon in crude cement: The crude cement for clinker production usually a small portion of organic carbon. After high temperature treatment, the organic carbon will turn into CO2. The contents of organic carbon in crude cement will differ greatly according to location and the type of materials, but will hold within 0.1%~0.3% (dry weight). In our calculation we 0.2% as the middle of this range. According to the average level in China, the conversion factor between crude cement and clinker is about 1.65. Therefore, producing one tonne of clinker, the CO2 emitted from organic carbon in crude cement is 1t×1.65×0.2%×3.67=0.012t.

d) CO_2 emitted from fuel combustion in kilns: Currently the fuel used in kilns in China is mainly coal. Few kilns use natural gas and petroleum coke. Oil is only used when initiating rotary kilns. Therefore, here we only consider the CO_2 emitted from coal combustion. The calculation formula is as below:

$E=3.67Fqka$

in which: E—Quantity of CO_2 emission, kg;
F—Quantity of fuel consumption, kg;
q—Value of fuel heat, MJ/kg;
k—Carbon emission factor of the fuel;
a—Percentage of carbon oxidation of the fuel.

It is calculated that one tonne of coal combustion will produce about 1.94 tons of CO_2.

According to the fact that the average coal consumption to produce one tonne of clinker is about 120kg, the CO_2 emitted from coal combustion to produce one tonne of clinker is about 0.2328t-CO2/t clinker.

2. Indirect emissions calculation

a) CO_2 emission from electricity consumption for clinker making: the electricity used in cement making is supplied by the local power grid; in other words, the CO_2 emission from electricity consumption is controlled by the power grid, and power grids in different areas will have different CO_2 emission factors (EF). Here we take the average EF of all power grids in China. According to the average electricity consumed by each tonne of NSP clinker in 2006 – 69.34 kWh/t(Cement Association, 2007), the CO_2 emissions from electricity consumption for each tonne of clinker made are 0.9273×0.06934=0.0643t.

b) CO_2 emission from cement grinding: during the whole process of cement making, grinding consumes 40% of the total electricity. According to the average electricity consumption during cement making in China – 98.31 kWh/t (Cement Association, 2007), the CO_2 emissions from cement grinding are 1t×0.09831×40%×0.9273=0.04t/tonne cement.

To conclude, the CO_2 emissions during the cement making process are mainly composed of raw material decomposition, fuel combustion and electricity consumption. Their emissions account for 59%, 26% and 12% respectively of the total emissions in cement making. The overall CO_2 emission factor is 0.8045t/tonne cement.

Bai Bing (2006) studies the main industrial sources of CO_2 in China, and collects production data of 8 types of plants (coal-fired electricity, iron and steel, cement, petroleum, ethylene, ammonia, ethylene oxide and hydrogen making). It calculates the CO_2 emissions of each type of plants according to the methodologies developed by other scholars. Calculation of CO_2 emissions usually adopts the IPCC methodology. In this methodology, the CO_2 emissions of industrial production are usually divided into two parts: fuel combustion and production processes. As the fuel data and product data are usually collected separately, it is not easy to represent the characteristics of concentrated emissions. The methodological feature of Bai Bing (2006) is: it is based on the plants' yields and production capacity, employs the comprehensive emission factor including both fuel combustion and production process, and then calculates the emissions from different point sources and sums to the total emissions. Emission factor is the function of fuel type, combustion efficiency, production process, technology status, mitigation level, technology progress and etc. This study considers the different fuels and production techniques used within different sectors, and the corresponding different emission factors of each sector. This study has concluded with the average emission factor of each sector – the CO_2 emission factor of dry process cement is 0.867 t- CO_2/t; the CO_2 emission factor of wet process cement is 1.102 t-CO_2/t. Assuming each taking up 50%, the comprehensive emission factor is 0.9 t-CO_2/t.

Using the data above, an emission factor for the cement sector in China of 0.85 t-CO_2/t can be estimated. From this, we can deduce that the cement sector in China emitted 10-12 billion tonnes of CO_2 in 2007.

3.4 Future trends technology research for the cement industry in China

The projections presented here are based on the Cement Industry Development Policy and the Cement Industry Development Specific Plan. The development goals of China's cement sector are:

- During the 11th five-year plan, the government encourages building large NSP production lines (producing 4000 tonnes or more cement per day)
- In western China, the production lines should produce at least 2000 tonnes cement per day
- Except for those special districts limited by market capacity and transportation conditions, it is not allowed to build cement producing projects less than 2000 tonnes per day
- It is forbidden to build any out-dated and backward cement production facilities, and also forbidden to build polluting and resource-intensive small cement plants
- By 2010, the NSP produced cement should make up 70% of the total cement production; indexes of equipment, energy consumption, environmental emissions, and resource utilization efficiency of NSP production facilities should all reach medium-developed countries level;

large NSP production lines with 4000t or more production per day should reach the target of comprehensive electricity consumption per tonne of cement of less than 95 kWh;

- The heat consumption per kg of clinker should be less than 740 kCal
- By 2020, the number of cement plants should decrease from the current 5000 plants to about 2000; there should be more than 10 plants with annual production more than 30 million tonnes, and more than 40 plants with annual production more than 5 million tonnes.
- Cement sector should generally achieve modernization; the techno-economic and environmental indexes should all reach the international advanced level.

In 2005, the cement consumption per capita in China was 806 kg, and the cumulative cement consumption per capita in China was 8.69 tonnes. Compared to the level in advanced countries, the cumulative cement consumption per capita in China is lower. However with the increased rate of urbanization, cement consumption will continue to rise. Estimates suggest that during 2011 to 2015, the cumulative cement consumption per capita in China will reach 14 tonnes, the cement consumption per capita will reach 900 kg, and the annual demand of cement will be around 1.25 billion tonnes, which is the peak of cement demand in China. It is estimated between 2020-2030, cement demand in China will maintain at around 1.3 billion tonnes.

3.5 CO_2 Mitigation Technologies in China's Cement Production

The main energy-saving and emission-reduction technologies in China's cement sector in the future 20 years include:

1. Cement kiln using alternative fuels: the secondary fuels that could be used include tire, plastics, polymer fabric, rubber, waste wood, and animal bones, as practiced in Europe.
2. Using alternative raw materials: the current available alternative raw material is calcium carbide sediment, which is mainly composed of $Ca(OH)_2$; when using this as the raw material, there won't be any CO_2 produced in the process. But due to limited resource availability, there is quite small potential for CO2 reduction.
3. Adding blended materials and reducing clinker
4. Cement kiln waste heat recovery: during cement production process, the residual heat of waste gas from the back-end pre-heater and grate cooler accounts for 33% of heat consumed in clinker calcining. Recovering heat from these gases can be used to dry raw materials thereby reducing coal which was originally used in drying and correspondingly reducing CO_2 emissions; the recovered heat can also be used to generate electricity, to be used in plants and reduce the purchased amount of electricity from power grid, thereby reducing the coal used in power plants and the corresponding CO_2 emissions.

5. Improving the grinding equipment and decreasing its electricity consumption; during cement production, 60%-70% of electricity will be used in grinding process; currently a lot of research has focused on the development of low power consuming grinding equipment, such as using roller mill and final grinding system of roller press to prepare crude cement, and using semi-final grinding system of roller press-steel ball mill or roller mill – steel ball mill to produce cement, instead of using tubular steel ball mill to grind powder.

In China, the NSP technology based on a pre-calcining kiln has developed considerably. Using a pre-calcining kiln and new grinding technologies will decrease the heat and electricity consumption by 50% and 20% respectively compared to traditional production techniques, resulting in a 15% decrease in CO_2 emissions.

Using clinker pre-calcining technology will decrease the heat consumption per tonne of clinker to the level of less than 2800 kg/kg. The production per unit volume of kiln will be increased by 35%; the CO_2 emissions will be decreased by 15% correspondingly. The key of Clinker Pre-calcining technology is to supply external energy according to the thermo-dynamics characteristics of clinker forming process, so as to utilize the energy to the biggest extent.

At present, the research hotspots in China include high-performance Portland cement, high-performance silicate-sulphoaluminate composite cement and high-performance slag Portland cement. The high-performance Portland cement is produced via patent technology and has introduced a large number of blended materials. The silicate-sulphoaluminate composite cement is produced according to the changes of crude cement components and thermal system. The clinker with silicate and sulphoaluminate will be calcined in kilns, and can also be blended with other materials. The high-performance slag Portland cement is produced with 70% of slag. The changes of components will ensure the strength of cement to meet the requirement of 42.5MPa level. The R&D and production of these cements will significantly reduce the CO_2 emissions in cement production. Therefore, improving the performance of clinker and increasing the percentage of blended materials are the key approaches to save energy and reduce emissions in cement sector.

Under the current technology level in China, the average heat consumption per tonne of cement is about 0.152 tce, and the average electricity consumption is about 110 kWh. According to the analysis of Xiliang Zhang (Tsinghua University), after considering all the possible energy saving technologies in China's cement sector, it is estimated that the comprehensive energy consumption per tonne of cement will be about 0.138 tce in 2010. By 2020 it is estimated that the comprehensive energy consumption per tonne of cement will reach 0.129 tce in China, close to the current international advanced level.

3.6 Application of CO_2 capture to the cement industry

In the cement clinker production process CO_2 is generated at 2 points:

1) Two thirds by the decomposition of limestone into cement clinker where concentrations of CO_2 in the off gas are 25% to 35%
2) One third from fuel combustion, if using an efficient kiln burning coal, about 95% of the CO_2 created could be captured through chemical absorption.

Potential Capture technologies include:

1) The CO_2 from limestone decomposition can in principle be captured in any of three ways:
    1. back-end chemical absorption;
    2. oxyfueling; or
    3. chemical looping using calcium oxide.
2) The CO_2 from fuel combustion can be captured through chemical absorption.

While the use of CCS in cement kilns is technically feasible, it would raise production costs overall by 40% to 90% (IEA GHG, 2008). Noting also the energy penalty that the application of carbon capture creates raises the fuel and electricity needed for clinker production by about 50%.

Table 8 Global Technology Prospects for CCS for Cement Kilns

CCS	2008-2015	2015-2030	2030-2050
Technology stage	R&D	R&D demonstration	Demonstration commercial
Investment costs (USD/t CO2)	500	250-350	150-200
Emission reduction (%)	95	95	95
CO2 reduction (Gt CO2/yr)	0	0-0.25	0.4-1.4

Source: IEA, 2008.

The IEA (2008) identify the follow research needs. Using oxygen instead of air in cement kilns would result in a pure CO2 off-gas, although process re-design might be needed to avoid excessive equipment wear. Different process designs using oxyfueling might halve the cost, but these are still at the conceptual stage. More analysis is needed, especially as the overall savings are potentially significant. The main reason for these savings is that the productivity of such kilns would be much higher than for conventional rotary kilns. This could bring benefit on CCS utilization.

There is also possibility of a non-geological CO_2 sequestration option for the cement sector. Whilst still at the R&D stage Novacem appears to offer significant CO2 savings over its life cycle relative to ordinary Portland cement. Novacem's cement uses magnesium silicates which emit no CO2 when heated. Its production process also runs at much lower temperatures - around 650℃. This leads to total CO2 emissions of up to 0.5 tonnes of CO2 per tonne of cement produced compared to standard

Portland cement of around 0.8 tonnes of CO2 per tonne cement. Ordinary Potrland cement can absorb up to 0.4 tonnes of CO2 when mixed with water for use in a building. But the Novacem cement formula absorb far more CO2 as it hardens - about 1.1 tonnes. So the overall carbon footprint is negative - ie the cement removes 0.6 tonnes of CO2 per tonne used. While it may take some years of testing to demonstrate the reliability of the production process and prove it's safety at a large scale, Novacem has the potential to significantly contribute to emissions reductions within the cement sector.[4]

3.7 Possible future application of CO_2 capture in China

According to the projections of cement production and the energy intensity, as well as the decreased CO_2 emission factor resulted from technological progress and energy efficiency improvement, the CO_2 emission in China's cement sector in the following several decades can be calculated. Due to lack of information on CCS utilization for different technologies, here we assume in the future in cement sector, CCS technology will be mainly used in the big and efficient NSP technique, such as the 4000t/d production facilities. According to the long-term development plan and technology improvement in China's cement sector, the ratio of big cement production lines is described in Table 9, from which we can deduce that the potential CO_2 that could be captured by CCS technology is around 300-400 million tonnes per year.

Table 9 Potential of CO_2 that could be captured in China's cement sector in the future

	2005	2010	2020	2030
1. Cement production/billion tonnes	1.06	1.2	1.25	1.3
2. Comprehensive energy intensity of cement production /Kgce/t	152	138	129*	125
3. Comprehensive CO_2 emission factor of cement production	1	0.8	0.75	0.7
4. CO_2 emissions in cement sector/Mt	1060	960	940	910
5. Ratio of direct CO_2 emissions /%	85	85	85	85
6. Direct CO_2 emissions/Mt	901	816	799	773.5
7. Ratio of NSP cement/%	45	70	80	90
8. Ratio of production lines larger than 4000t/d /%	15	50	60	65
10. Potential of CO_2 to be captured /Mt	60	290	380	450

Note: The emission factor of cement production will change according to the comprehensive energy intensity.

*Close to the current international advanced level.

---

[4] http://www.guardian.co.uk/environment/2008/dec/31/cement-carbon-emissions

4 Ammonia

4.1 Current status of ammonia industry in China

By the end of 2006, there were in total about 500 ammonia enterprises in China, of which 47 enterprises have a capacity of more than 0.3Mt. In 2006, the total capacity ammonia production was 55.46Mt ammonia (the total output is 49.37Mt and the operation rate is 89%), of which the capacity of 47 large- and middle-size enterprises is 23.42Mt, about 42.2% of total. In all enterprises, those using coal (or coke), gas and oil as feedstock account for 79.5%, 18.8% and 1.7% of total capacity respectively. Coal and coke are thus the main type of feedstock in ammonia industry in China. Enterprises using gas as feedstock take some share in total capacity and will grow gradually in the future while oil is hardly used as feedstock and will be substituted by other fuel types in the future.

The main downstream products of ammonia industry include urea, ammonium bicarbonate, ammonium chloride, ammonium phosphate, nitric acid, etc. The situation of the main down-stream products is explained as follows.

1) Urea: In 2006, the total production of urea is 48.5Mt in China and equivalent to 29.2Mt ammonia output, which accounts for 55.4% of total. About 71.8% of urea is used to produce fertilizer. In the Chinese market, urea with high nitrogen concentration are replacing the ammonium bicarbonate with low nitrogen concentration gradually
2) Ammonium bicarbonate is the second largest downstream product of ammonia industry and 99% of it is used to produce fertilizer. However, the share of it in fertilizer market has been reduced from 42.4% in 1993 to 18.4% in 2006.
3) Ammonium chloride of which almost all is from the byproduct of soda production and 95% of it is used to produce fertilizer. In 2006, the production of soda is 7.3Mt and the output of byproduct ammonium chloride is 7.3Mt, equivalent to 2.69Mt ammonia.
4) Nitric acid production is also a large consumer of ammonia. In 2006, about 2.8% of ammonia is used to produce nitric acid.

4.2 Application of CO_2 capture to the ammonia industry

In the synthetic ammonia industry, the CO_2 concentration of by-product gas is 28% to 99%. Its high purity and stable production make it advantageous for the use of carbon capture technology. At present, the existing capture, recovery and utilization of CO_2 in by-product gas of ammonia production has been commercialized with relatively mature technologies. The recovered and purified CO_2 can be used in industrial products and food industries. Since the 1970s and 1980s, some of synthetic ammonia factories in China have begun to capture, recover and reuse CO_2, which is mainly for own use. By the end of 1997, more than 50 medium-sized domestic ammonia plants have built 34 sets of

CO_2 recovery units with the total capacity of about 0.23Mt per year, of which the smallest unit capacity is 1,000t per year, and the largest is 30,000t per year. There are totally 9 sets of units with capacity more than 10,000t per year.

For the collection and recovery of CO_2 in by-product gases in synthetic ammonia production, there are four mature methods. All of them may be considered as “end of pipe”’ technologies.

1. Absorption methods:
    - As for the physical absorption, the CO_2 characteristic of higher solubility under high pressure is utilized to absorb CO_2 selectively and separated it from mixed gases. Then, under a relatively low pressure CO_2 is released again and the solvent can be reused. The typical physical absorption method is represented by low-temperature methanol method and carbonate method. Though this kind of method needs less energy, the purification of it on mixed gas is lower than the chemical absorption. For example, the carbonate method can only achieve the CO_2 absorption rate of 70% and the CO_2 purity is more than 98.5 %. No data on energy consumption of this method is available.
    - The chemical absorption method is to let chemical solvent react with CO_2 in mixed gases and then the resultant of reaction is heated to release CO_2 and the solvent can be renewed and reused. The main chemical methods include Benfield method and active MDEA method. In this kind of method, the CO_2 absorption rate can achieve 95%-98% and the energy consumption for it is about 330-340 kWh/tonne CO_2.
2. Membrane separation method: It is to use the characteristic of membrane that different gases have different infiltration rate and let only CO_2 penetrate through the membrane and be separated from other gases in mixed gases. When using this method, the recovery rate of CO_2 in flue gases in power plants is usually 82%-88% and the energy consumption of it should be 70-75 kWh per tonne CO_2.
3. Low-temperature method: The low-temperature distillation method is to control the temperature and pressure and let CO_2 to be condensed in super low temperature and separated from other gases in mixed gases. The CO_2 recovery rate of it is 90-95% and energy consumption is as high as 600-660 kWh per tonne liquid CO_2.
4. Pressure swing absorption method (PSA): PSA method is to use the characteristic of solid sorbent to selectively absorb the component gases in mixed gases under different pressures. The impurity components in mixed gases will be separated as absorbed by sorbent when the pressure is increased and then the sorbent will be renewed under the low pressure conditions that all impurity components will be desorbed again. Following this process, CO_2 should be separated and recovered. The recovery rate of this method is about 85%-90% and the energy consumption of it is 160-180 kWh per tonne CO_2.

The calculation of life cycle emissions of these four types of methods shows that the lifecycle[5] CO_2 emissions of chemical absorption, membrane separation, low-temperature and pressure swing absorption methods are respectively 78.7, 186, 179 and 172kg CO_2 equivalent under the condition of recovery rate of 95%, 82%, 90% and 85%.

As mentioned above, the main feedstock of ammonia production is coal and coke and to a lesser extent natural gas. The enterprises using oil as feedstock is quite few and mostly small-scale, and will be eliminated gradually in the future. As the process with different feedstock will consume different energy amount, the by-product CO_2 emissions of them are different, which means the available stationary large emissions are also different. Meanwhile, the process with different downstream products will also lead to different amount of collectable CO_2 emission. Therefore, the magnitude of total available large stationary CO_2 emission should depend on the feedstock type and the types of downstream products.

Xie Weiping (2003) undertook a theoretical analysis on recoverable byproduct CO_2 gas in ammonia production. He assumed that the ammonia production uses the coal, gas and oil as feedstock for gasification, and the syngas gas after the processing in gasification furnace and purification should mainly consist of N_2, H_2, CO_2 and CO. After the decarbonization process, the remaining mixed gases should consist of N_2 and H_2 and they can further synthesize to ammonia which can be used to produce urea, ammonium bicarbonate, etc. The separated CO_2 has two directions: one is to produce the urea or ammonium and ammonium bicarbonate and another is as byproduct gas and emitted to air directly. He calculated the amount of byproduct CO_2 for different types of ammonia enterprises based on the theoretical balance. The result shows that the produced CO_2 in ammonium bicarbonate production will be reused by 100% and those in urea production and methanol production will be partly used and the byproduct CO_2 in these processes can be separated and recovered.

Table 10 The theoretical analysis of byproduct CO_2 in ammonia production

Product	**Reaction formula**	**Theoretical output of CO_2**	**Practical output of CO_2**
Ammonia	$0.885C+1.5H_2O+0.5N_2+0.135O_2=NH_3+0.885CO_2$	$2.29tCO_2/tNH_3$	$2.31tCO_2/tNH_3$
Urea	$0.885C+H_2O+0.5N_2+0.135O_2=0.5CO(NH_2)_2+0.385CO_2$	$0.565tCO_2/tCO(NH_2)_2$	$0.57tCO_2/tCO(NH_2)_2$
Methanol	$12/7C+2H_2O+3/14O_2=CH_3OH+5/7CO_2$	$0.97tCO_2/tCH_3OH$	$1.6tCO_2/tCH_3OH$
Ammonium bicarbonate	$0.885C+2.385H_2O+0.5N_2+0.135O_2=0.885NH_4HCO_3+0.115NH_3$	0	0

Though the results of this analysis is basically right but there are still two problems with this study: one is the calculation in this study is based on the plants using gas as feedstock and will not reflect the situation of plants using coal as feedstock; the other is that the result is on the basis of theoretical

---

[5] calculated CO_2 emission from raw material.

calculation and could not reflect the practical situation which might consume more feedstock than theoretical calculation.

Chen Xiangmin et al. (2008) meanwhile estimated the CO_2 amount of ammonia plants using coal and gas as feedstock and the energy consumption and CO_2 emissions of some typical ammonia production processes (see Table 11).

Table 11 The byproduct CO_2 in ammonia production

		Total energy consumption per tonne of NH3 (GJ)	CO_2 output per tonne of NH3 (tonne)	n(CO_2):n(NH3)
Coal as feedstock	Texaco/GE furnace	67	7.02	2.71:1
	UCI furnace	50.16	5.28	2.04:1
	Lurgi furnace	44.12	4.62	1.79:1
Gas as feedstock	Kellogg MEAP process	28.4-30	2.99-3.14	(1.15-1.21):1
	Brown process	28.4-29.3	2.99-3.07	(1.15-1.19):1
	Brunner Mond AM-V process	28.4-29.3	2.99-3.07	(1.15-1.19):1
	LCA process	29.3	3.07	1.19:1
	KPES and KAAP process	25.96-27.21	3.26-3.42	(1.26-1.32):1

From the point view of available CO_2 emission, the results is study may lead to some errors since the energy consumption used in this study is the comprehensive energy consumption, which include the steam and electricity power consumption but they do not produce any CO_2 emission inside the plant scope. In addition, this study does not consider the using of produced CO_2 and could not give an explanation of how much CO_2 is emitted to air.

By summarizing the methods and results of above two studies and based on the fuel consumption data of ammonia enterprise (data source: Chinese energy efficiency analysis and its comparison with international levels) and CO_2 emission amount in large- and middle-scale of ammonia enterprise (data source: China National GHG Inventory), we calculate the byproduct CO_2 amount of ammonia plants with different feedstock and downstream products (Table 12).

Table 12 Available large stationary carbon emissions in ammonia industry

		Feedstock Type		
		Coal (Coke)	Oil	Gas
Feedstock consumption per tonne of ammonia (GJ/t)		40.18	42.67	32.54
CO_2 output per tonne of ammonia (tCO_2/t)		3.69	2.37	2.47
By product CO2 per tonne of ammonia (tCO_2/t)	Urea	2.36	1.05	1.14
	Ammonium bicarbonate	0	0	0
	Other fertilizers	3.69	2.37	2.47

4.3 Possible future application of CO_2 capture to the ammonia industry in China

According to the IEA GHG's CCS database and the report of ammonia industry, there are a total of 68 large- and middle-scale ammonia enterprise appropriate for large stationary CO_2 emission sources (some of them belong to same corporation, but since their locations are different, they are regarded as individual enterprises). In 2006, the capacity of these 68 enterprises is 23.72Mt ammonia, 42.8% of total capacity of ammonia industry in China. Most of these enterprises are using urea as their downstream products.

Integrating these data with the production data of large- and middle-scale ammonia enterprise, and using the principle of calculation listed in table 12, the available large stationary carbon dioxide emissions in ammonia industry in 2006 is estimated to 40.83Mt CO_2, which has the potential for CCS in the industry. Some principles are considered here:

- Most of small-scale enterprise use coal or coke as feedstock and seldom use gas as feedstock;
- In 2006, most of small-scale ammonia enterprises seldom produce urea as their downstream product. The capacity of enterprises with ammonium bicarbonate being downstream products is 9.13Mt and remained capacity is mainly used for other fertilizer production or chemical production.
- The unit feedstock consumption of small-scale enterprises is smaller than that of large- and middle-scale enterprise, and correspondingly, the CO_2 output per tonne of ammonia is also lower, about 3.36 tCO_2 per tonne of ammonia.

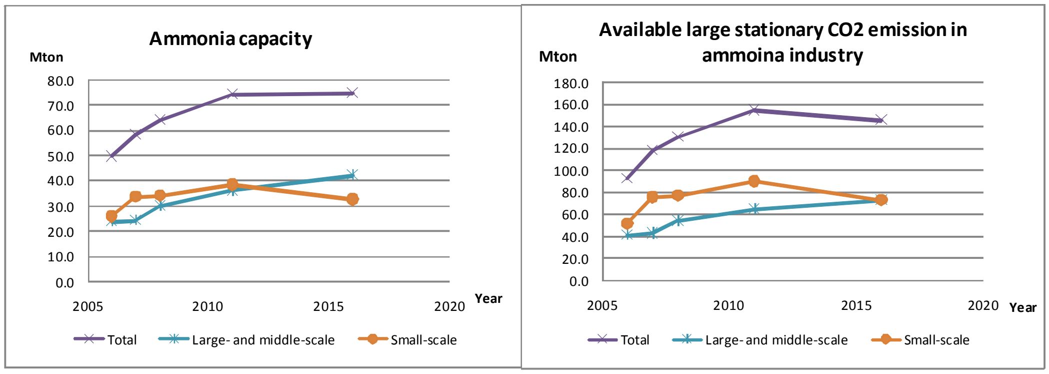
Based on the above data, it is estimated that in 2006, the available large stationary CO_2 emission in small-scale ammonia enterprise is 51.2Mt.

In addition, the future trend of ammonia capacity and available large stationary CO_2 emission in the future is estimated according to the current installed projects and projects planned to be installed and the general trend of ammonia industry (including the trend of enterprise with different downstream products). (See Table 13 and Figure 4)

Table 13 Available large stationary carbon emissions in ammonia industry (both direct and indirect Unit: Mt)

Scale of enterprise		**2006**	**2007**	**2008**	**2011**	**2016**
Capacity of ammonia	Large-scale	23.7	24.3	30.0	36.1	42.2
	Small scale	25.8	33.7	34.1	38.3	32.6
	Total	49.5	58.1	64.1	74.4	74.8
Available CO_2 emission	Large-scale	40.8	42.5	53.8	64.3	72.6
	Small scale	51.2	75.4	76.6	89.7	72.9
	Total	92.0	118.0	130.4	154.0	145.5

Figure 4 Available large stationary CO_2 emissions in ammonia industry



It can be concluded from the above results that the ammonia industry in China will keep growing in next 3-4 years and will maintain stable after 2011. The production structure of ammonia industry will be optimized in that the capacity of large- and middle-scale enterprises will increase and substitute that of small-scale enterprises gradually. During the twelfth-five-year planning period, the capacity of large- and middle-scale ammonia enterprises will surpass that of small-scale enterprise. (See figure 4 left)

The available large stationary CO_2 emission in ammonia industry will increase as a result of growth of ammonia production in the future. It will attain to 154Mt CO_2 by 2011, about 1.67 times as that in 2006, and then decline to 145.52Mt in 2016 due to changing of fuel mix and efficiency improvements. The available CO_2 emission of main emission sources (large- and middle-scale ammonia plants) will increase year by year and maintain the same level with that of minor emission sources (small-scale ammonia plants) by 2016. (See figure 4, right)

The potential for CCS to be used in ammonia industry is not clear so far. Table 13 provide pictures for CO_2 emission in the industry, but what part of the emission could be captured is not yet clear. Basically the emission could be captured, and as mentioned above, if CCS could be available for large ammonia industry, which is 68 enterprises in China, the potential for CCS is 40.83million tonne- CO_2.

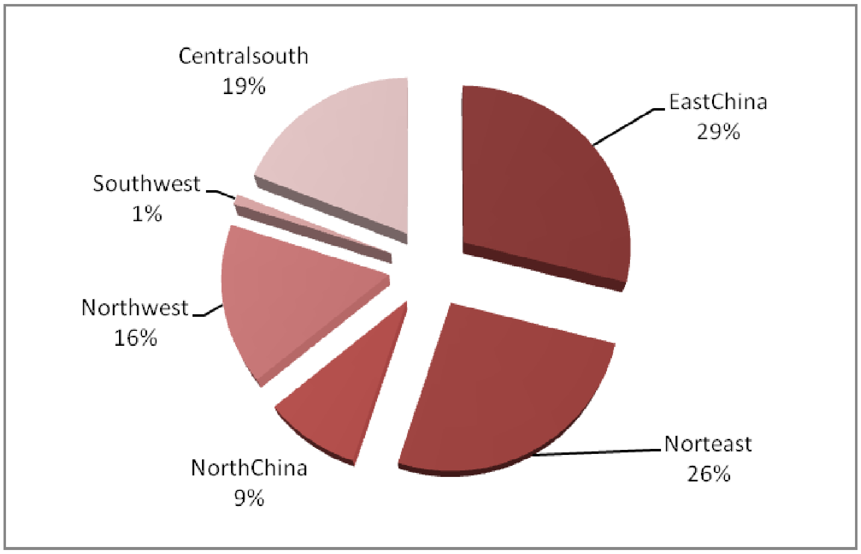
5 Oil refinery

5.1 Current status in of oil refinery in China

Due to the increasing demand for oil, the oil refinery industry has grown rapidly in recent years. The total oil refining capacity in China has reached 360Mt, the majority of which is operated by the two main oil refinery corporations, China Petrochemical Corporation (SINOPEC) and China National Petroleum Corporation (CNPC). The oil refining capacity of SINOPEC and CNPC are 194Mt and 138Mt, ranking in 3rd and 9th place in the world respectively.

The main capacity of oil refinery in China is concentrated in the oil production regions, such as north-east region and north-west region. However, by comparison, the demand for oil products in these areas is not high, so the growth of oil demand there is limited. As a result, the pattern of “transferring oil from north to south” and “transporting oil from west to east” has developed. The allocation of oil refining capacity in year 2007 in China can be shown in figure 5.

Figure 5 The allocation of oil refining capacity in China in 2007



In 2006, SINOPEC had 27 oil refining plants and CNPC has 33 oil refining plants. Of the total 312Mt of crude oil refined in China in 2006, 157Mt is from SINOPEC and 116Mt from CNPC. The total refined crude oil in these two corporations accounted for 87.3% of the total in China. The total refined crude oil from 2002 to 2006 are listed in table 14.

Table 14 The refined crude oil in SINOPEC and CNPC from 2002 to 2006 (Unit: 10000tonnes)

	China total	SINOPEC	CNPC*
2002	21897	11176	8482
2003	24255	12597	9254
2004	27290	14285	10370
2005	29457	15077	11061
2006	31212	15760	11587

*Excluding the crude oil refined outside China

According to the national planning on oil refining facilities, the oil refining capacity of China will be greatly expanded in the next few years and will approach 420Mt by 2010. The newly installed refining units will be located in East China, South China and South-western China. The scale of refining plants will be increased and about 22 large-scale refining bases with capacity of more than 10Mt oil will be established by the end of the eleventh-five-year planning period (2005-2010). If all newly large-scale refining projects are completed, the allocation of oil refining capacity in China will be changed as shown in Table 15.

Table 15 The allocation of oil refining capacity in China in 2010 (Unit: 10000tonnes)

Region	**Refining capacity**
North	4580
Northeast	9150
East	12800
Centralsouth	9600
Westsouth	200
Northwest	6800

5.2 Energy consumption China’s oil refining industry

The energy efficiency of oil refining industry in China is relatively low, though improvements have been seen in recent years as shown in the following table.

Table 16 The integrated energy consumption of SINOPEC and CNPC in year 1996-2006 (Kgoe/t)

Year	SINOPEC	CNPC
1996	84.39	
1997	80.27	90.46
1998	87.14	94.36
1999	85.4	92.54
2000	79.34	91.07

2001	78.25	86.44
2002	78.32	88.03
2003	76.06	85.39
2004	73.68	82.9
2005	68.59	80.00
2006	66.89	77.98

Source: Annual report of SINOPEC; Yearbook of SINOPEC; Yearbook of CNPC

The energy consumption of oil refining industries can be separated to fresh water, electricity, steam, coking, fuel for burning furnace and heat output, in which the main source of carbon emission is from the fuel combustion in burning furnace, which accounts for about 1/3 of total energy consumption in refinery plant.

In a refinery plant, the energy consumption devices generally include the atmospheric and vacuum crude distillation unit (CDU), catalytic cracking device, catalytic reforming device, delayed coking device, hydrogenization cracking device and gasoline and diesel hydrogenization device, in which the common- and reduced-pressure device and catalytic cracking device are two main devices consuming energy. In general, they are responsible for about 45-50% of energy consumption in refinery plant. The average energy consumption for each device in China is shown in table 17.

Table 17 The average energy consumption by device in oil refinery plants in China (Unit: Kgoe/t)

Year	Atmospheric and vacuum crude distillation unit	Catalytic cracking device	Catalytic reforming	Delayed Coking	Hydrogenization cracking	Gasoline and diesel hydrogenization
1990	12.80	74.46	190.80	28.30	-	-
1995	12.41	71.18	120.82	27.36	62.88	24.37
2000	12.13	73.72	113.00	30.73	58.50	19.66
2001	11.77	65.17	99.49	30.07	59.41	19.78
2002	11.56	71.74	98/103.0	27.22	55.00	18.47
2003	11.59	69.27	107.35	27.10	52.47	17.90
2004	11.58	65.34/72.40	96.05	28.91	49.70	13.56/19.13

The energy consumption for each device is as follows.

1. Crude distillation and vacuum distillation units: This is the first stage of crude oil refining with energy consumption of it will account for about 14% of total energy consumption of plant. In this type of energy consumption, that for fuel combustion takes more than 70%

and is mainly used for burning furnace.

2. Catalytic cracking device: This is used for the further processing of heavy oil. Along with the increase in using this type of processing, the share of catalytic cracking device is increasing gradually. In general, the energy consumption of this device accounts for 25-35% of total plant energy consumption and is becoming the main energy user in a refinery plant.
3. Catalytic reforming device: As the demand for high-grade gasoline ascends in China, the capacity of catalytic reforming device grows gradually. The catalytic reforming process is relatively complicated and long and can be attributed to high-temperature reaction process. Accordingly, the reaction heat of this device is high and the number of burning furnace in this process is large. The energy consumption of this device is generally as high as 80-110Kgoe/ton, of which the energy used in burning furnace takes most.
4. Catalytic hydrogenization device: It is an integration of catalytic reaction technology, refining technology and high-pressure technology. The hydrogenization device can be categorized to hydrogenization disposal device and hydrogenization cracking device. The energy consumption of these devices usually constitutes 10-25% of total energy consumption in the refinery plant, in which 30% is for the electricity use for lifting pressure.
5. Delay coking device: With the advantages such as simple process, low investment and low operation expense, this type of device is broadly used in refinery enterprises in China. It can be expected that the application of coking technology will grow with an annual rate of more than 7% in next 20 years. In 2005, the total capacity of scorching devices in refinery plants in China has attained to 45Mt per year, accounting for 20% of total capacity of primary processing of crude oil. The energy use for fuel consumption shares 70% of total energy consumption in this kind of device.

By integrating the fuel consumption for all these devices, it can be estimated that the fuel consumption for burning furnace is very large and accounts for 30-40% of total energy consumption in refinery plants. Based on the statistic of SINOPEC, of all energy consumption in refinery plants in 2004, the energy use of fuel combustion is 33.9%, ranking the first in all energy consumption types. The tubular-type burning furnace is the main device to consume the fuel, and beside it, there are also some industry boilers consuming the fuel in refinery plants.

5.3 Possible future application of CO_2 capture to the oil refinery industry in China

Based on the above analysis, it can be primarily concluded that in refinery plants, the potential large stationary carbon emissions are mainly from the burning furnace and partly from the industry boilers. Since most of refinery plants in China are large-scale, the carbon emitted from fuel combustion in burning furnaces and industry boilers can all be regarded as large stationary emission sources.

However, since the scale and refining capacity of plants are different, the numbers of burning furnaces and industry boilers are also different for each plant. Some plants may have a large number of burning furnaces. Therefore, the method to collect CO_2 emission from such dispersed emission sources is a key factor influencing the commercial use of carbon capture technology in the refinery industry. For example, in 2005, there are totally 570 burning furnace in 26 refinery plants of SINOPEC and by average 22 burning furnaces per plant. There are totally 107 industrial boilers in these 26 plants, an average 4.1 boilers per plant. Of all these refinery plants, Zhenghai Refinery plants ranks first in the number of burning furnaces and has totally 86 burning furnaces. Fujian Refinery Plants, however, only has 4 burning furnaces. To simplify the calculation of CO_2 emission from burning furnaces and industry boilers, we assume here that all fuel consumptions in refinery plants are used in burning furnace and industry boilers and can be regarded as stationary emission sources. According to this principle, we estimate the large stationary carbon emissions in refinery plants as follows.

Firstly, we calculate the fuel combustion in refinery plants. The statistic data of SINOPEC and CNPC shows the average fuel consumption is about 33%. Based on this figure and the total energy consumption of them, the fuel consumption of the refinery plants under these two corporations can be calculated. Regarding the energy consumption data, those of SINOPEC and CNPC are based on their official data and those of other refinery plants are based on the data of CNPC, considering that they are similar in technology and energy management level.

Secondly, the fuel consumption of refinery plants should be separated by fuel type. As for the fuel types used in refinery plants, generally both heavy oil and refinery gas are used. In the past, as the processing ability of refinery plants is not so high and the amount of refinery gases is few, the heavy oil is mainly used as the fuel for combustion. However, along with the rising application of secondary processing devices in refinery plants, the percentage of refinery gases in fuel combustion grows rapidly. Meanwhile, in some plants the coal is also used as fuel input, but the total percentage of it is so small that we neglect here in this analysis. In 2005, 26 refinery plants under SINOPEC consumed 1.02Mt heavy oil and 4.19Mt of refinery gases in total, and by converting them into tonne of oil equivalent, we can get that the share of heavy oil and refinery gas in fuel consumption in refinery plants is 18% and 82% respectively.

Finally, the fuel consumption by fuel type is multiplied by the emission factors of each type of fuel. Then, the available large stationary CO_2 emissions in refinery plants can be obtained. As to the emission factor for different fuel type, the emission factors in the China's Initial National GHG Inventory are used (See table 18).

Table 18 The emission factors of heavy oil and refinery gas in refinery industry

	Potential emission factor * tC/TJ	Oxidation rate	Emission factor tC/toe
Heavy oil	20.67	98%	0.865
Refinery gas	18.02	99%	0.754

*Assumed emission factor if 100% carbon embodied in the fuel is oxidized.

Following the above procedure, the available large stationary carbon emissions in refinery industry in China from year 2002 to 2006 are calculated. Meanwhile, based on the planning of future refining capacity installation, the available large stationary carbon emissions in 2010 are also estimated. The results are listed in table 19.

Table 19 The available large stationary CO_2 emissions in refinery industry in China

	Refined oil (Mt)	Available carbon emission (Mt carbon)	Available CO_2 emission (Mt CO_2)
2002	218.97	4.69	17.20
2003	242.55	5.04	18.49
2004	272.90	5.50	20.16
2005	294.57	5.64	20.68
2006	312.12	5.83	21.38
2010	388.17	6.65	24.37

*Assuming the refined oil is 90% of refining capacity

The result of our estimation shows the total potential for carbon capture in refinery industry is not so large. However, this does not include the refinery units that generate H2 for the hydrogenation devices. This is important since the CO_2 stream could be a concentrated one, making capture easier. It should be noticed that the oil demand of China will keep increasing and correspondingly the refining capacity will grow rapidly, which will result in a fast growing of CO_2 emissions in the refinery industry. In a word, the refinery industry is one of important industry with high potential to apply the carbon capture technology in far future. It should be strengthened in refinery industry to study and demonstrate the implementation of carbon capture technologies.

6 Ethylene

6.1 Current status of the ethylene industry in China

In recent years, ethylene production in China has been growing rapidly. As shown in table 20, the total output of ethylene has increased from 5.34Mt in 2002 to 9.41Mt in 2006. In 2005, China became the second largest producer of ethylene in the world.

Table 20: The annual ethylene outputs from 2002 to 2006 (Unit: Mt)

	2002	2003	2004	2005	2006
Ethylene output	5.34	6.12	6.27	7.55	9.41

Currently in China, there are 19 ethylene large-scale production plants. Of these, 6 plants belong to China National Petroleum Corporation (CNPC), 11 plants belong to China Petrochemical Corporation (SINOPEC), and 2 plants are owned by China National Offshore Oil Corporation–Shell (CNOOC-Shell) and Liaoning Huajing Chemicals Group Corporation (HuajingChem).

There are 24 sets of ethylene production units in these 19 plants, including 11 sets with capacity higher than 0.3Mt, 9 sets with capacity between 0.15-0.3Mt and 4 sets with capacity lower than 0.15Mt. In all sets of ethylene units, 9 sets belong to CNPC, 12 sets belong to SINOPEC and 3 sets belong to CNOOC-Shell and Huajing Chem.

By the end of 2006, the ethylene capacity of CNPC, SINOPEC, CNOOC-Shell and Huajing Chem reached 2.63Mt, 6.25Mt, 0.8Mt and 0.16Mt respectively and the total ethylene capacity in China was 9.85Mt. In 2006, the total ethylene output reached 9.23Mt, of which CNPC, SINOPEC and the two other enterprises accounted for 22%, 67% and 9% respectively.

As an industry to which the Chinese government attaches high importance, the ethylene industry will maintain a high-growth trend in the coming decades. Adding the currently on-going and planned projects, the newly-installed projects and projects to be expanded will amount to 11 by year 2010 with a total capacity of 7.05Mt, which will drive the total capacity of ethylene industry to 17Mt by 2010. From 2010 to 2015, another 5 new ethylene projects with total capacity of 4.6Mt will be installed and the capacity of ethylene industry will reach 21.62Mt by 2015. From 2015 to 2020, 7 new ethylene projects with total capacity of 6.8Mt will be installed and the capacity of ethylene industry will attain to 28.42Mt by year 2015. The prediction of future expansion of ethylene industry can be seen in table 21.

Table 21: The prediction of total capacity and output in ethylene industry (Unit: 10000tonnes)

	Capacity	Operation rate, %	Ethylene output
2006	984.5	95.6	941.2
2010	1702.0	96.0	1633.9
2015	2162.0	96.0	2075.5
2020	2842.0	96.0	2728.3

6.2 Estimation of large stationary carbon emissions in ethylene industry

Though the scale of ethylene plants and units in China are all large, the energy efficiency of them is still lower than the world advanced level by 25% on average. Accordingly, the potential of energy saving in ethylene industry is very high. Of the total energy consumption in an ethylene plant, that for fuel combustion accounts for the main part, and is mainly used in the cracking furnace, which is correspondingly the main large stationary emission source in an ethylene plant.

From point of view of the whole world, almost 95% of ethylene production is using the tubular-type cracking furnace technology. In China, all ethylene is produced through the cracking process. Therefore, the tubular-type cracking furnace consumes a large part of total energy consumption in the ethylene plant.

The tubular-type cracking furnace is a combination of reactor with heating furnace. The feed stock flows through the radiation tube surrounding the high-temperature flue gases produced from the fuel combustion. The heat of fuel combustion will be transfer through the radiation tube to the feed-stock and the cracking reaction will occur in the tube at high temperature and without any catalyst. Since the cracking furnaces are the main device used by ethylene enterprises, their number is huge. In 2005, there were about 100 cracking furnace in 11 ethylene plants under SINOPEC. The fuel used in the cracking furnace is mostly refinery gas.

Based on energy consumption of some typical ethylene plants, the cracking furnace accounts for as high as 70-75% of total energy use. For example, the percentage of fuel use by cracking furnace in total energy use in Yanshan Petrochemical Plants, Zhongyuan Petrochemcial Plants and Guangzhou Petrochemical Plants are respectively 70%, 73.5% and 75% respectively. Even for some plants using less energy for cracking furnace, the share of fuel used is around 60%. Therefore, it can be estimated that the energy use for fuel combustion in cracking furnace is on average 70% of total energy use in an ethylene plant. Based on this, the carbon emissions of ethylene plants are calculated as described in the following paragraph.

In 2006, the average total energy use per ethylene output in ethylene plants under SINOPEC is about 677kgoe/tonne, and that for ethylene plants under CNPC is 758.25kgoe/tonne. The weighted average value of them by ethylene output is 697kgoe/tonne and this shows the average energy consumption level of ethylene industry in China. This level of energy consumption should be reduced along with the energy efficiency improvement of ethylene plants and replacement of old production units with new units. The energy saving target for ethylene industry in 2020 is that the average energy consumption per unit of ethylene output should be reduced to 650kgoe/tonne.

6.3 Possible future application of CO_2 capture to the ethylene industry in China

The ethylene industry is one of large stationary sources for the application of carbon capture technology. According to the IPCC report (2005), among all worldwide large CO_2 stationary sources emitting more than 0.1Mt CO_2 per year, there are 240 large emission sources from ethane production plants, emitting 258MtCO_2 per year and accounting for 1.93% of total large stationary sources in the world.

In ethane production plants, the main emission facility is the cracking furnace. A typical cracking furnace as a stationary source contain a gas stream with CO_2 content of 8% (percent by volume in dry gas) and gas pressure of 0.1MPa. According to the IEA CCS database, the total number of large stationary sources in ethylene production enterprises in China is 21 (before the end of 1999).

In terms of carbon capture technology, only the post-combustion decarbonization technologies can be used in ethylene industry. However, so far there is no demonstration or commercial use of decarbonization technologies in the ethylene industry.

Based on the data and analysis above, large stationary carbon emissions in ethylene industry from year 2006 to 2020 can be estimated as follows.

Table 22: Available large stationary carbon emissions in ethylene industry in China

	Ethylene output (Mt)	Available carbon emission (Mt carbon)	Available CO_2 emission (Mt CO_2)
2006	9.41	4.95	18.15
2010	16.34	8.38	30.73
2015	20.76	10.41	38.18
2020	27.28	13.38	49.06

It can be concluded from the above results that the potential for carbon capture in the ethylene industry is quite high. Moreover, ethylene plants are mainly large-scale plants and the emission sources are also large and concentrated. The available CO_2 emissions in ethylene plants are huge and even though the energy efficiency is improved by large degree in the future, the growth of available CO_2 emission will be high. The ethylene industry should be regarded as a key research and demonstration area for the application of carbon capture technology.

References

Bai, B., et al., (2006). Concentrated CO_2 emission sources survey and their distribution characteristics in China. Chinese Journal of Rock Mechanics and Engineering 25(Add.1), 2918-2923.

Borlée (2007), “Low CO_2 Steels – ULCOS Project”, ETP 2008 Workshop on Deploying Demand Side Energy Technologies, OECD/IEA, Paris

Chen, C., et al., (2007). Material consumption and environmental emissions analysis of cement production in China. Journal of Anhui Agricultural Sciences 35(28), 8986-8989.

Chen Wenying, et al., (2007), CO_2 Carbon Capture and Storage (CCS) and Its Potential Role to Mitigate Carbon Emission in China, Environmental Science, Vol 28, No. 6, 1178-1182

Chen Xiangmin et al., (2008), Analysis on the absorption of CO_2 in flue gas from power plant with ammonia for CO2 sequest ration, Hebei Journal of industrial science and technology, Vol 25, No. 1, 24-26

China International Engineering Consulting Corporation, (2006). Analysis of China’s energy efficiency and its international comparison, Energy Bureau Report.

China National GHG Inventory(2007)National Development and Reform Commission/Energy Research Institute, Chinese Environmental Science Press

Chinese Energy Office(2007)Chinese energy efficiency analysis and its comparison with international levels, Beijing

Cui, Y., et al., (2007)The energy saving and emission reduction potential of China’s cement sector and her development strategy. China Building Materials News. April 24.

Cui, S., et al., (2008)CO_2 emission reduction potential analysis in cement production process. China Cement .

International Aluminium Institute (IAI) website http://www.world-aluminium.org/Sustainability

International Council on Mining and Metals (ICCM) website http://www.icmm.com/page/2420/alcoa-develops-carbon-capture-process

IEA (2008) CO_2 Capture and Storage: A Key Carbon Abatement Option

IPCC (2005) IPCC special report on carbon dioxide capture and storage, UNEP/WMA

IPCC (2007)Climate Change 2007, <http://www.ipcc.ch/ipccreports/ar4-wg3.htm>)

Jiang Kejun, Hu Xiulian, Zhuang Xing, Liu Qiang, Liu Hong (2009) China’s 2050 Energy and CO2 Emission Scenarios, in China’s 2050 Energy and CO2 Emission Report, China Science Publishing House, Beijing

Liu, Y., et al., (2007). Analysis of the stresses of population and economic growth on CO_2 emissions from cement manufacturing. Research of Environmental Sciences 20(1), 118-122.

Meng Xianling (2005), A review of energy saving in China’s refining industry

NDRC (2006) National Special Planning on Cement Industry, 2006, NDRC

NDRC (2008)Energy Conservation in Aluminum Industry, NDRC

National Development and Reform Commission (NRDC)/Energy Research Institute (2007) China National GHG Inventory, Chinese Environmental Science Press

Qian Bozhang (2007) The ethylene production scale in China is approaching global level, China Petrochemical, No.1

Ryozo Tenaka (2005), Carbon Capture Technologies in Japan, Science and Innovation Section, British Embassy Tokyo, https://ukinjapan-stage.fco.gov.uk/resources/en/pdf/5606907/5633507/36463X.pdf

Song Aiping (2008) "Poor in south and rich in north"- the new pattern of refining capacity in 2010, China Petroleum and Petrochemical Engineering, No. 10

SRI(2008)The report of chemical product development in China – Ammonia

Steel Industry Yearbook 2007(2007)Steel Industry Yearbook Publishing House, Beijing

The Annual Report of China National Petroleum Corporation (2003-2007), www.cnpc.com.cn

The Annual Report of China Petrochemical Corporation (2003-2007), www.SINOPECgroup.com

The effect of reducing the fuel consumption in ethene units in Zhongyuan Petrochemical Plants is remarkable, http://www.bmlink.com/news/message/153351.html

The Yearbook of China National Petroleum Corporation (2007), 2007, China Petroleum Industry Press, Beijing

The Yearbook of China Petrochemical Corporation (2007), 2007, China Petroleum Industry Press, Beijing

The Statistic Yearbook of China Petrochemical Corporation (2005), 2006, SINOPEC, Beijing

Wang, L.(2006) Energy saving of cement products. Proceedings of cement technology conference in 2006, 73-77.

Wang Huanmei, et al.(2007)The organic chemical production technology, High Education Press, 2007, Beijing

Wang Ke (2006) CO2 Emission Reduction Potential in Steel Industry of China Based on LEAP Model, Journal of Tsinghua University, 2006 Vol 46 No.12

Warren H. Hunt(2004) The China Factor: Aluminum Industry Impact, The Minerals, Metals & Materials Society.

Van Bergen, F., J. Gale, K.J. Damen, and A.F.B. Wildenborg(2004) Worldwide selection of early opportunities for CO_2-EOR and CO2-ECBM, Energy

Xie Fangyou, et al., (2003) The research development of comprehensive use of CO_2, Chemical production and technology, vol 10, No.3, 30-33

Xie Weiping (2008) The Recovery and Utilization of C02 as a By-Product from Synthetic Ammonia Production, Environmental protection and science, Vol 34, No. 2, 10-13

Xu Jinlin (2006) Energy saving potential in China refining industry and technical measures, Petroleum Refinery Engineering, vol 36, No. 4

Xu Jinlin (2004) The energy saving situation and countermeasures in refining enterprises in China, Petroleum and Petrochemical Today, No.8

Yao Xiaosheng (2005)The analysis of energy consumption situation of Anqing Refining Plant, Petroleum and Petrochemical Today, No.4