Climate Change Adaptation and Mitigation Efforts with Special Attention to CCUS Technologies and Iron/Steel Industry in China

An Interim Report

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Foreword

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Fight against climate change calls for concerted efforts by governments, firms, universities, and other social forces, both domestically and globally. Similarly, as reflected in our on-going research in this field, cross-disciplinary approach is not only necessary but also desirable. Presented here is an interim report on the joint efforts by scholars and experts organized through what is strategically envisioned as a triple helix of National School of Development, Guanghua School of Management and College of Engineering at Peking University -- with financial support from BPH Billiton.

A principal focus of the report is on carbon capture, utilization and storage (CCUS) technologies, and their related -- albeit still evolving -- policy and legal frameworks in China. Where relevant, we've tried to make international comparisons on both legal/policy and technology fronts. The sectoral cut is China's iron/steel industry, as this sector has huge implications for adaptation and mitigation efforts. It contributes significantly (about 15%) to China's total carbon emissions, and approximately 51% of the global total from the iron/steel sector.

Organizationally, our interim report is made of four main chapters.

Chapter 1 sets an institutional background that is market-oriented and still evolving, and would presumably have long-term commercial implications for industrial firms in their decisions as to whether or not to invest, develop and deploy technologies (e.g., CCUS) for carbon emission reductions. Notably, as part of China's low-carbon strategies to fulfill its commitments to the Paris Agreement, since 2014, China has rolled out seven pilot projects on carbon permit trading markets (i.e., in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen), and, if successful, they are expected to scale up to the national level in 2017.

This chapter represents an independent study of the efficacy of these pilot projects -- including their institutional designs, horny issues of measurement and monitoring, and comparative performances on carbon emission reductions. Using econometric methods,

our scholars (from National School of Development and School of Environmental Science and Engineering at Peking University) find that carbon emission reductions are positively correlated with the volumes of trading on these pilot markets. Success, however, is limited and uneven across the pilot projects, partly because of the lack of liquidity on these experimental markets. They suggest caution against rapid expansion of the pilot projects before gaining a deeper understanding of their underlying causes.

Chapter 2 is collective research work by a dedicated team from China's National Center for Climate Strategy and International Cooperation (NCSC). The chapter begins with a brief overview of the general trends of China's industrialization and urbanization process and their short- and long-term implications for the iron/steel industry. In particular, the study includes simulated scenarios on the prospects or challenges of carbon emissions in China, and the necessary adaptation and mitigation efforts for China to fulfill its commitments to the Paris Agreement. Systematic comparisons – including innovation-oriented subsidies, incentives, tax breaks -- are also made between international and Chinese low-carbon legal and policy frameworks, and with a special attention to CCUS demonstration projects.

According to their findings, internationally, large scale CCUS projects have been concentrated mostly in natural gas fields and coal-fired power plants; few are in cement, iron/steel and biotransformation industries. Similarly, in China, there are about 12 CCUS pilot projects targeted either at coal-fired power plants or at coal chemical projects; none of them has captured CO_2 from the iron/steel sector. They argue that Chinese CCUS-related R&D and demonstrations are in infancy, and that large potential exists in China for an expansion of CCUS projects in the next 10-20 years.

To facilitate that happening, they propose that better alignments of existing Chinese legal and policy frameworks, as well as better administrative co-ordinations, are needed, such that CCUS projects become an integral part of the country's long-term efforts for a low-carbon economy. Deserves special mention here is the fact that legal provisions are lacking in China regarding the ownership of underground space for, and possible cross-border subterranean movements of sequestrated carbon. As is true elsewhere, institutional or legal uncertainties would deter long-term financing and investment.

Chapter 3 is intended for a deeper understanding of the technical complexity of CCUS technologies at the firm level in the iron/steel sector. One overarching consideration of our interdisciplinary research is that policy studies need to interact with and be supported by technical expertise. To better understand the behavior of the iron/steel sector, cost/benefit analyses with respect to CCUS technologies, must therefore descend from macro to micro levels to take account of the heterogeneity of the different techniques, methods, and processes involved in iron/steel making.

Here, our scholars and experts – representing a good fix of business perspectives and industrial knowhow – have attempted a systematic techno-economic analysis of the

efficacies of different CO_2 capture technologies (e.g., absorption, membrane, and cryogenic distillation) for different sources in the iron/steel making processes (e.g., lime kiln, coke oven, converter, hot blast furnace, and power generation unit).

Their findings are tabulated schematically for easy reading and cross checking in this chapter. The conclusion is that one size does not fit all. In a typical iron/steel making process, as emission sources have diverse characteristics, CCUS technologies have diverse technical applicability and economic performance as well. Accordingly, they suggest that technical applicability and cost/benefit analysis of different CCUS technologies -- individually or combined -- have to be calibrated at the firm level to take account of firm-specific conditions.

Chapter 4, penned by the Dean of College of Engineering at Peking University, can be regarded as reinforcing Chapter 3, insofar as our efforts to understand and look for a "fit" between the iron/steel making processes and most appropriate carbon capture technologies are concerned. That said, this chapter also includes a systematic review of various ways of carbon utilization. Pointedly, and reflecting policy impact on business behavior, the author argues that the commercial viability of CCUS technologies depend partly on the prices of carbon emissions which is set by government policy.

Adding further contribution to our understanding of CCUS technologies, the chapter also contains analyses of the costs and risks associated with different ways or options of CO_2 transport and geological storage, and, in particular, has emphasized the importance of proximity studies from sources (e.g., power plants, steel mills, cement factories) to sinks (e.g., oil reservoirs, deep saline aquifers, coal beds and the ocean) to enhance the integrity of CCS system. Here, research in China is glaringly in shortfalls.

The chapter ends with a warning: while the Paris Agreement sets a goal of limiting global temperature rise below 2 Celsius degrees by 2050; and CCUS technologies have an important role to play, yet the overall trend of CCUS is not very encouraging. Currently and globally, CCUS projects that have failed to reach an investment decision outnumber successful ones by a factor of 2 to 1 -- a sign that does not indicate rapid progress. To reverse the trend would require more policy support, finance and investments, advanced technologies and international cooperation.

CHAPTER 1

Pilot Projects on Carbon Permit Trading System in China Preliminary Assessment

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Abstract: A carbon emission permit trading system (ETS) is purported to give China a useful tool to realize its Paris commitment. Since 2014, seven pilot projects of ETS have been established to test its validity. If valid, China would scale up these projects to the national level by the end of 2017. This paper provides an independent assessment of these projects against the premises established for the pilots and future ETS system in China. Synthetic control method is used to evaluate the efficacy of these projects in carbon emission reductions. We find that success is limited and uneven among these projects, which warrants further examination of their underlying causes. We therefore suggest cautions in project expansion at the national level, and provide policy recommendations for improvement.

1 Introduction

Addressing climate change and reducing greenhouse gas emission has become the consensus of the world's major countries. Policy makers are employing or contemplating the use of market-based instruments for climate policy. In recent years, cap and trade has commanded most of the attention in discussions relating to climate change. A main theoretical attraction of Cap-and-trade is its potential to achieve emissions reductions at lowest cost than conventional, direct regulations such as mandated technologies or performance standards.

In October 2011, the National Development and Reform Commission (NDRC) designated seven provinces and cities—Beijing, Chongqing, Guangdong, Shanghai, Shenzhen, Tianjin and Hubei–as regional mandatory ETS pilots. Chinese government explicitly proposed to build their own nation-wide carbon emissions trading market by the end of 2017. While there is wide agreement among economists as to the potential advantages of market-based instruments, there is much debate as to whether cap-and-trade is the best policy option for China.

This article provides an overview and analysis of China carbon market after 3 years in operation. A background and design elements of the emissions trading scheme are introduced, along with comparison between 7 pilots in China. We use synthetic control method to evaluate compliance performance in regional level, and sector level in following work. Challenges existed in China carbon market are identified and policy recommendations to further improve the China carbon market are also provided.

The rest of this paper is organized as follows. The next section lays out the legislation of China cap-and-trade systems, and analyzes existing conventional forms of regulation. Section 3 then focuses on the actual implementation and market

performance of seven pilots. Section 4 introduces the evaluation of emission reduction achievements of seven pilots based on synthetic control method. The final section provides highlights of key conclusions from the analyses, main challenges and policy recommendations for the program to go nationwide.

2 Policy Overview

Theoretically, cap-and-trade scheme affects the total greenhouse gas emission by creating a market for emission permits allocated to individual emitters under an aggregate emission cap. The regulatory authority stipulates the total allowable quantity of emission (the cap), in doing so the level of scarcity of allowable greenhouse gas emissions is determined; total allowable emission then is divided into a certain number of emission permits which are allocated to individual emitters based upon certain rules. Recognizing difference in marginal cost of implementing the permits by different individual emitters, trading of permits is allowed and equilibrium price of the permits emerges. This equilibrium price provides a signal of the level of scarcity of the emission permits and can guide individual emitters (firms most likely) to choose between reducing GHG emission or increasing GHG emission, and technologies corresponding to their choices. Moreover, an effective cap-and-trade scheme achieves the set cap with minimum social cost.

Generally, an emitting source will buy additional permits if the market price of permits is less than what it would cost the emitter, at the margin, to bring emissions down to the level implied by its initial permit holding. Likewise, an emitter will sell permits if the price is higher than what it would cost to achieve the additional reductions made necessary by the sale of permits. Every permit purchase by one entity corresponds to an equal reduction in the permit held by the selling entity. Thus, permit trading does not affect total allowable emissions because they do not alter the total number of permits in circulation.

2.1 Legislation Basis

In 2009, China pledged to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40% to 45% from the level of 2005. On 1st December 2011, China suggested in its "Twelfth Five-Year Plan for the National Economic and Social Development" for the first time to "gradually establish a carbon emission trading market" as a way to control greenhouse gas emissions. The "GHG Emission Control Work Schedule for the 12th Five-Year" specifically pointed out "to carry out carbon emission trading pilot" and "to develop China's overall program for carbon trading market." This indicates that China's carbon trading policy will follow the principle of "first pilot at local level, then scale-up". In October 2011, "Notice on Conducting Carbon Trading Pilots" by NDRC confirmed the first 7 designated pilots. The pilot

provinces and cities established institutional basis for carbon trading and officially launched trading during 2013-2014. On the basis of the pilot experience, China will accelerate the construction of the national carbon trading market and strive to put it in operation in the end of 2017.

The legal basis of the policy is an important prerequisite for the successful implementation of the policy. In order to create the companies' demand for emission permits and to stimulate their enthusiasm and confidence to participate in the carbon market, it is important that the government administrative departments can legally impose mandatory punishments in companies that do not comply with reporting, trading or compliance rules. Therefore, legal documents that give administrative departments the legitimacy to impose punishments are a key component of establishing an emission trading scheme. Legal authorities listed in Table 1 have different weights in effectiveness - some are resolution passed by the local People's Congress Standing Committee, while others are government orders. In addition to legal tools, some pilot also used administrative methods such as confiscation of the next year permits, as well as public shaming to promote enterprises' compliance efforts.

Tab.1 Legislation of the Carbon Trading Pilots

Region	Legal Documents
Beijing	"Beijing Municipal People's Congress Standing Committee - Resolution on Beijing to Carry out Carbon Trade Pilot under the Premise of Strictly Controlling Total Carbon Emissions"
Shanghai	"Shanghai Carbon Emission Management Interim Guidelines" (Shanghai Municipal People's Government Order No. 10, November 18, 2013)
Guangdong	"Guangdong Province Carbon Emission Management Interim Guidelines" (Guangdong Provincial People's Government Order No. 197, January 15, 2014)
Shenzhen	"Regulation on Carbon Emission Management for the Shenzhen Special Economic Zone" (approved by the Shenzhen Municipal People's Congress on December 30, 2012)
Tianjin	"General Office of Tianjin Municipal People's Government – Notice on Issuing the Interim Measures on Carbon Emission Trade in Tianjin"
Hubei	"Hubei Province Carbon Emission and Trade Management Interim Measures" (Hubei Provincial Government Order 371, April 23, 2014)
Chongqing	"Chongqing Carbon Emission and Trade Management Interim Measures" (approved by the Chongqing Municipal People's Government 41st Executive Meeting on March 27, 2014)

2.2 Operating mechanism

China embarks on building a carbon trading market from scratch to reduce greenhouse gas emissions. The science, rationality and effectiveness associated with the system design are critical for the success of the pilot and of the future national carbon market. In addition to learning from existing markets including the European emission trade scheme (EU ETS) and the Regional Greenhouse Gas Initiative (RGGI) in the United States, China also studies its actuality in-depth and established a locally appropriate market. Overall, carbon trading policy in China's seven pilots has the following characteristics:

－Executive entity: mostly local Development and Reform Commission, mainly by its department in charge of resource, environment and energy. Local finance bureaus and other departments provide support to the implementation.

－Industries regulated: basically all energy intensive industries are covered including electricity, steel, cement, chemicals in the pilot trading scheme. Beijing, Shanghai and Tianjin also included building and service industry.

－Emission scope covered: Most pilots cover both direct and indirect emissions, but there are some differences in the specific definition of indirect emissions - some only account for the consumption of purchased electricity, while others cover consumption of purchased electricity and heat. Hubei trades direct emissions only.

－Government intervention: government intervention on the carbon market includes mostly emission data collection, emission permit allocation and auction, and intervention on market price when necessary. For example, Beijing, Shanghai and Shenzhen clearly put forward market conditions and methodologies to regulate prices for emission permits

－Permit allocation methodology: all pilots adopted the historical emission method to allocate permits, while benchmarking method is used for new facilities or certain industries. Guangdong, Shenzhen and Hubei conducted auction for emissions permit allocation. Other pilots generally distributed permits free of charge.

－Regulation on the use of carbon emission reduction credits: all pilots recognize China Certified Emission Reductions (CCER) approved by NDRC or other types of emission reduction credits other administrative authorities for trading. Yet certain regulations are made for ceiling amount and conditions for usage. For example, Beijing and Guangdong required respectively that 50% and 70% of carbon reduction credits are generated locally in the region.

－Transaction Threshold and Reporting Threshold: The pilots also set market access conditions for companies involved in the trading scheme and announced thresholds of emissions reporting for other large emitters that haven't yet been covered by the trading system (referred as "reporting companies"). The reporting companies need to

report their annual emissions to the government every year so the latter could determine whether they should be included in the future carbon trading scheme or not. The emissions of companies involved in carbon trading (referred as "emission control companies") account for about 60% of total regional emissions in Guangdong and Tianjin, and for more than 40% in other pilot regions.

Fig.1 "Transaction Threshold" and "Reporting Threshold" in Seven Pilots
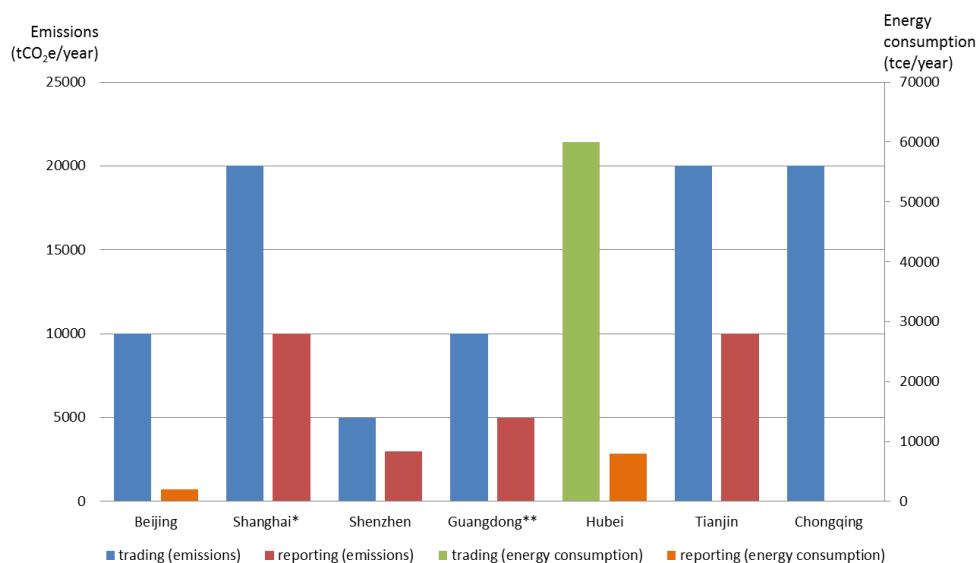
3 Implementation and Market transaction

The effectiveness of emission trading pilots relies not only on institutional design but also on the actualities in policy implementation. Table 2 lists indicators associated with performance of the carbon trading policy. Overall, in the existing system design, all procedures for the carbon trading including permit distribution, emission data collection, punishment enforcement and issuance of certified carbon emission reduction credits have been completed successfully, although there are flaws in the system.

Tab.2 Implementation of China Seven Carbon Emission Trading Pilot

Activity				
Licensing, permitting and procurement function	Indicator	Responsible Institution	Data Source	Status

Allocate permits to companies from time to time	Total amount of permits allocated by the government	Local Development and Reform Commission (DRC)	Local DRC Website	The ETS pilots allocated 2013 and 2014 emission permits on time (about respectively 730 million tons and 1285 million tons in total)
Information collection and tracking function	Indicator	Responsible Institution	Data Source	Status
Collect emission control companies' emission reports and third-party verification reports based on accounting and reporting rules	Number of emission reports and verification reports collected	Local DRC	Local DRC Website, Interviews with ETS staff	Collected emission reports and third-party verification reports from 1736 emission control companies in the five pilots that came to operation in 2013 (including 197 buildings in Shenzhen)[1]
Conduct sample checks on third-party verification reports	Number of verification reports checked	Local DRC	Local DRC Website, Interviews with ETS staff	No data found on sample check for verification reports
Collect and disclose information on trading volume and price	Whether regularly publish reports on trade volume and price	Local DRC, carbon trading exchanges in each pilot region	Carbon trading exchanges in each pilot region Website carbon K-line website	All carbon trading exchanges released complete information on trading volume and price except the one in Guangdong, which only announces data of the most recent trades
Collect and disclose information on the overall compliance	Whether timely announce the compliance rate	Local DRC	Local DRC Website	All pilots published reports on compliance of the previous year within 3 months after compliance cycle closure (Sino-Carbon Innovation and Investment Co. 2015)
Compliance and enforcement function	Indicator	Responsible Institution	Data Source	Status
Impose punishments on non-compliance companies for reporting or permit surrendering according to rules	Number of companies that are imposed with punishment	Local DRC	Local DRC Website, news report	14 companies were imposed punishment due to noncompliance. No data found on what kind of penalty was given.

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[1] 415 companies in Beijing, 191 in Shanghai, 184 in Guangdong, 114 in Tianjin, and 635 companies and 197 buildings in Shenzhen

Other policy administration activities	Indicator	Responsible Institution	Data Source	Status
Issue China Certified Emission Reduction (CCER)	Total CCER issued	Dept. of Climate Change in National Development and Reform Commission (NDRC)	China Certified Emission Reduction Exchange Info-Platform	As of January 14, 2015, a total of 13.72 million tons CCER has been issued
Intermediate effects				
Effects on behavior, technology and practice	Indicator	Responsible Institution	Data Source	Status
Emission control companies use carbon trading to adjust their operation and comply with requirements	Amount of emission permit traded	Carbon trading exchanges in each pilot region	Carbon trading exchanges in each pilot region	By June 30, 2017, a total of 114.58 million tons permits was traded
Emission control companies fulfill their compliance obligation through operation and production adjustment	Compliance rate (percentage of companies that surrendering sufficient permits in time)	Local DRC	Local DRC Website	Compliance rates for the 7 pilots in 2013 were: Beijing 97.1%, Shanghai 100%, Guangdong 98.9%, Shenzhen 99.4% and Tianjin 96.5%

(Summarize based on Local DRC website of Beijing, Shanghai, Shenzhen, Tianjin, Chongqing, Guangdong, Hubei).

Timely emission permit allocation is a necessary prerequisite for the carbon market to operate. Each pilot established its carbon emission registration e-platform to enable timely allocation of the 2013 and 2014 permits. Information on permit allocation was also announced at local DRC website. Guangdong, Shenzhen and Hubei conducted auction for emission permits. It should be noted that disclosure of data of government-allocated emission permits needs to be improved. For example, the Beijing Municipal Commission of Development and Reform did not formally disclose the exact data of its emission permits allocated in 2013 and 2014.

Accuracy and transparency of emissions data is an important basis for carbon trading. The role of the government is to collect and track data on corporate-level emissions, market-wide carbon trading and overall compliance situation. Currently, all governments in pilot regions require emission control companies to submit their emission reports and third-party verification report. In 2013, five pilot regions officially started launched the trading, and collected reports from 1736 emission control companies (including some building owners). Third-party verification report is required to be issued by the agency designated by the government to ensure the accuracy of emission data. Administrative authorities also regularly sample check the verification reports as an additional data quality control method. However, the pilot did not announce any information on the random checks of verification reports and,

therefore, the effect of this mechanism and the quality of these verification reports has to be further investigated. Announcement on transactions and compliance are mainly published on local DRC's website. All carbon trading exchanges released complete information on trade volume and price. All pilots published reports on compliance of the previous year within 3 months after closure of the 2013 compliance cycle. Information on market transactions and compliance is rather transparent.

Strict regulation and enforcement can encourage companies to pay attention to carbon emission limits and to actively participate in carbon trading. Pilot regions set different rules of punishments on companies failing to report or surrender permits according to the rules, including fines and urges for compliance. Later in 2013, Beijing and Guangdong imposed punishment respectively to 12 and 2 companies that failed to perform their obligations in time but did not release any data on what kind of penalty was given. Shenzhen urged 4 companies failing to surrender permits in time to complete their compliance operation before the extended deadline without giving penalty. Tianjin had 4 companies fail to perform the 2013 annual obligation in time but its Interim Measures did not include any penalty clause such as fines or deducting from future quota. Beijing and Guangdong are the most stringent with enforcement for non-compliance, while Shenzhen provides a certain grace period to urge companies to correct their non-compliance behavior. Enforcement in Tianjin is the weakest as no clear rules were set for penalties, resulting in lax attention or respect for carbon emission quota. It should be noted that there was no non-compliance in Shanghai in 2013, as when deadline was approaching (June 30) Shanghai DRC auctioned 580,000 tons emission permits that companies could buy and use for compliance – this is also a way to increase compliance rate. Overall, pilot regions mostly take the form of fines and other penalties to enforce carbon trade policies, while their actual enforcement strength varies. Some pilot region assisted companies to comply through granting grace period or auctioning additional permits. Enforcement could be weak when there were no punishment rules set, as in the case of Tianjin.

Intermediate effects of the carbon trading policy may be seen in participation of the emission control companies in the market. This study selected three indicators – active ratio, trading volume, and trading turnover to evaluate the intermediate effects of the carbon trading policy.

Tab.3 Trading indicators of seven pilots in China

Pilots	Starting date	Total trading days	Active ratio	Average price	Average trading volume	Average trading turnover	Share of total volume
Shenzhen	19-Jun-13	1003	90%	47	18604	612295	16%
Beijing	28-Nov-13	891	69%	50	7869	396690	6%

Shanghai	19-Dec-13	876	63%	25	11819	251740	9%
Guangdong	19-Dec-13	876	71%	26	34399	508819	26%
Tianjin	26-Dec-13	871	52%	22	3450	47261	3%
Hubei	2-Apr-14	806	96%	21	50163	988459	35%
Chongqing	16-Jun-14	752	18%	20	6644	30968	5%
Average		868	66%	30	18992	405176	-

Note: 1.Active rate = number of days that have trading volume/ Total trading days; 2 .Data source: http://k.tanjiaoyi.com/; 3. Statistical deadline is 30th June 2017.

Comparing compliance situation across the piloting regions, from its starting date to the ending date of the trading period, reveals that Hubei, Guangdong and Shenzhen ETS have more active trading than other pilots. From the perspective of secondary market performance, the design and operation of Hubei ETS is successful. Carbon trading is relatively active in Hubei: by June 30, 2017, Hubei ETS has sold 40.48 million tons of permits, with a turnover of 797.82 million Yuan. A complete price curve of carbon market is formed, with a minimum price of 28 Yuan and maximum price of 143 Yuan. By June 30, 2017, trading volume of seven carbon trading pilots reached 114.58 million tons. According to this study, among the seven pilots Beijing had the highest average price for emission permit - about 50 yuan/ton, followed by Shenzhen with 47 yuan/ton. The price for Shanghai, Chongqing, Hubei and Tianjin were approximately 20-25 yuan/ton. The active rate, average daily trading volume and turnover for Hubei all rank first among seven pilots. At the same time, Tianjin and Chongqing seems to be far behind the average level, reflected by fairly low market liquidity in the two places.

The low liquidity seems to be a big challenge for China's carbon market. In comparison, California carbon market had total of 62495 million tons of emission permit within one year compliance (from Jan 7th 2015 to Dec 24th 2015), and on a single day on January 21, 2015, trading volume surged to 10 million tons, the equivalent of 2/3 of China's total trading volume in all seven pilots[①]. Although the overall size of China's seven pilot carbon markets is substantial, companies were not enthusiastic in participating in carbon trading. It is mainly because of policy uncertainty after the trial period that most companies stayed cautious. In addition, emission control companies are often pressured by other existing energy conservation policy (e.g. key energy users need to complete their assigned energy saving targets) when carbon trade policy could no longer substantially influence corporate behavior.

[①] Source: http://calcarbondash.org/

In addition, trading occurred the most around June when the compliance deadline was approaching.

Fig.2 Historical Trend of Emission Permit Trading in the 7 Pilot Regions
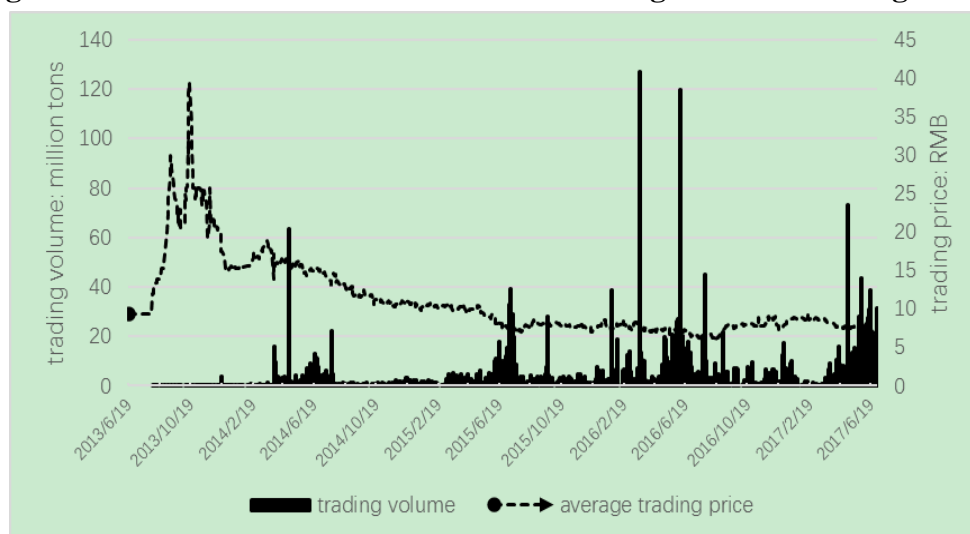
4 Emission Reduction Achievements

4.1 Method and Data

To estimate the effects of events or policy interventions that take place at aggregate level, researchers often use comparative case studies. In comparative case studies, researchers estimate the evolution of aggregate outcome (in this case, carbon dioxide emission) for a unit affected by a particular occurrence of the event and compare it to the evolution of the same aggregates estimated for some control group of unaffected units. However, it is difficult to estimate the emission reduction achievement of carbon trading because of the lack of solid control groups in this case.

Synthetic control method is used for effect estimation in settings where a single unit (a state, country, firm, etc.) is exposed to an event or intervention. The synthetic control method was firstly introduced and implemented in Abadie et al (2003) and Abadie et al (2011). Other comparative study includes investigating the economic impact of German reunification (Abadie 2015) and local impacts of nuclear power facilities (Ando M.,2015). There are also a series of research focusing on China. Liu and Fan (2013) examines the economic impact of China's house property tax pilot based on Chongqing Pilot, and Zhang et al (2016) uses this method to answer the question that "Did Olympic Games improve air quality in Beijing".

Our outcome variable of interest is annual CO2 emission, calculated based on energy consumption at the provincial level. We use annual provincial-level data of energy consumption during the period 1995-2015 from Provincial statistical yearbook. Since

seven carbon trading pilots officially went into effect one by one from late 2013, we mark 2013 as treated year. This gives us 17 years of pre-intervention data. Our sample period begins in 1995 because it is the first year for which data on energy consumption are available for all our control provinces. It ends in 2015 because newer data has not been published yet. Based on method proposed by IPCC, we calculate annual CO2 emission level for all provinces.

Take Hubei for an example. We construct the synthetic Hubei as a weighted average of potential control provinces, with weights chosen so that the resulting synthetic Hubei best reproduces the values of a set of predictors of CO2 emission in Hubei before the carbon trading system. Because the synthetic Hubei is meant to reproduce the CO2 emission that would have been observed for Hubei in the absence of carbon trading pilot, we discard from the donor pool provinces that adopted carbon trading system during out sample period. Therefore Beijing, Guangdong, Shanghai, Tianjin, Chongqing are excluded from the donor pool. Finally, our donor pool includes the remaining 24 provinces.

Using the techniques described above, we construct a synthetic for each of Hubei, Guangdong, Tianjin, Shanghai, Beijing, Chongqing that mirrors the values of the predictors of CO2 emission for themselves before the introduction of carbon trading system. We estimate the emission reduction effect of carbon trading pilots as the difference in CO2 emission between Hubei pilot and its synthetic versions after 2013. We then perform a series of placebo studies that confirm out estimated effects for carbon trading pilots are unusually large relative to the distribution of the estimate that we obtain when we apply the same analysis to the provinces in the donor pool. Then we repeat the work for Beijing, Shanghai, Tianjin, Chongqing, and Guangdong.

4.2 Results

As explained above, we construct the synthetic Hubei as the convex combination of provinces in the donor pool that most closely resembled Hubei in terms of pre-pilot values of CO2 emission predictors. The results are displayed in table 1, which compares the pretreatment characteristics of the actual Hubei with that of the synthetic Hubei, as well as other five pilots.

Tab.4 The society and economy characteristics of actual and synthetic seven pilot

	HB_real	HB_syn	BJ_real	BJ_syn	SH_real	SH_syn	TJ_real	TJ_syn	CQ_real	CQ_syn	GD_real	GD_syn
GDP	7862.2	7887.3	7172.3	5186.2	9186.0	9141.2	4385.7	3414.2	4029.2	4048.1	23489.4	17520.6
GDP_per	13703.1	13746.8	42862.0	17454.5	47094.2	21964.8	37534.3	14944.7	13678.4	13286.3	24596.6	24505.5
Population	5742.4	5759.0	1544.7	2108.6	1848.4	3309.1	1086.8	1979.9	2850.1	2860.6	9033.3	6532.9
Sec_rate	42.6	42.8	29.9	33.5	46.5	50.4	52.8	48.9	44.2	44.3	48.4	49.0

Note: sec_rate refers to the share of second industry in total GDP;

Tab.5 Synthetic weight for each synthetic pilot

Region	Hubei_weight	Beijing_weight	Shanghai_weight	Tianjin_weight	Chongqing_weight	Guangdong_weight
Anhui	0.036	0	0	0	0.027	0
Fujian	0.025	0	0	0	0.03	0
Gansu	0.019	0	0	0	0.047	0
Guangxi	0.033	0	0	0	0.031	0
Guizhou	0.025	0	0	0	0.042	0
Hainan	0.096	0.682	0	0	0.08	0.144
Hebei	0.026	0	0	0	0.02	0
Heilongjiang	0.018	0	0	0	0.034	0
Henan	0.045	0	0	0	0.015	0
Hunan	0.059	0	0	0	0.023	0
InnerMongolia	0.024	0	0.018	0	0.036	0
Jiangsu	0.057	0	0	0	0.012	0.856
Jiangxi	0.025	0	0	0	0.034	0
Jilin	0.017	0	0	0.566	0.04	0
Liaoning	0.024	0	0	0	0.026	0
Qinghai	0.013	0	0.352	0.381	0.301	0
Shaanxi	0.02	0	0	0	0.036	0
Shandong	0.027	0	0	0	0.01	0
Shanxi	0.017	0	0	0	0.039	0
Sichuan	0.322	0	0	0	0.02	0
Xinjiang	0.021	0	0	0	0.043	0
Yunnan	0.025	0	0	0	0.036	0
Zhejiang	0.029	0.318	0.629	0.052	0.02	0

Because social and economic characteristics vary substantially across provinces, different synthetic results emerge. Generally, the closer to the average level of whole country, the better synthetic result is. For example, Hubei, Guangdong, Tianjin have a better synthetic result than Shanghai, Beijing and Chongqing.

Figure 6 plots the trends in CO2 emission in Hubei and the synthetic Hubei. As this figure suggests, since 2013, CO2 emission in Hubei and synthetic Hubei differed notably.

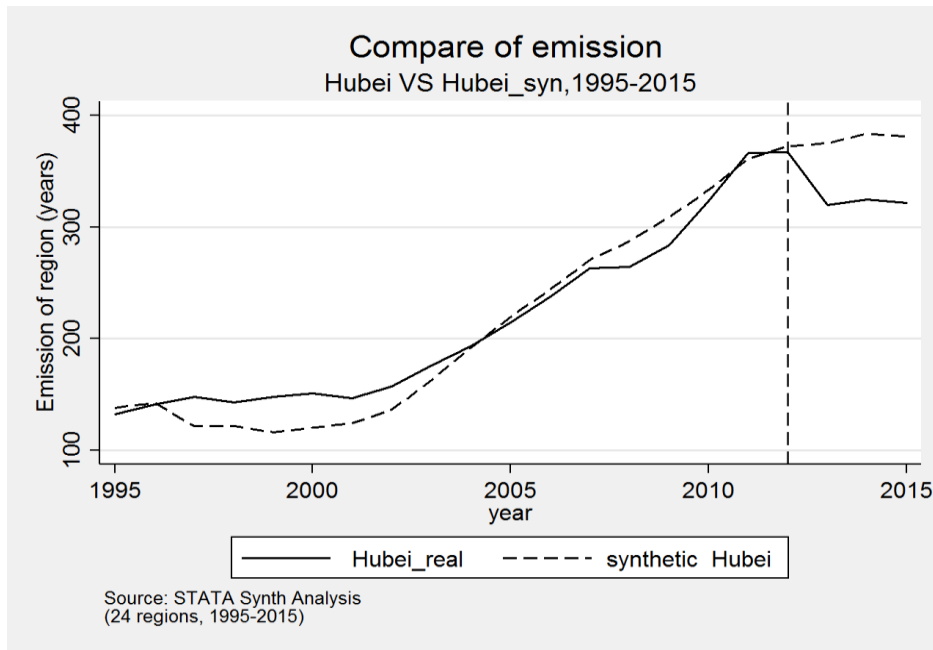**Fig.6 CO2 emission between synthetic Hubei and real Hubei**

Figure 7 shows that before 2012, the synthetic data fits the actual data quite well for Guangdong. After 2013, the gap between CO2 emission of Guangdong and that of the synthetic Guangdong emerges, which shows a deviation from the synthetic data.

Fig.7 CO2 emission between synthetic Guangdong and real Guangdong
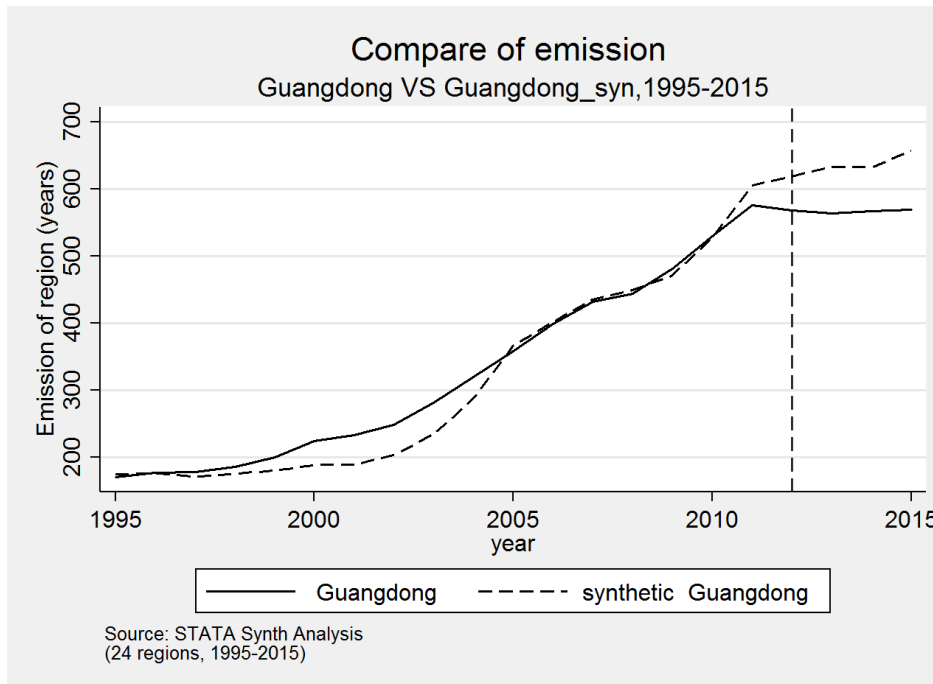
From the perspective of trading indictors, Hubei and Guangdong (including Shenzhen) have more active trading than other 5 pilots. The synthetic results support our expectation: more trading volume results in more emission reduction.

Figure 8 plots the trends in CO_2 emission in Tianjin and the synthetic Tianjin. As this figure suggests, since 2013, CO_2 emission in Tianjin and synthetic Tianjin did not differed notably. The result can be expected from the low liquidity of Tianjin trading market.

Fig.8 CO_2 emission between synthetic Tianjin and real Tianjin
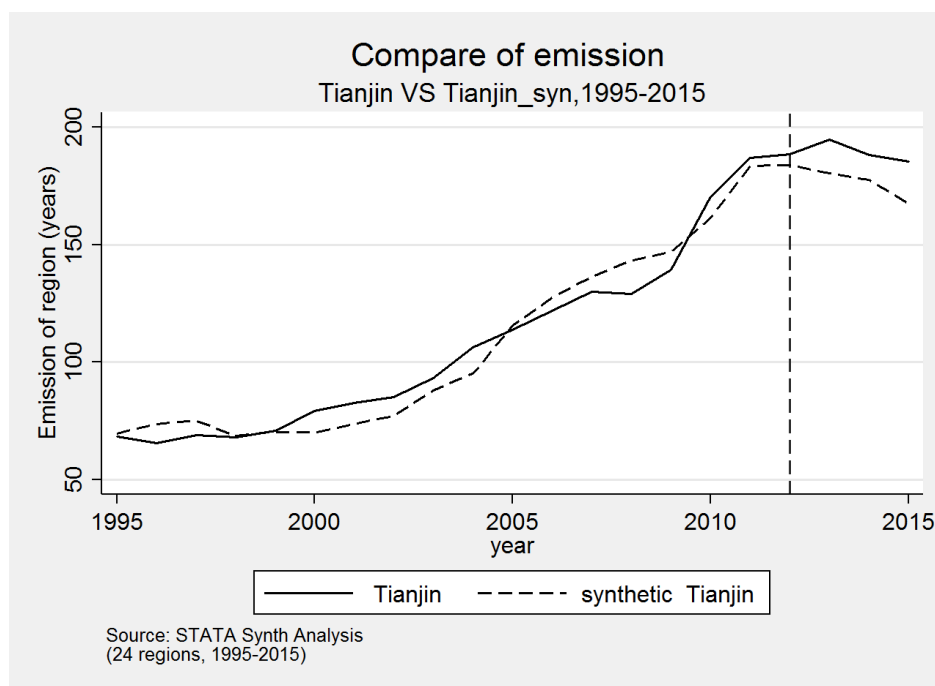
However, we cannot get a good simulation before 2013 for Beijing, Shanghai and Chongqing, their results are attached in Appendix.

4.3 Robustness test

First we will discuss estimation results for Hubei. The previously empirical result reveals a gap between CO_2 emission of Hubei and that of synthetic Hubei. The robustness check in this context is permutation test which is similar to rank test in statistics. The purpose is to test the statistical significance of our results.

For example, are there any other provinces among the donor pool shows a gap between CO_2 emission and synthetic CO_2 emission when these provinces are viewed as treatment group respectively? In other words, what is the probability of appearing the same large gap as Hubei province does? To answer these questions, we iteratively

apply the synthetic control method to estimate the impact of carbon trading pilot on every other province. Before doing this test, we need exclude the provinces that do not fit the original data before 2012 well. The gap after the treatment may not be caused by the treatment, but by the bad fitness before the treatment. Therefore, we exclude the provinces whose MSPE before 2012 are larger than 100. Finally, we obtain 22 provinces as potential control groups here.

Figure 9shows the results of permutation test. Each province is viewed as treatment group each time and the gap between CO2 emission and synthetic CO2 emission is drawn respectively.We find that Hubei province is below the zero line, which means the probability of estimating a gap of the magnitude of the gap for Hubei under a random permutation of the treatment in our data is 1/22. In other words, the previous result is statistically significant at 4.5% or so.

Fig.9 Placebo test for Hubei
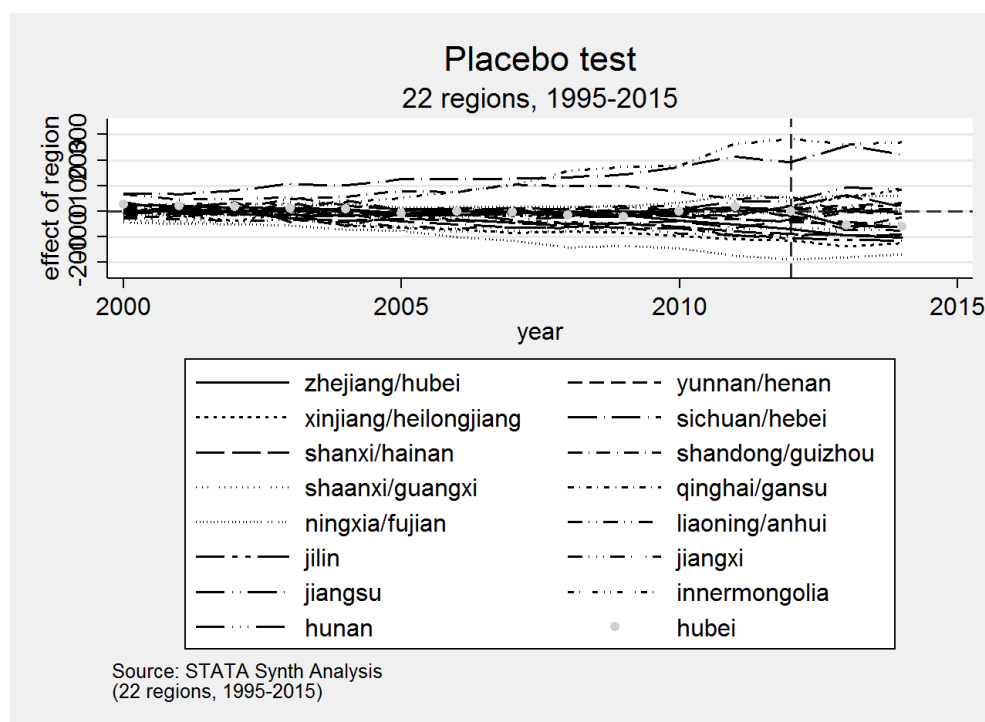
5 Discussion

5.1 Main Challenges:

Generally, China carbon trading market is not liquid enough to be well functioning.

The low trading activity in market and unenthusiastic transaction of companies make the volume and value of transaction remained at relatively low level. There are policy restraints (for example, cross- provincial trade is prohibited) on trading platform to make the market more liquid. This reduces the attractiveness of China carbon market to investors, especially the institutional investors.

The awareness of and participation in the carbon market of participating companies is still relatively low. The high volume in the month before compliance date shows that companies still treat the carbon emissions trading as a means of political cooperation rather than an investment opportunity. Carbon assets are not considered valuable for all companies.

Information disclosure needs more improvement. What information should and how it can be disclosed are tasks to be explored and completed step by step in the future.Our analyses revealed variable and limited success among the seven pilots. Hubei produced the best performance among all pilots. . Based on our synthetic result, Hubei has reduced about 59.47 million tons in 2015 due to the carbon trading scheme. Guangdong and Shenzhen also perform better, and they have reduced 37.06 million tons in 2015. However, Tianjin has done poorly during the pilot period.

Some preliminary explanations are handy. Hubei has been a province with a progressive environmental agenda. In 2009, a pilot program for converting pollution levy into environmental tax was launched in Hubei. Zheng (2015) has proved that this pilot significantly reduced domestic pollutions. This perhaps better prepared industries in Hubei for carbon trading scheme as well. Shenzhen has always been China's leading city in innovations in environmental protection. It was China' first city to realize its "Blue Sky: plan. The willingness to succeed in sustainable development by the city government and business world underpins success in its carbon trading program, which perhaps explain largely the success of Guangdong province. We cannot say we know what's going on in Tianjin. But the low trading volume just indicates that it is not ready to be an active player in carbon market.

5.2 Policy recommendations:

The limited indication of success from our assessment calls for caution when thinking of nationwide expansion. More and deeper evaluation should be conducted before any decision of expansion is to be made. Data transparency with regard to actual carbon emission is necessary to conduct such a deep evaluation and to improve transparency of the program implementation.

The limited achievement by the pilots triggers a more fundamental issue: the role of local government. It has been long argued that local government incentive has been the weakest link in China's environmental protection value chain, as the main pursuits of local governments are economic growth rather than sustainable development. An ordinarily designed ETS scheme will not be sufficient to alter local government

behavior when carbon emission permits are freely distributed. A main lesson has been that in the future a priced carbon permit should be tested. It might even be better if a carbon tax scheme can be tested as an alternative economic policy tools.

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<div align="right">**CHAPTER 2**</div>

Legal and Policy Frameworks for Low-Carbon Economy With Special Attention to CCUS Technologies

<div align="right">**CCUS Research Team**</div>

<div align="right">National Center for Climate Change Strategy and International Cooperation</div>

Contents

1. Industrial developments in China: brief review

1.1 Development status and trends of Chinese industrial sectors

Industry has developed rapidly in China with accelerated construction and industrialization since the reform and opening up. It has supported the high-speed development of national economy and continued enhancement of national strength. In 2011, China became the world's largest industrial country, topping the output of over 220 of 500 major industrial products. As China economy has entered the "new-normal" status in recent years, the industrial sector as a whole remains huge despite growth slowdown of industrial added value. In terms of industrial structure, the secondary industry has secured a dominate position until overtaken by the tertiary industry in 2012. In the industrial sector, labor-intensive industries and heavy industries advance along with accelerated urbanization and industrialization. Particularly, heavy industries, represented by automobiles, petrochemicals and heavy-duty equipment, have received government support at national and local levels since the mid-1990s. The ratio of light and heavy industries in China maintains 3:7 beyond the 11th Five-Year Plan (FYP) period, significantly higher than the current level and even the peak level of developed countries.

1.2 Development status and trends of Chinese iron/steel sector

The iron and steel industry is an important pillar of the national economy. China has been the world's largest iron and steel producer with leapfrog growth in iron and steel production since 1996. The crude steel production surged from 1.6 million tons in 1949 to 804 million tons in 2015, and increased at a high rate from 2000 onwards. Given the huge population base in the current stage of economic development, China's crude steel production per capita stays at a high level, though still lower than that of South Korea, Japan and other developed countries. In 2015, the crude steel production per capita reached 586 kg, 2.6 times the world's average. In contrast to crude steel production expansion, the capacity utilization rate fell from 88.7% in 2006 to 64.8% in 2015, implying serious overcapacity of the iron and steel sector. The product structure is dominated by low-end iron and steel products, such as building-used steel product, so the added value rate of China's iron and steel sector needs further improvement. Long-process production remain the mainstream in China's iron and steel production. The short process production accounts for only about 10% in China, but over 30% on average in the world. The proportion of electric arc furnaces (EAF) even exceeds 50% in the United States and other advanced countries.

Under the impact of the above-mentioned factors, China's iron and steel sector continues to reduce energy consumption and carbon emissions per ton of crude steel. In 2010-2015, the comprehensive energy consumption per ton of crude steel decreased from 605 to 527 kilograms of coal equivalent (kgce) and reached the international

forefront for leading iron and steel enterprises such as Bao Steel Group. Nevertheless, regarding energy consumption and carbon emissions per unit of steel production, China lags behind international leaders, due to the disparity of steel enterprises and structure of steelmaking processes. There are still significant gaps among domestic steel enterprises which are widely divided by facility scale, energy-saving technology, and product structure.

1.3 Energy consumption and carbon emissions in iron/steel sector

The National Center for Climate Change Strategy and International Cooperation (NCSC) has constructed a low carbon assessment model in order to calculate and forecast the energy consumption and carbon emissions of the iron and steel sector. Through analysis of different development scenarios, the model simulates the energy production and consumption and carbon dioxide (CO_2) emissions of the iron and steel sector in each year during 2016-2020 with 2010-2015 as the base years. The model framework is as shown below.

Figure 1. Assessment model for iron and steel sector
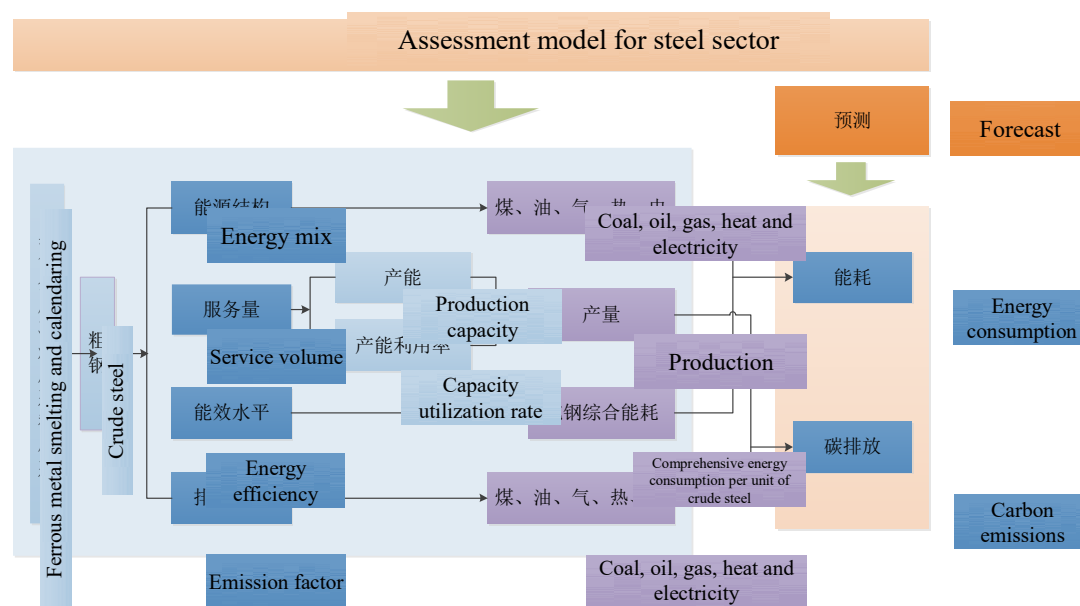
Based on the assumption that the intensity and quantity of national steel consumption will both decline in the 13th-Five-Year planning period, and taking into account the different change of such factors as the energy consumption per unit of crude steel, elimination of steel capacity and improvement of capacity utilization rate under the historical trend and national target requirement, two scenarios, i.e. the baseline scenario

and planning scenario, are set in this analysis. The China's crude steel energy consumption in the two scenarios is given as follows.

Figure 2. Historical change and forecast of energy consumption (100 million tons)
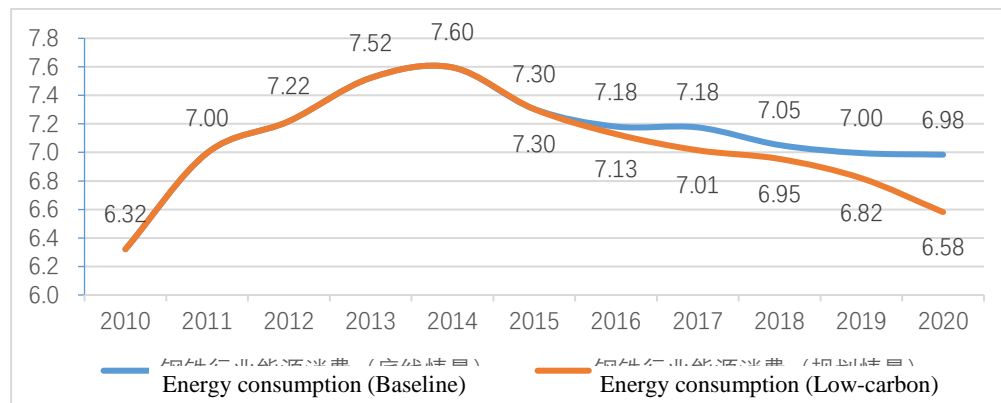
According to the related analysis and calculation, the CO2 emissions of China's iron and steel sector (including process emissions) peaked at 2.17 billion tons in 2013. If only the CO2 emissions from energy consumption in iron and steel sector is counted, it reached the peak level of 18.1 million tons in 2014. The future CO2 emissions of energy combustion in the iron and steel sector in two scenarios are shown as follows, considering such factors as steel production and capacity reduction, EAF utilization improvement, waste heat power generation alternative to coal-fired power generation, and expanded application of new low-carbon technologies.

Figure 3. Historical change and trend of carbon emissions (100 million tons)
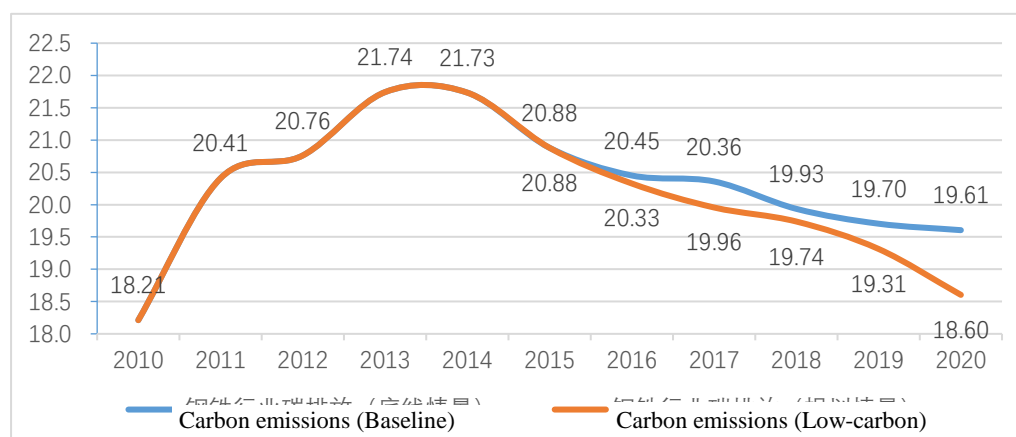
2. International and Chinese CCUS demonstration projects

2.1 International CCUS projects

According to the Global Carbon Capture and Storage Institute (GCCSI), there were a total of 38 large-scale integrated projects(LSIPs) [1] at the end of December 2016. Among them, 15 projects in the operate stage have captured more than 29 million tons of CO2. The LSIPs are mainly based in the United States and China, but for those in operate and execute stages are mainly based in the United States and Canada. From an industrial perspective, most of the LSIPs in the operate stage involve natural gas and coal-fired power plants, with only one related to the iron and steel sector.

The existing international demonstration projects still have mitigation potential as the generated emission reductions are far from expected to control global temperature rise below two degrees. According to the International Energy Agency (IEA), there will be a 50% chance to control the global temperature rise below two degrees by 2050 when the CO2 emissions are cut by 60% from the 2013 level and the emission reductions total 1,000 billion tons. By then, the CCUS-derived emission reductions will reach 6.1 billion tons, which implies an average annual increase of 50% from the current level of 2,9 million tons only. Besides, CCUS is currently used only mostly in natural gas and coal-fired power generation. As not yet deployed well in cement, steel and biotransformation industries, the potential to reduce emissions in the industrial sector remains to be further tapped. In addition, the investment in CCUS applications -- either from the government or the private sector -- is extremely limited and falls far short of demand. The control of global temperature rise below two degrees by 2050 requires an input of 2.2 trillion US dollars in the power sector and 1.3 trillion US dollars in the fuel switch sector, while the global cumulative investment registered only 19,000 US dollars during 2004-2013.

2.2 Chinese CCUS projects

China has made remarkable technological progress in CCUS in recent years. It has deployed systematically the basic research, development and demonstration on CCUS in terms of mitigation potential, carbon capture technologies, biotransformation, EOR and geological storage. China has designed and implemented a variety of CCUS projects that cover different emission sources, technological directions, and conversion and utilization modes. At present, there are about 12 CCUS demonstration projects built or under construction in the country. In terms of emission sources, half of these projects are targeted at coal-fired power plants, with the rest mainly focused on coal chemical projects, and none of them captured CO_2 from the iron and steel sector yet. In terms of

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[1] Large-scale integrated projects (LSIPs) are large-scale projects that integrate capture, transport and storage, which refer to projects with an annual capture capacity of 800,000 tons for coal-fired power plants and projects with an annual capture capacity of 400,000 tons for other emissions-intensive sources.

carbon transportation mode, tankers are supplemented by pipelines. In terms of treatment of carbon, most of them are EOR, the rest of them are industrial applications and saline aquifer storage.

Three findings can be given through the analysis. Firstly, there is a large demand and potential for CCUS demonstration project in China. According to the preliminary calculations and statistics, in the next 10 to 20 years, the annual carbon emission reductions due to CCUS is quite large and will exceed 10 million tons of CO_2 through conversion or utilization of CO_2 for the production of synthesis gas/ liquid fuel, synthesis of methanol and synthesis of carbon acid esters and polymer materials; and will reach about 500 million tons for EOR and synthesis of carbonate and inorganic materials. Secondly, the CCUS demonstration projects are still in the start-up phase in China and the related experiences are quite limited. As a whole, CCUS research, development and demonstration is in its infancy. The longest duration of carbon capture projects is only five years, and that for EOR and coal chemical projects only seven years. Most of CCUS demonstration projects were launched after 2008 and put into operation after 2010, of which the majority run for less than three years. Thirdly, the demonstration is not comprehensive, but rather concentrated in certain fields. After years of efforts, though China has laid a certain foundation for CCUS in all sectors, it's still lags behind from international leaders. Especially, the current demonstration projects mostly focus on carbon capture and EOR, and little cover geological storage, sequestration monitoring and early warning, and large-scale CO_2 transport and storage.

3. Low-carbon policy frameworks: comparative perspective

3.1. Foreign low-carbon policies

Low-carbon development, as the future trend of global development, requires the joint action of the international community. Currently, countries around the world have acquired valuable experience in the practice of green low-carbon development, embodied in the following aspects:

(1) Highlight overarching design and develop low-carbon strategy. Although low-carbon development was not long proposed, the major countries and regions are gradually incorporating this concept into the national mainstream development strategies. A number of countries have developed macro-strategies and roadmaps that pave a solid foundation for accelerating low-carbon transformation and promoting medium and long-term low-carbon development. For example, Britain has integrated low-carbon development into the national overall strategy and taken a series of policy measures. Japan has considered low carbon in the strategic planning in energy, economic and social fields in early 21st century. The European Union has launched an energy and climate package, including the amendment to the EU emissions trading system (EU ETS), decision of supporting task assignment for EU member

states, CCUS legal framework, renewable energy directive, legislation on automotive CO2 emissions, and fuel quality directive, and drawn the roadmap to promote the development of low carbon technologies.

(2) Enhance implementation safeguard measures and improve laws and regulations. Legal or policy documents set out specific targets for low-carbon development, and on this basis, policies of investment, price and tax incentives are introduced to ensure the realization of these targets. The Comprehensive Climate and Energy Package, adopted by the European Union in 2009, made it clear to raise the share of renewable sources in EU energy consumption to 20% and the share in energy consumption of the transport sector to 10% by 2020 and cut the greenhouse gas (GHG) emissions by 20% from 1990 levels, and set out binding national targets for renewable energy, emissions trading system and CCUS application. The *Act on Promotion of Global Warming Countermeasures*, enacted by the Japanese Government in 1998, clearly stipulated that the control of carbon emissions target is the shared responsibility of governments, business operators and the general public.

(3) Introduce taxation policies and encourage innovative mechanisms. Many countries roll out policies and incentives in favor of low-carbon innovation in the whole society, which has injected new vitality to global low-carbon development, covering enterprise development model, energy supply and utilization, industrial upgrading, and financial investment. In 2001, Britain introduced the Climate Change Levy on energy use in industrial, commercial and public sectors. Germany widely uses such fiscal policies as subsidies, incentives, tax breaks, and through *Renewable Energy Sources Act*, guarantees the feed-in tariff for renewable energy sources over 20 years and provide financial support. Japan's taxation policies in favor of low-carbon development include tax system reform, preferential rate loans and subsidies, and incentives to environmental protection investment.

(4) Make flexible adjustments and use market mechanisms. Countries around the world have come to realize that government-led or technical means solely are difficult to achieve carbon reduction targets and market mechanisms are conducive to scientific and technological innovation and broad mitigation action. Lunched in January 2005, EU ETS is the largest inter-national, multi-sectoral GHG emissions trading system. In addition to emission trading schemes, the market mechanisms to mitigate climate change include the Renewable Portfolios Standards as in Britain, Australia, Italy and the United States and the Energy Performance Contract as in the United States, Canada, Europe and India.

(5) Strengthen standards and push for scientific and technological progress. Policy instruments are highly valued in promoting the development of low-carbon technologies. The technological innovation system is combined with leading standards to stimulate scientific and technological innovation. In the United States, the carbon emissions standards for new power plants in the *Clean Power Plan* undeniably gave a strong impetus to mitigation in the power supply sector and pushed forward low-carbon

technologies, though overturned by the incumbent President Trump's executive order. The British Government starts from institutional mechanisms to encourage innovation in low-carbon technologies. It continues to adjust the focus of policy support and increase the financial support year by year by channeling the Environmental Transformation Fund and other traditional funding sources in the field of environmental protection, which covers a series of new key low-carbon technologies, such as smart grid, renewable energy, CCUS, electric vehicles, energy-efficient buildings. Recognizing the importance of low-carbon technologies, the Japanese Government focuses research on nuclear power, renewable energy and clean fossil energy utilization and carries out research and development projects for renewable energy and energy efficiency, fuel cells, distributed energy network systems, and CCUS applications. The massive medium- and long-term plans for technological research, development and demonstration, involving huge financial investment, have yielded remarkable results.

3.2. Chinese low-carbon policies

China has made unremitting efforts to tackle climate change and promote low-carbon development. Low-carbon development has been identified as a major strategy for climate change adaptation and mitigation and economic and social transformation and considered as a major opportunity to accelerate the change of economic development patterns for economic restructuring and industrial transformation. The policies and targets for low-carbon development rely on the existing climate change policy system and environmental and energy management systems. They have gradually formed a full-fledged system that encompasses laws and regulations, administrative orders, economic incentives, market mechanisms and pilot projects. This system provides all-round, deep-level guidance and paves a solid foundation for low-carbon development.

(1) Improve legislation for top-level design. As a code of conduct to adjust power relations and social relations, laws not only provide legal protection but also establish the top-level design for low-carbon development. In China, there currently are about 30 laws and 90 regulations pertaining to low-carbon development and special laws and regulations under preparation and amendment to address climate change and low-carbon development. The National Leading Group for Climate Change Legislation was set up in 2011, comprised of the Environmental Protection and Resources Conservation Committee and the Law Committee of the National People's Congress (NPC), the Legislative Affairs Office of the State Council, and 17 ministries. In particular, the National Development and Reform Commission (NDRC) spearheads legislative research, survey and drafting, and expedites the legislative process of the *Climate Change Law* and the *Administrative Regulations on Carbon Emissions Trading*. Many cities have presented local legislation to address climate change and low-carbon development and explored legislation on climate change and emissions trading. *China's National Plan on Climate Change (2014-2020)* put forward targets for emissions control, low-carbon pilot and demonstration, climate change resilience, capacity

building and international cooperation. In the sectors of energy, industry, building and transport, special plans have been formulated to address climate change, or provisions drawn from energy conservation and emissions reduction plans of other sectors. China's planning framework for climate change and low carbon is as shown in Figure 4. In addition, China presses ahead with low-carbon transition under the framework of national policy of ecological civilization construction. It takes low-carbon development as a basic way to accelerate the construction of ecological civilization.

Figure 4. Climate change planning by sectors
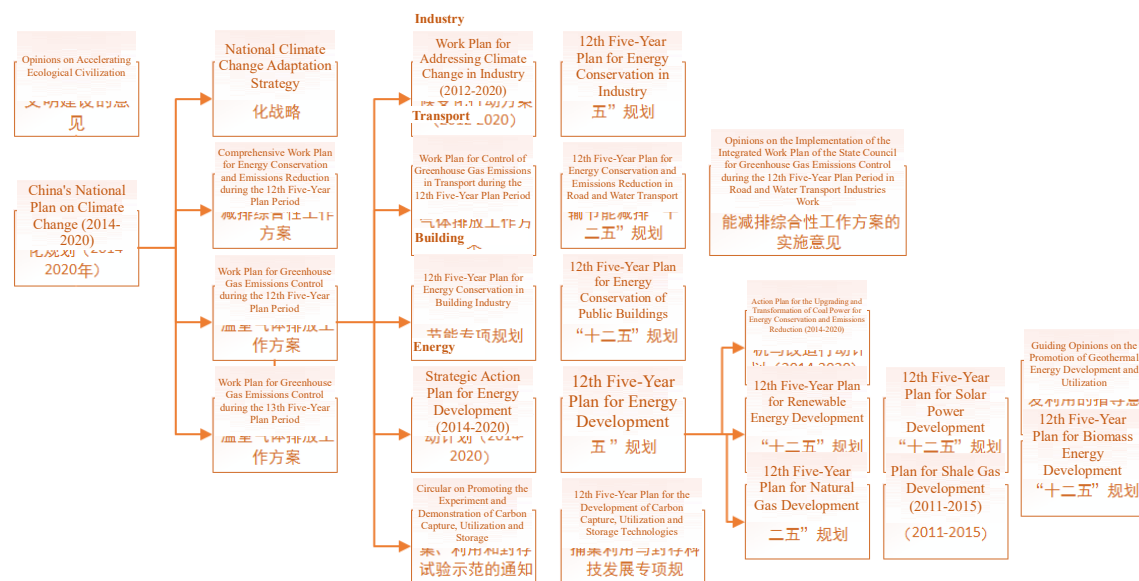
(2) Apply executive orders for low-carbon management. Herein administrative orders refer to mandatory orders for energy conservation and emissions reduction of government agencies, enterprises, individuals and the whole society. The policy instruments include mandatory standards and industry thresholds, with measures specific to backward production capacity elimination, transportation, construction and green government procurement. During the 12th FYP period, the 100 Energy Efficiency Standards Promotion Program was implemented for two consecutive phases, which witnessed the approval and release of totally 221 national standards for energy efficiency. In 2015, the Standardization Administration of China (SAC) approved and issued 11 national standards for GHG emissions in such key industries as power generation and steel production, and the Ministry of Transport, National Railway Administration, and State Forestry Administration promulgated respective standards for low-carbon development. NDRC provided the accounting methods and reporting guidelines for GHG emissions in 23 key industries and another industry in three batches. The National Technical Committee on Carbon Management, established with SAC's

approval, is responsible for formulating and revising national standards for carbon management and building the system framework for national GHG management standards. In 2015, a unified low-carbon product certification system took shape with the introduction of *Administrative Measures for Certification of Low-carbon Energy-efficient Products*. Totally seven kinds of products have been listed in the *Low-carbon Product Certification Catalogue*.

(3) Strengthen economic incentives to provide financial support. Economic incentives mainly encompass price instruments and financial support funds. There are a wide range of financial support funds associated with low-carbon development. The funds are sourced from the central and local governments, including special fund for renewable energy development, incentive fund for energy management contracting, subsidies for building energy efficiency, and special fund for energy conservation and emissions reduction. Funds can be put in place before the implementation of projects, such as support funds for cleaner production, recycling economy and energy conservation, or after the implementation of projects, such as provincial and municipal contributions to low-carbon pilot. In terms of form, there are subsidies for project investment, incentives instead of rewards based on results, public investment of government agencies in low-carbon management, clean development mechanism fund, and financial support for repayment.

(4) Encourage market mechanisms to increase market vitality. The Outline of the 12th Five-Year Plan first proposed "gradually establishing a carbon emissions trading market", in order to actively make use of market mechanisms and explore the control of GHG emissions at low cost. Later, NDRC decided to carry out the carbon emissions trading pilot in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen. At the end of 2015, the carbon market opened in the seven pilot areas. With the preparatory work from 2014 onwards, the national carbon market will start in 2017.

(5) Conduct pilot and demonstration, and sum up practical experience. China continues the low-carbon pilot and forms an all-round multi-level system for low-carbon pilot which encompasses provinces (cities), industrial parks, communities, districts (towns). A total of 86 low-carbon pilot areas have committed or intend to peak carbon emissions. The pilot work plays an active role in the national response to climate change and low-carbon development. All pilot provinces and cities have drawn the GHG emissions inventories. In addition, China actively carries out CCUS experiment and demonstration and low-carbon transport system construction. Issued by NDRC in 2013, the *Circular on Promotion of Experiment and Demonstration in Carbon Capture, Utilization and Storage* promotes and guides CCUS experiment and demonstration.

Table 1. China's low-carbon policy system

	Laws and regulations	Administrative orders	Economic incentives	Market mechanisms	Pilot and demonstration
Policy instruments	Laws (approximately 30) Regulations (about 90)	Compulsory standards Mandatory tasks Industry access systems	Price instruments Financial support funds (investment subsidies, loan discounts, replacement subsidies with rewards)	Carbon emissions trading Pilots Certified emission reductions trading	Low-carbon pilot in provinces and cities, parks, communities, towns, and other demonstration projects
Important content	Energy conservation law Renewable energy law Climate change law	Elimination of backward production capacity Green procurement Low carbon identification and certification Energy conservation and low carbon action for 10,000 enterprises	High energy consumption industry differential price Low-carbon special funds Energy - saving emission reduction fiscal policy comprehensive demonstration funds Clean Development Mechanism	Administrative measures for certified emission reductions trading Emissions trading pilot in seven provinces and cities, pushing to establish a national carbon market	6 low-carbon provinces and 36 low-carbon cities, 51 national low-carbon industrial parks, 8 national low-carbon districts (towns), and about prospective 1,000 low-carbon communities Low-carbon transport and CCUS pilot and demonstration

3.3 China's low-carbon policies for industrial sectors

3.3.1 Overview

Industry sector, a major energy consumer and carbon emitter in China, accounts for about 70% of the national energy consumption and carbon emissions. It is therefore urgent to change the model of industrial development towards low-carbon path. Industry-related low-carbon policies implemented during the 12th FYP period are summarized in this study, which include 10 plans, 9 programs, 13 opinions, 6 notices, and 8 decisions, measures and guidelines. They are divided into six categories: structural adjustment, standard development, regulatory instruments, economic incentives, market-based instruments and policy guidance, as shown in the table below.

Table 2. Categories and highlights of low-carbon policies for industry

	Structural adjustment	Standard development	Regulatory instruments	Economic incentives	Market-based instruments	Policy guidance
Policy instruments	Plans, programs, opinions, decisions and other documents released by the State Council, NDRC and MIIT	Two product promotion catalogues involving 13 batches of products and seven cleaner production evaluation indicators released by NDRC and MIIT	Administrative regulations and departmental rules promulgated by the State Council, NDRC and MOF	Administrative regulations and departmental rules promulgated by the State Council, NDRC and MOF	Administrative regulations, departmental rules and local rules promulgated by the State Council, MIIT, NDRC and local governments	Administrative regulations, departmental rules and local rules promulgated by the State Council, MIIT, NDRC, and local governments
Policy highlights	Inhibition of the fast growth of energy-intensive and high-emission industries Elimination of backward production capacity Adjustment of energy consumption structure Production capacity replacement Increase of the proportion of services and strategic emerging industries Industrial transformation and upgrading	Energy consumption caps and energy efficiency standards for products Promotion of energy-saving low-carbon technologies Development of cleaner production indicator system for key industrial sectors	Decline in total industrial energy consumption Energy efficiency and low carbon action for 10,000 enterprises, energy conservation and emissions reduction targets and tasks Elimination of backward production capacity Control of energy-intensive projects Implementation of caps on energy consumption per unit of product Special funds for energy conservation and emissions reduction	Differential prices and punitive prices Preferential policies concerning special funds, income tax, tariff and value added tax (enhance technological research and development, promotion and application, as well as introduction for renewable energy utilization, energy conservation and emissions reduction in the industrial sector implement energy management contracts)	Carbon emissions trading market construction Electric power system reform and market construction	Measures for technology promotion and management Transformation and upgrading projects guidebook Special actions and demonstration projects National pilot low-carbon industrial parks to guide and promote low-carbon development

3.3.2 Evaluation

The industrial development policy during the 12th FYP period aims at transformation and upgrading towards a resource-saving and environment-friendly industry and rests on energy conservation and emissions reduction to change development mode and adjust industrial structure. Vigorous efforts have been made to advance technological transformation and promote new energy-efficient and eco-friendly technologies, facilities and products. With the establishment of a sound work system for energy conservation and emissions reduction, remarkable results have been achieved in low-carbon development. First, the industrial structure continued to optimize as the proportion of energy-intensive industries declined and that of high-tech industries increased. In 2015, energy-intensive industries accounted for 27.8% of the added value of enterprises above the designated scale, down by 2.5% from the 2010 level. High-tech industries grew rapidly and took up a larger proportion. The average annual increase of added value hit 11.4% since the 18th CPC National Congress, 3.4 percentage points higher than that of enterprises above the designated scale. The percentage in the added value of enterprises above the designated scale reached 11.8% in 2015, up by 2.9 percentage points from the 2010 level. Second, a large amount of backward production capacity has been removed during the 12th FYP period, including 90.89 million tons of iron, 94.86 million tons of steel, 2.05 million tons of electrolytic aluminum, 657 million tons of cement (clinker and grinding), and 169 million weight cases of flat glass. Third, industrial energy efficiency was significantly improved. The energy consumption per unit of added value of enterprises above the designated scale dropped by 28%, representing 690 million tons of coal equivalent energy savings, while backward production capacity was eliminated more than tasked during the 12th FYP period. Particularly, the six major industries (steel, nonferrous metals, petrochemicals, chemicals, building materials and paper) narrowed the gap with the international advanced level by drastically cutting energy consumption per unit of product.

3.4 China's low-carbon policies for iron/steel sector

3.4.1 Overview

China's iron and steel sector started the work in energy conservation and emissions reduction in the early 1980s. It placed focus on leakage control, publicity and education, and institution and team formation, and carried out energy conservation of individual facilitates and processes in that period. During the 7th FYP period, attention was shifted to the overall energy efficiency while modern energy management was highlighted. The energy management system became independent of the enterprise management system. During the 9th FYP period, the iron and steel sector continued to emphasize on the transformation for energy conservation and development and application of energy-saving technologies and equipment, and introduced economic value into energy management. In the next five years, a number of policies were unveiled concerning energy efficiency and emission control of the iron and steel sector, which require

controlling total iron and steel output, curbing blind capacity growth, removing backward production capacity, and expediting structural adjustment. During the 11th FYP period, China for the first time included energy intensity in the five-year plan for national economic and social development. It put forward binding targets for energy conservation and energy efficiency and took proactive measures to adjust economic structure, change economic development mode, inhibit energy-intensive industries, and promote low-carbon energy. In the 12th FYP period, carbon intensity was integrated into the five-year plan for national economic and social development, and emissions control became an important consideration of industry, including the iron and steel sector.

A total of 36 key policies were rolled out for the iron and steel sector since 2006, including 12 during the 11th FYP period, 17 during the 12th FYP period and 7 during the 13th FYP period. They are classified into five categories: structural adjustment, industry standards, economic incentives, mandatory tasks, and guiding tasks, with highlights described in the table below. According to preliminary statistics, **structural adjustment** is addressed in many administrative regulations and departmental rules promulgated by the State Council, NDRC, and Ministry of Industry and Information Technology (MIIT). The policies focus on the control of production capacity by cutting excessive capacity, eliminating backward capacity, controlling new capacity and replacing capacity of the same or reduced amount, and on industrial concentration improvement through merger and reorganization, as well as demand structure improvement. **Industry standards** are embodied in the standards and specifications released by SAC, MIIT, NDRC and SAC, including integrated energy consumption standards and process energy consumption standards for existing, new and expansion enterprises, higher access thresholds and strict access requirements. **Incentive mechanisms** are put in place through administrative regulations and departmental rules promulgated by the State Council, NDRC and Ministry of Finance (MOF). They include tax incentives, subsidies to replace rewards, differential prices, punitive prices, and ladder prices, as well as carbon emissions trading scheme. **Mandatory tasks** are assigned through administrative regulations, departmental rules and local rules formulated by the State Council, MIIT, NDRC and local governments. Among them are the reduction of industrial energy consumption, control of industrial production, energy conservation and emissions reduction assigned to enterprises by central and local governments, as well as compulsory coal-to-gas and coal-to-electricity transformation in some areas. Assigned in the same way as mandatory tasks, **guiding tasks** aim to encourage industries and enterprises to carry out technological research, development and promotion, develop circular economy, conduct energy saving transformation and upgrading, and take measures for energy conservation and emissions reduction (including energy management system, supporting facilities, energy efficiency assessment and review). Industry policies of different highlights that mention such tasks also fall into this category.

Table 3. Categories and highlights of low-carbon policies for iron and steel sector

	Structural adjustment	Industry standards	Incentive mechanisms	Mandatory tasks	Guiding tasks
Policy instruments	Administrative regulations and departmental rules promulgated by the State Council, NDRC and MIIT	Standards and specifications released by SAC, MIIT and NDRC	Administrative regulations and departmental rules promulgated by the State Council, NDRC and MOF	Administrative regulations, departmental rules and local rules promulgated by the State Council, MIIT, NDRC, and local governments	Administrative regulations, departmental rules and local rules promulgated by the State Council, MIIT, NDRC, and local governments
Policy highlights	Concentration enhancement through merger and reorganization Production capacity control (including excessive capacity reduction, backward capacity elimination, and new capacity control) Production capacity replacement (including equal and reduced replacement) Demand structure improvement	Higher access thresholds and strict access requirements Integrated energy consumption standards and process energy consumption standards for existing enterprises Integrated energy consumption standards and process energy consumption standards for new and expansion enterprises National GHG management standards	Carbon emissions trading scheme Differential prices, punitive prices, and ladder prices Subsidies to replace rewards Tax incentives	Targets to reduce industrial energy consumption Production control targets Energy conservation and emissions reduction targets assigned to enterprises by central and local governments Compulsory coal-to-gas and coal-to-electricity transformation in some areas	Technological research, development and promotion Development of circular economy Energy saving transformation and upgrading Implementation of energy conservation and emissions reduction measures (including energy management system, supporting facilities, energy efficiency assessment and review)

3.4.2 Evaluation

During the 11th FYP period, the low-carbon related policy for the iron and steel industry centered on structural adjustment. It intended to improve the overall technical level and energy efficiency through production capacity control with a view to industrial optimization and upgrading. The specific policy measures included merger and reorganization to improve industrial concentration, inhibition of blind production capacity expansion and elimination of backward production capacity to control total steel production capacity, and relevant financial and economic means. Under the combined policy impact, the iron and steel sector phased out 122.72 million tons of backward iron production capacity and 72.24 million tons of backward steel production capacity over the five years. At the same time, large-scale modern facilitates were put into use. Among the key steel enterprises, the proportion of blast furnaces with a capacity of 1000 m^3 or more increased from 48.3% to 60.9% and that of converters with a capacity of 100 tons or more from 44.9% to 56.7%. A more rational industrial structure was conducive to energy conservation and emissions reduction. At the end of 2010, there was an overall improvement in the main indicators of key steel enterprises. The energy consumption per ton of iron fell to 605 kilograms of coal equivalent, down by 12.8% compared with 2005.

During the 12th FYP period, the policy for the iron and steel sector has undergone some changes under the realistic conditions of tightening energy and environmental constraints and strengthening low-carbon efforts. With more focus put on energy conservation and emissions reduction, carbon reduction stood out as a constraint. In the five-year plan for the steel industry, "low carbon" was identified as the principle and objective, and the target of a 18% reduction in carbon emissions per unit of added value was defined. To this end, the thresholds for access to the sector were further raised and strict thresholds set for the phase-out of facilities. The completion of binding targets for energy consumption and environmental projects was made necessary to project approval. It is noteworthy that there was no policy specific to the control of carbon emissions in the iron and steel sector despite the binding target for carbon intensity. From 2011 to 2015, the iron and steel sector phased out 90.89 million and 94.86 million tons of backward iron and steel production capacity respectively. However, overcapacity still existed and evolved from regional and structural excess into absolute excess. The crude steel capacity utilization dropped from 79% to 70% or so over the five years, and the debt rate of key large and medium-sized enterprises exceeded 70%. Meanwhile, though the energy consumption per ton of steel declined, such as from 605 kg to 572 kg, but this could not offset incremental energy consumption with growth in iron and steel production.

During the 13th FYP period, China adopts a more robust policy to resolve steel overcapacity, and begins to explore the practical policy for CO2 emissions control. In view of sluggish steel demand, serious excess capacity, and tight environment and energy constraints, the country elevates resolving the excess steel capacity into major decisions and arrangements of the CPC Central Committee and the State Council and

into the major tasks for supply-side structural reforms. It aims to slash the crude steel production capacity by 100-150 million tons based on an elimination of more than 90 million tons of backward production capacity. The production capacity that fails to reach certain standards will be withdrawn by a combination of different policies and measures, including laws, regulations and policies concerning environmental protection, energy efficiency, quality, safety and technology. At the same time, better incentives will be offered to encourage enterprises to cut capacity through active reduction, mergers and acquisitions, transformation and conversion, relocation and renovation, and international cooperation. To provide support and strengthen policy guidance, national ministries and departments including MOF rolled out eight special policy documents, covering rewards and subsidies, fiscal and tax support, financial support, employee relocation, land use, environmental protection, quality and safety. In order to ensure the implementation of capacity reduction tasks, a 25-member inter-ministerial joint conference system for iron and steel and coal overcapacity resolution and poverty alleviation has been set up with approval of the State Council. The relevant provinces and cities have formulated the work programs and clarified work arrangements, targets and tasks in the five years period. A total of 28 provincial-level people's governments and Xinjiang Production and Construction Corps have also signed the letter of responsibility for reducing excess capacity and eradicating poverty. In addition, the Chinese Government proposes low-carbon development as a basic approach of ecological civilization construction, and starts exploring policy specifically for carbon emissions control of the iron and steel sector. The national carbon emissions trading system to be launched in 2017 will cover such key industries as steel, electricity, chemicals, building materials, paper and non-ferrous metals, according to the 2015 China-US Joint Presidential Statement on Climate Change. Effectively control the carbon emissions of steel and other key industries is listed as a key task in the five-year plan for national economic and social development for the first time.

Among the low-carbon policies for the iron and steel industry, the structural adjustment policies that focus on production capacity control grasp the principal contradiction and the key issues of industrial development. The policy to cut production capacity provides a breakthrough to promote green low-carbon development. Also, it should be noted that the dedicated policy for carbon emissions control in the iron and steel sector remains absent and the supporting mechanisms are under preparation. Emission reductions are only a spin-off effect of industrial restructuring, energy conservation and energy efficiency improvement.

3.5 Policy recommendations on carbon reduction for China's iron/steel sector

<u>Attach importance to top-level design for low-carbon development.</u> Climate change adaptation and mitigation and low-carbon development become more and more important. Amid the growing demand for low-carbon transition, the traditional ideas and technologies of energy conservation and pollutant emissions reduction can not

completely represent and cover low-carbon development. At the national level, we should study and formulate a strategic plan that regulates and guides the low-carbon development of iron and steel industry by integrating binding targets for carbon reduction. Local governments should pay more attention to low-carbon development, reflect this priority indicator in the government performance evaluation, and establish an evaluation and examination system for low-carbon development. At the enterprise level, companies should change ideas and develop strategies oriented to low-carbon development. They are expected to refresh the traditional ideas in the pursuit of green development as social responsibility and obligation and compete for green low-carbon development not limited to cost efficiency.

Deepen industrial restructuring based on existing policies. First, the cost of steel product exports with low added value will be increased, while creating the conditions for research, development and production of high-end steel products. Second, the recovery and reuse of scrap steel will be strengthened. Support should be given to enterprises engaged in scrap steel recovery, processing and distribution based on advanced technologies. Given the current steel stock, the management of scrap steel recovery needs to be strengthened and in particular, the social steel recycling system should be improved. Changes needs to be made to promote technological upgrading for better scrap steel recovery and utilization, covering operating mechanism, equipment configuration, processing technology, product quality, and secondary pollution control.

Give full play to the regulation and guidance of standards for the iron and steel sector. First, the steel standards for downstream consumer industries will be raised through enhanced cooperation with building, automotive, machinery, vessels and home appliances industries, so as to adjust and upgrade product structure from the demand side. Second, industry standards should be improved, covering equipment, process energy consumption and steel performance and quality, and the implementation should be supervised more effectively. On this basis, product standards will be upgraded and refined, while sound industry standards are essential to industrial upgrading. Third, it is necessary to timely explore the carbon emissions standards for iron and steel industry based on the national GHG management standards and GHG emissions accounting methods and reporting guidelines, so that the standards can serve as both constraint and guidance.

Enhance capacity building to support the management of carbon emissions. First, enterprises are required to establish the support system and evaluation system for carbon emissions management, including carbon emission statistical monitoring system and emission database, and set up a special independent body to monitor pollutant emissions at any time. Second, the robust systems for the statistical monitoring, supervision, evaluation and examination of carbon reduction should be put in place. In addition, study, exchange and training should be maintained. Teaching materials should be prepared for carbon management in the iron and steel sector, and a variety of activities carried out for carbon reduction, including policy interpretation, experience extension, personnel training, exchange and cooperation at home and abroad. Experts

will be organized to provide enterprises with advisory services in carbon management, carbon emission trading, and mitigation technology application.

4. CCUS policy frameworks: comparative perspective

4.1 International CCUS policies

At present, many developed countries have laid down CCUS policies and strategies according to respective conditions. They amend or add laws to regulate CCUS development and carry out active exploration in supporting policies and measures, in order to promote CCUS projects and technologies.

(1) The strategic layout indicates the direction for CCUS development. The strategic planning in the fields of low carbon, energy and climate change clarifies CCUS's importance in tackling climate change and makes arrangements for the CCUS deployment. The *Green Paper: A European Strategy for Sustainable, Competitive and Secure Energy*, published by the European Union in 2006, identifies CCUS as one of the three policy priorities to address the root challenges of energy security and climate change. Further, the *European Strategic Energy Technology Plan* (SET-Plan) unveiled in 2007 proposes the use of a dedicated policy to accelerate the development and application of low-carbon technologies. In the United Kingdom, the Stern Review released in 2006 has laid the basis for CCUS development and the *Meeting the Energy Challenge: A White Paper on Energy* in 2007 put forward process-wide CCUS demonstration in power plants across the country. Released in 2006, the *U.S. Climate Change Technology Program* (CCTP) suggests controlling GHG emissions through carbon capture and storage.

(2) Advancing legislation provides a legal basis for CCUS development. The European Union has made significant breakthroughs in CCUS legislation. It has developed the world's first CCUS legislation *(Directive/2009/31 /EC of the European Parliament and of the Council on the GeologicalStorage of Carbon Dioxide*which stipulates the various aspects of geological storage, and adopted a series of detailed directives on all CCUS aspects. In the United Kingdom, the *Energy Act 2008* provides a framework for licensing, enforcement and registration of storage sites, and the world's first *Climate Change Act 2008* incorporates CCUS into the emission reduction plan for the power industry. The United States *Carbon Capture and Storage Early Deployment Act 2009* encourages the related industries to early deploy CCUS applications and the *American Clean Energy Leadership Act* released in July 2009 further clarifies the regulatory framework and financial assistance for CCUS development.

(3) The sound standard system regulates CCUS development and clarifies responsibilities and rights. Since CCUS is a complex technology involving multiple links and stakeholders, a standard system is needed to guide and regulate the CCUS

development and define the responsibilities and rights of interested parties. There are safety standards for carbon capture in the *EU Directive 85/337/EEC* and environmental standards in the UK *Pollution Prevention and Control Act* and the *Control of Substances Hazardous to Health Regulations*. In regard to carbon transport, Norway and the United States specifically develop the appropriate standards and the European Union's existing pipeline standards can be applicable. The United States is the only country to introduce regulations on interstate and state transfer of pipeline responsibility. As to carbon storage, detailed provisions can be found in the *Directive on the Geological Storage of Carbon Dioxide* of the European Union (EU CCS Directive), the *Guidelines for Carbon Dioxide Capture, Transport, and Storage* of the United States, and the *Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage* of Australia. In regard to monitoring and incident handling, the EU CCS Directive dedicates *Articles 13* and *Article 16* to leakage, and the *Recommended Practice: Design and Operation of CO_2 Pipelines* of Det Norske Veritas makes specific provisions for monitoring tools and content and incident response.

(4) Taxation means provide financial support for CCUS development. Internationally, the financial support for CCUS projects mainly include government subsidies, tax breaks, and investment from fund capital and private capital. In terms of fiscal policy, the EU's *Seventh Framework Programme for Research and Technological Development* (FP7) released in 2007 proposes funding projects related to carbon capture and sets aside 300 million EU ETS allowances to support 10-12 commercialized CCUS projects. In terms of tax policy, the *Climate Change Levy* stipulates that the UK electric power enterprises can enjoy an 80% tax relief as long as reaching certain targets for energy efficiency or emission reduction through CCUS applications. The *Section 45Q of the USA Internal Revenue Code* provides 20-dollar tax credit per ton of CO2 captured and stored, and 10 dollars per ton of CO2 captured and used for EOR.

Table 4. CCUS policies of major countries

Country	Policies and regulations	Highlights
European Union	Green Paper: A European Strategy for Sustainable, Competitive and Secure Energy (2006)	Identify CCUS as a preferred option to tackle climate change
	European Strategic Energy Technology Plan (SET-Plan) (2007)	Propose the adoption of specific policies to accelerate the development and application of low-carbon technologies
	Seventh Framework Programme for Research and Technological Development (FP7) (2007)	Fund CCUS projects and develop effective capture technologies
	Climate and Renewable Energy Package (2008)	Agree to finance CCUS projects and studies under the policy framework
	EU Emission Trading Scheme (2008)	Clarify CCUS' position in the scheme
	Directive 2008/1/EC (2008)	Rule the effects of carbon capture on the environment and human health

	CCUS Directive 2009/31 (2009)	Form the world's first detailed legislation on CCUS
United Kingdom	Meeting the Energy Challenge. A White Paper on Energy (2007)	Implement process-wide CCUS demonstration in power plants
	Energy Act (2008)	Set the legal framework for CCUS storage permits
	Climate Change Act (2008)	Identify CCUS as an important technical choice for the electric power industry
	Energy Act (2010)	Include provisions on agreeing and using CCUS technologies
United States	Climate Change Technology Program (CCTP) (2006)	Plan to control GHG emissions through capture and storage
	Bill for Regulation for Underground Storage of Carbon Dioxide (2008)	Update the *Safe Drinking Water Act* by including injection wells purely for carbon sequestration
	Guidelines for Carbon Dioxide Capture, Transport, and Storage (2008)	Stipulate that CCUS specifications should meet the requirements of *Clean Air Act* and *Clean Water Act*
	Carbon Capture and Storage Early Deployment Act (2009)	Stipulate that the related industries can collectively vote to set up CCUS research institutions
	American Clean Energy and Security Act (2009)	Dedicate a chapter to carbon capture and storage
	Regulations for Safe Actions on Carbon Storage Technologies (2010)	Regulate the specific implementation of CCUS projects
	House Bill to Include the Carbon Storage Act into the Legal System (HB259) (2010)	Provide the ownership of stored gas and responsibility transfer after CCUS projects are shut down
Australia	Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage (2005)	Establish a unified CCUS framework within the jurisdiction of Australia
	Offshore Petroleum and Greenhouse Gas Storage Act (2006)	Provide the legality of offshore storage of CO2

The above-mentioned developed countries have formulated policies to promote CCUS development at different dimensions, which largely recognizes the vital importance, regulates operating standards, and emphasizes the environmental impact. Nevertheless, there have not yet been perfect legal frameworks for CCUS development. In addition, the CCUS related policy and legal system is too vague to meet the requirements of government-expected large-scale commercial applications.

4.2 Chinese CCUS policies

China's CCUS-related policies are relatively vague and mostly provide macro guidance compared with those of developed countries and groups. China has published a total of 26 CCUS-related policy documents at the national level (including plans, programs, notice and opinions released by the State Council and ministries), including four CCUS specific documents. These policy documents can be classified into five categories:

technology promoting (19, promoting and guiding the development and progress of CCUS technologies), demonstration support (12, encouraging to accelerate CCUS demonstration projects), target setting (3, setting stage-specific CCUS development targets), and environmental management (2, providing regulation on potential environmental risks and impacts of CCUS projects), and others (1). Among them, certain policy documents may fall into several categories. In general, China takes a positive attitude to CCUS development by indicating technology development directions supplemented by uncompulsory targets, but the existing policies do not specify fiscal support.

As there are not yet dedicated laws and regulations in China for CCUS, CCUS projects are regulated by the existing legislation. Herein, the laws, regulations and rules that CCUS projects can follow or refer to are summarized, covering project approval, ownership recognition, project operation, environmental management, safety supervision, closure management (Table 5)

Table 5. China's existing legal and regulatory framework for CCUS projects

	Project approval	Ownership recognition	Project operation	Environmental management	Safety regulation	Closure management
Laws	Construction Law Tendering Law Administrative Licensing Law"	Property Law Land Management Law Contract Law	Capture: Production Safety Law Transport: Highway Law, Law on Protection of Oil and Gas Pipelines Storage and utilization: Mineral Resources Law	Environmental Impact Assessment Law Regulations Concerning Environmental Protection in Offshore Oil Exploration and Exploitation Law on Protection of the Marine Environment Law on Air Pollution Prevention and Control	Production Safety Law Labor Law Regulations on Work-related Injury Insurance General Principles of the Civil Law Tort Liability Law Criminal Law	Environmental Protection Law Marine Environmental Protection Law

Regulations	Administrative Regulations for Government Approval and Registration of Investment Projects Catalogue of ", Government Approved Investment Projects (2014) Decision of the State Council on Cancelling and Adjusting a Number of Items Subject to Administrative Examination and Approval	-	Transport: Road Transport Regulations	-	Projects: Regulations for Quality Management of Construction Projects, Regulations for Safety Production of Construction Projects, Regulations on Investigation for Administrative Accountability for Extraordinarily Serious Safety Accidents Carbon: Regulations for the Management of Hazardous Chemicals	-
Rules	Directory of Items Subject to Administrative Examination and Approval of the National Development and Reform Commission	-	Pressure Pipeline Regulations for Chemical Enterprises	Circular on Strengthening Environmental Protection of the Experimental and Demonstration Projects for Carbon Capture, Utilization and Storage Catalogue of Construction Projects for Classified Management of Environmental Impact Assessment	Regulation for Safety Management and Supervision of Pressure Pipelines Directory of Hazardous Chemicals Implementing Measures for Safety Permits of Construction Projects Involving Hazardous Chemicals	-

4.3 Policy recommendations for Chinese CCUS projects

Make regulation in key aspects to make up for the blank overall legal system. As shown in the table above, there are specific CCUS laws and regulations at all levels. (1) China has a complete set of project approval procedures as reflected in the appropriate laws, regulations and rules, but the approval of CCUS projects is not specified. (2) China has confirmed the ownership of land and property in the legal form, but the legal provisions remain absent regarding ownership of underground space and sequestrated carbon and possible cross-border underground movement of carbon. (3) CCUS projects can follow the existing laws, regulations and rules in operation, covering such technical aspects as capture, transport, storage, and use, but the targeted CCUS standards are still needed. (4) China has established a full-fledged legal system and operational procedure for environmental impact assessment. CCUS projects shall carry out environmental impact assessment in accordance with the *Environmental Impact Assessment Law*, but the technical guidelines for CCUS projects were just released recently. (5) Since the legislation has classified compressed and liquid CO_2 into hazardous chemicals, the transport and storage of CO_2 shall follow the regulations for management of hazardous chemicals. However, whether carbon capture and compression is subject to such regulations needs to be clarified. (6) There are neither legal provisions on post-closure carbon storage projects, nor relevant laws, regulations and rules in any other industry on similar long-term responsibility. In the absence of legal basis for regulation on long-term responsibility and duty of care, the responsible bodies for CCUS projects remain unclear.

Comprehensive national strategy and systematic policy framework should be established. The CCUS development involves many competent authorities that have different concerns and attitudes, including NDRC, MOF, MIIT, Ministry of Science and Technology (MOST), Ministry of Environmental Protection (MEP), Ministry of Land and Resources, and State Oceanic Administration. For example, NDRC mainly considers the impact on energy supply security and carbon emissions reduction, while MOST focuses concentration on technological research and development. Authorities such as NDRC, MOST and MEP introduced a number of documents to promote CCUS development based on their competence and business focus. Nevertheless, a comprehensive national strategy or policy or regulatory system has not been formed, disabling coordinated resource deployment and unified management. In addition, only 4 of the 26 existing CCUS-related policy documents are dedicated to carbon capture and storage, but without specifying policy support, they serve as encouragement more than constraint. The supporting measures are not in place, except the detailed rules on environmental management released by MEF.

Funding and incentive policies that provide enough support and momentum for enterprises is needed. Lack of funds is a major obstacle to CCUS development in China. Currently, CCUS pilot projects are mainly financed by the national program of science and technology research and development. However, such access to financial resources is far from enough to cover project costs, and there is no special fund for

CCUS pilot and demonstration projects. The important contribution of CCUS projects is mitigation of carbon emissions, but the mitigation efficiency of enterprises cannot be reflected if the mitigation cost is internalized. CCUS experimental and demonstration projects are basically the spontaneous behavior of business investment, and many cannot start or sustain due to lack of funds.

Firm-level Techno-Economic Analyses of CCUS Technologies in Iron/Steel Industry

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Contents

1. Abstract

CO_2 capture, utilization and storage technology (CCUS) is not only a large-scale CO_2 emission reduction technology with great potential for China's iron/steel industry, but also the only technology that can deliver large-scale direct emission reductions for the industry, and with less restructuring costs on existing energy structure. This study attempts a systematic techno-economic analysis of the efficacy of different carbon capture technologies for major sources of carbon emissions in the iron/steel industry. Our initial findings are that many factors could affect the technical and economic performance of carbon capture technologies, including but not limited to, temperature, pressure, content impurity, and CO_2 concentration of each emission source. It is necessary to conduct future research with real-world cases to assess the technical applicability and economic performance of CO_2 capture in China's iron/steel industry, both for individual gas source and for overall gas system.

2. Introduction

Carbon emission of China's steel/iron industry accounts for about 51% of the global steel/iron industry's carbon emissions and about 15% of China's total carbon emissions. It was surpassed only by the power industry and cement industry in China, being the third among all the industries in China [1] (Li et al., 2015). According to the data from *China Industrial Statistics Yearbook 2015 (Year 2005-2014)* (Table 1), China's crude steel production reached 820 million tons in 2014 from the 350 million tons in 2005, growing by 2.33 times in 10 years; meanwhile, the associated carbon emission also grew 1.8 times. From the perspective of carbon emission of per ton steel, it was 28,200 tons CO_2 per tons steel in 2005, and 21,800 tons CO_2 per tons steel in 2014. It is indicated that the carbon emission of per ton steel has a significant reduction. Whereas, comparing with 13,000 tons of per ton steel CO_2 emission by Germany in 2000, 17,000 tons of per ton steel CO_2 emission by Japan in 2001 [2] (Han et al., 2011), there is a huge emission gap for improvement by China's steel/iron industry.

Table 1 Carbon emission of China's steel/iron industry in 2005-2014 10^4t

Year	CO_2 emission reduction of steel making process	CO_2 emission of purchased electricity	Total CO_2 emission of steel/iron industry	CO_2 emission of per ton steel
2005	5,077.46	1,719.69	99,577.30	2.82
2006	6,096.33	2,074.16	110,037.80	2.63
2007	7,038.82	2,501.88	114,141.57	2.33
2008	7,053.79	2,447.34	118,696.98	2.36
2009	8,162.16	2,658.35	143,476.32	2.51
2010	8,802.44	3,007.36	153,007.88	2.40
2011	9,436.93	3,515.30	164,838.53	2.41
2012	9,764.04	3,355.19	173,097.07	2.39
2013	10,437.18	3,672.62	177,366.94	2.18
2014	10,464.37	3,605.78	179,566.30	2.18

The steel/iron production process can be divided into a main process and an auxiliary process. The main process can be further categorized into long process (BE/BOF) and short process (EAF). The long process (BF/BOF) starts with raw materials such as iron ore, through the processes of mining, milling of ores, blast furnace, converter secondary metallurgy, continuous casting, steel rolling and other processes. The short process (EAF) refers to the use of scrap steel as raw materials to make steel product, though casting of electric furnace, ladle furnace, continuous rolling and other processes. The auxiliary process refers to the production process which has a great influence on the environmental, such as coking, boiler, oxygen production, fuel gas processing, energy discharge and internal transportation. At present, the long process is mainly adopted by China's iron/steel industry; crude steel production accounts for 90% of total steel production in China [3] (Cui, 2016); in addition, the per ton steel CO_2 emission of crude steel produced by a short process is far less than that of crude steel produced by a long process (CO_2 emission associated with converter process is 5 times than that associated with electrical furnace process [4] (Ran and Weng, 2006)). Therefore, the CO_2 produced by long process production process is the main CO_2 emission source of China's steel/iron industry.

The high CO_2 emission in the steel/iron production process is mainly related to high energy consumption, therefore, the current general mitigation strategy of China's steel/iron industry is to reduce emission by ways of energy conservation. Su (2007)[5] indicated that, the key pathways of energy conservation and emission reduction in China's steel/iron enterprises are mainly on three ways: optimization of process, phased-out of low-efficiency unit, and development of advanced energy conservation and emission reduction technologies. The advanced technologies of energy conservation and emission reduction should focus on energy conservation and emission reduction of steel making process, energy saving of electric motor, energy conservation through management and development of new materials for energy conservation and emission reduction.

Shu (2008)[6] analyzed the overall operation of China's steel/iron industry, and proposed that the approaches of energy conservation and emission reduction for China's steel/iron industry be phased out of low-efficiency production facilities, using advanced technologies and enhancing recycle and reuse of secondary energy. Zeng (2009)[7] discussed the specific technical path of energy conservation and emission reduction carried out in China's steel/iron steel industry, and emphatically analyzed Coke Dry Quenching (CDQ), TOP gas pressure recovery turbine (TRT), blast furnace gas-steam Combined Cycle Power Plant (CCPP), Dry (LT) Purification Recovery Technology of Linz-Donawitz gas and sintering plant waste gas closed-circuit recycling waste heat recovery technology and other major fields suitable for the development of clean development mechanism projects in China's steel/iron industry. Xu (2010)[8] proposed that the steel/iron production industry needed an environmental friendly green development path. Equipping large-scaling and application of advanced technology were the main ways to improve comprehensive competitiveness for China's steel/iron

industry. Liu and Wang (2010)[9] summarized that short steel-making process had the characteristics of low input, low energy consumption, high benefit and high added-value product. They pointed out that an important pathway to achieve low-carbon emission reduction for steel/iron industry was to promote short steel-making process.

Zhu and Ning (2010)[10] introduced the advanced technologies that suitable for China's steel enterprise by different processes and pointed out that promote and application key energy conservation and emission reduction technologies in all production processes and auxiliary system are effective ways for steel/iron industry to achieve energy conservation and emission reduction. The "Thirteenth Five-Year Plan (13th FYP)" of China's steel/iron industry – *Steel/iron industry adjustment and upgrade plan (2016-2020)* clearly proposed the target which was total energy consumption of steel/iron industry by 2020 should be reduced by 10% than that of 2015.

For small and ium-sized steel/iron enterprises with low technical level, reducing energy consumption is very effective to achieve their indirect emission reduction target; while for the large scale steel/iron enterprises with high technical level, energy conservation means not only the challenge of breaking their established internal energy balance, but also the challenge of high energy conservation cost due to the more and more limit space for energy efficiency improvements. This leads to the difficulty for China's steel/iron industry to meet their long-term emission reduction target. Therefore, it is urgently need to develop a cutting-edge technology of direct emission reduction. CO_2 capture, utilization and storage technology (CCUS), as the only technology that can achieve large-scale direct emission reduction for steel/iron industry, has received more and more attention from the international community, *China's Steel/iron industry adjustment and upgrade plan (2016-2020)* also incorporated CCUS technology into its prioritized frontier reserved energy conservation and emission reduction technologies.

At present, a number of carbon capture technology demonstrations have been developed by global steel/iron industry, and the techno-economic assessment studies have been conducted based on those demonstrations, however, these researches are short of China's engineering economical and technical background, thus it is hard to be referred by China's steel/iron industry. In addition, there is also lack of systematic techno-economic analysis of CO_2 capture technologies for all emission sources, combining with indirect emission reduction and internal CO_2 utilization opportunities by China's iron/steel industry, thus unable to identifying the priorities of CO2 capture for each emission sources by China iron/steel industry.

In view of those shortcomings, with the financial support of the BHPB-Peking University Carbon Dioxide Capture Project, the objective of this research is aimed at a comprehensive techno-economic analysis of major CO_2 capture technologies for China's steel/iron industry. The first research task will introduce the main CO_2 emission sources of a typical production process of China's iron/steel industry; the second task will discuss suitable carbon capture methods for each emission source; finally, the technical and

economic assessment of different capture methods for each emission sources will be conducted and recommendations on the application of capture technologies are proposed accordingly to provide decision bases for large-scale project demonstration of carbon capture in China's and even global steel/iron industry.

3. Carbon emission sources from iron/steel industry

The production processes of a long process steel/iron industry mainly include 5 processes: coking, sintering, iron-making, steel-making and steel rolling. The iron-making process has three types: blast furnace iron-making, direct-reduction iron-making and molten reduction technology. The steel-making process has two types, which is converter steel-making and electric furnace steel-making. In the process of coking, sintering, iron-making, steel-making and rolling steel, fuel coal, coking coal, coke, natural gas and fuel oil are not only the source of energy, but also raw materials. Some part of carbon in these energy and material sources is converted and released in the form of CO_2 by the way of reduction or oxidation reaction in the whole production process. The main CO_2 emission sources are released from units include lime kiln, coke oven, hot blast furnace, blast furnace, converter and self-provided power plant.

3.1. CO₂ emission from lime kiln

In iron-making process, lime kiln is used to produce lime as flux and slag materials to be used in blast furnace iron-making and converter iron-making processes to remove harmful elements from smelting, such as sulphur, silicon, phosphorus other impurities. Lime is formed by the limestone calcination, the main component of limestone is calcium carbonate. The basic principle of burning limestone can be expressed by the following chemical reaction equation (Equation 2-1):

$$CaCO_3 \xrightarrow{>900℃} CaO + CO_2 \uparrow \qquad \text{(Equation 2-1)}$$
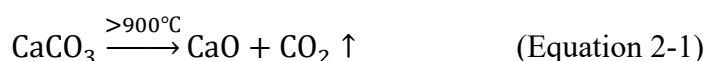
The limestone and air are preheated to about 900℃ in the lime kiln preheater. After lime produced, the lime (product) will be cooled to below about 100℃ by cooling gas. After the cooling gas enters a roast area to mix with the exhaust gas from combustion, the temperature of mixed gas will reach about 900℃. The mixed gas is then recycled and reused for heating limestone and air in the subsequent limestone preheating process. After the preheating process, the temperature of flue gas is reduced to 60 ~ 80℃. Although when the breakdown of limestone can release about 40% of its weight in the form of CO_2, after mixing with exhaust gas from combustion and circulating, CO_2 content in the flue gas will be significantly decreased. CO_2 from different lime kiln unit

may have different concentrations. In according with the report of *Applying carbon capture and storage to a Chinese steel plant* which is prepared for Global Carbon Capture and Storage Institute Ltd By Toshiba International Corp Pty Ltd/Toshiba Corporation in collaboration with Tongfang Environment Co. Ltd, China Shougang Caofeidian plant has 6 sets shaft lime kilns, used for production of lime needed by steel mill. The flue gas composition of #4 lime kiln from Caofeidian plant is given in table 2, indicating 19.3% CO_2 concentration. Shen (2008)[11] reported that the CO_2 concentration of flue gas of a typical limestone kilns outlet in the integrated iron and steel enterprise was 15-21%.

Table 2 Flue gas composition of #4 lime kiln in Shougang Jingtang

	Flow rate	Temperature	Concentration (CO_2)	CO_2 emission	
	m^3N/h	℃	Vol.%	t/d	kt/y
#4 lime kiln	75,304	110	19.3	685	205

3.2. CO_2 emission from coke oven

The coke oven flue gas from steel/iron plant is the exhaust gas produced by combustion and discharged through a coke oven chimney. The mixture of coke oven gas and blast furnace gas is generally used for coke oven heating by integrated iron and steel enterprises. Accordingly, the CO_2 concentration is mainly affected by the combustion condition and the composition of combustion feed gas. According to the report of *Applying carbon capture and storage to a Chinese steel plant* which is prepared for Global Carbon Capture and Storage Institute Ltd by Toshiba International Corp Pty Ltd/Toshiba Corporation in collaboration with Tongfang Environment Co. Ltd, the CO_2 concentration of the combustion flue gas from coke oven in China Shougang Jingtang was 11%. The report of Global Carbon Capture and Storage presented a concentration range of 10-15% (Global CCS Institute, 2016).

There is another gas source related to coking produced by coking process. It is called raw coke oven gas or raw coal gas. The raw coal gas can be purified though a coke oven gas purification system (Figure 2-1). Coke oven gas purification process is differentiated mainly based on different desulphurization and deamination configurations. Generally, there are two kinds desulfurization system: dry desulfurization and wet desulfurization. Wet desulfurization process can be further categorized into two types: wet oxidation process and wet absorption process. The wet absorption process has the function of removing CO_2 simultaneously, leading to a low CO_2 concentration in the purified flue gas.
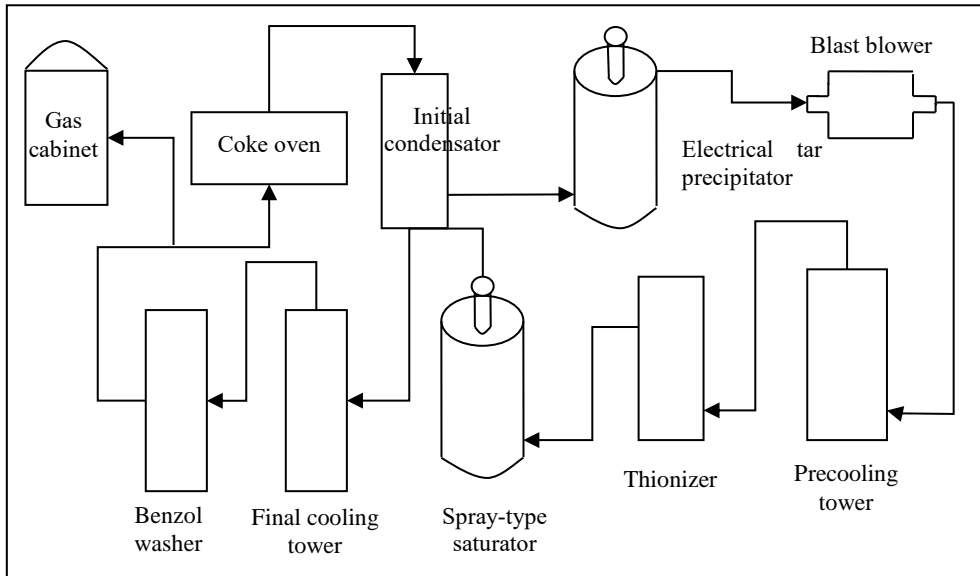
Figure 2-1 Coke oven gas purification system

The Sulfiban method of wet absorption process was applied in the coal gas refining system in Baosteel phase II which was put into operation in May 1997. Through an intermediate cooling tower, the coal gas after naphthalene removed enters an ammonia absorption facility, where a 75% of ammonium dihydrogen phosphate is used as absorption solution. The rich solution is ammonium hydrogen phosphate. Ammonia solution with concentration of18% is obtained after desorption. Anhydrous ammonia with the concentration of 99.8% is finally obtained after further pressurized and concentrated. The absorbents can be recycled after desorption. The coal gas which absorbed ammonia enters a final cooling tower after dephenolization and decyanation. The coal gas without ammonia enters a benzol scrubber to remove crude benzene. The gas is then delivered to a gas cabinet for storage after desulfuration and decyanation processes. The sulfur enriched solution is desorbed in a desorption facility. The obtained H_2S, HCN and CO_2 are then sent to combustion furnace to generate SO_2 and NO_x.

The composition of a typical purified coal gas is illustrated in Table 4. Because CO_2 is partially removed by ammonia absorption process, the concentration of CO_2 is as low as 2.1%. Comparing coke oven flue gas and coke oven gas, the former is a combustion product discharged through a coke oven chimney, its CO_2 concentration is relatively high; the latter is a direct product produced in the coking process of coal, its CO_2 concentration is relatively low particularly after absorption of ammonia. Therefore, coke oven flue gas is more suitable for the application of carbon capture technology than the coke oven gas.

Table 3 Composition of a typical coke oven gas

Composition	CO	CO_2	H_2	N_2	CH_4	C_2H_4	C_2H_6	C_3H_6	O_2	H_2O
Coke oven gas	5.9	2.1	58.8	3.8	25.6	2.3	0.9	0.2	0.4	saturation

3.3. CO_2 emission from blast furnace

An iron-making process makes use of iron ore, fuel (coke, sometimes it is supplemented by heavy oil, pulverized coal, natural gas etc.) and other auxiliary raw materials to produce molten iron and two by-products (slag and coal gas) through heating, decomposing, revivification slagging, desulfuration and other reactions in a blast furnace. In the production of blast furnace, iron ore, coke and limestone are put into the furnace from the top. After preheated through a hot blast furnace, air is blown into the furnace from the bottom by a blast blower. Under high temperature, carbon of coke, pulverized coal, heavy oil, natural gas and other fuels and blowing oxygen burn to generate carbon monoxide (CO). In the rising process of CO in a furnace, the oxygen in iron ore is removed, the iron ore is reduced to molten iron. The molten iron is released from a iron hole as the product of blast furnace; the non-reductive impurities in iron ore reaact with the fluxes such as limestone to generate slag, discharging from a slag hole; the generated gas (blast furnace gas) is released from the top of the furnace. After removal of dust, the gas can be used as the fuel of hot blast furnace, heating furnace, coke oven, boiler, etc. The pressure of blast furnace gas (BFG) mainly depends on the pressure of blowing air.

Blast furnace gas can be classified into coarse dust removal coal gas, semi-clean dust removal coal gas and fine dust removal coal gas. According to different purification methods, blast furnace gas can be purified by dry dust and wet dust removal methods. The coarse dust removal is usually conducted with dry method. The coarse dust removal is the first purification in a dust removal process. The semi-clean dust removal can adopt wet method or dry method. The fine dust removal is the final stage of BFG dust removal. The purified fine gas can be sent to a gas pipeline after energy recovered by a blast furnace top gas pressure recovery turbine system (TRT). Blast furnace top gas pressure recovery turbine (TRT) system makes use of pressure energy and sensible heat of BFG. Through the system, the blast furnace gas pressure energy and part of heat energy can be converted into mechanical energy and then drives a generator to generate electricity.

The capacity of TRT should be matched to the gas amount of a blast furnace and the furnace top pressure, while amount of blast furnace gas is associated with the capacity of blast furnace blower. Temperature and pressure will be mainly changed between the inlet and outlet of TRT. Table 4 illustrated a typical operating condition at TRT inlet and outlet. It is observed that pressure and temperature decrease significantly after TRT. The main composition of blast furnace gas after TRT is CO, CO_2, N_2, H_2 and CH_4. Table 5 is the blast furnace gas composition of a typical steel/iron plant in China. The CO_2

concentration is 23.1% which is higher than that of flue gas from lime kiln.

Table 4 Operating condition at TRT inlet and outlet

Item	Numerical value
Blast furnace top pressure	0.20MPa
TRT inlet pressure	0.17 MPa
TRT outlet pressure	0.01 MPa
TRT inlet gas temperature	100℃
TRT outlet gas temperature	50℃

Table 5 BFG composition of a typical steel/iron plant in China

Composition	CO	CO_2	H_2	N_2	O_2
Vol %	21.8	23.1	3.2	51.7	0.2

3.4. CO_2 emission from converter

In the Linz-Donawitz smelting process, the molten iron in the furnace reacts with the blown oxygen. The produced gas is called Linz-Donawitz gas (LDG), which is mainly from the oxidation of carbon in molten iron. Due to the high temperature in a converter furnace, the main oxide of carbon is CO, account for about 90% of total amount carbon oxides. A small portion of carbon reacts directly with oxygen to produce CO_2 and some CO could escape from the surface of molten steel and react with oxygen to produce CO_2.

At the beginning of blowing oxygen process, the temperature of molten iron is low, the easily oxidized elements silicon and manganese in the molten iron are first oxidized, then phosphorus, sulfur and other elements; meanwhile, a small portion of iron is also oxidized. Because carbon has a lower oxidation rate, furnace gas volume produced is relatively small and the furnace gas temperature is relatively low. With huge heat released associated with the oxidation reaction of above elements, the temperature of the molten pool increases correspondingly. When the temperature of the molten pool exceeds 1400℃, carbon and oxygen react violently, leading to CO content in the furnace gas gradually increased. The amount of furnace gas produced per unit time is related with the intensity of blowing oxygen and carbon reduction speed. The greater of the intensity of blowing oxygen and the faster of the carbon reduction speed, the more of the amount of furnace gas produced in unit time. In the later period of converting, with the decrease of carbon in molten iron, the amount of LDG production decreases, but the temperature of LDG rises with the rising temperature of molten pool.

The Linz-Donawitz steel-making is usually intermittent. One process may take about

40 minutes. In the time of beginning and end of converting, the amount of furnace gas is small and CO content is low, hence, the furnace gas is normally taken in the middle section. The former and latter periods are called pre-combustion period and post-combustion period. The middle period for capture furnace gas is called capture period. Due to the periodicity of a Linz-Donawitz steel-making process, the capture time is intermittent, resulting in furnace gas intermittently discharged.

In the process of converting, when adding auxiliary raw material to a converter, the amount of furnace gas will increase rapidly. The auxiliary raw materials are slagging flux and coolant. The slagging flux mainly uses lime and the coolant mainly uses steel scrap, iron ore and oxidized scale. After the gas leaves the furnace mouth of converter, it will burn when meets air. In addition, the gas contains highly toxic materials. Therefore, the high temperature flue gas needs to be captured at the furnace mouth of converter. When the high temperature flue gas pass through a evaporation cooling facility, the flue gas is initially cooled while some heat energy is recovered. The temperature at the outlet the evaporation cooling facility is about 900℃[12] (Zhang et al, 2017). After initially cooling and coarse dust removal, the flue gas needs to be further cooled and depressurization to meet operating conditions of fine dust removal units.

Dust removal purification methods have two types: wet method and dry method. ① The typical process of wet purification system is: after released from a converter, the gas is initially cooled to 800～1000℃ through a vaporizing cooler, then go through the first-degree venturi tube, the first elbow dehydrator, the second-grade venturi tube and the second elbow dehydrator successively. Spraying water at the throat of the venturi tube will decrease gas temperature to about 35℃ and reduce the dust content in the gas. The purified gas is then sent to a gas storage cabinet by an induced draft fan. ② A typical process of dry purification system is: the gas temperature is dropped to 1000℃ through vaporizing cooler, then further dropped to 200℃ by using an evaporative cooling tower. Through dust removal of dry-type electrostatic precipitator, the purified gas is fed into a gas storage cabinet by an induced draft fan. Compared to wet method, dry method purification system has the following advantages:

1) The dust content of gas is low;
2) Because of well-developed automation system leading to a quick switch of gas capture system, gas capture rate is increased. Normally, the capture rate of dry method system is 15-30% more than that of wet method one.
3) The dust content of gas is low after purification, resulting in longer life of draught fan and less workload of maintenance s;
4) System resistance is small;
5) Water conservation;
6) Total power load of dry method system is much less than wet method;
7) Increase the recycled amount of dust containing iron and reduce the associated transportation cost;
8) Water treatment system is unnecessary, reduce land use;

9) Reduce secondary pollution of waste water and reduce dispersed gas amount.

The disadvantage is:

1) Complex system, high failure rate and high maintenance cost;
2) Requires high management and operational skills. More training for manager and operators be carried out.
3) Fixed investment cost is high. (Wang et al, 2008)[13]

Table 6 demonstrates the composition of a typical Linz-Donawitz gas (LDG) after dust removal. The temperature of the gas is about 100 ℃ and the pressure is slightly higher than the ambient pressure.

Table 6 Composition of a typical LDG

Composition	CO	CO_2	H_2	N_2	CH_4	C_2H_4	C_2H_6	C_3H_6	O_2	H_2O
Vol %	58.5	15.1	3.7	21.5	1.0	0.1	0	0	0.1	saturation

3.5. CO_2 emission from hot blast furnace

An iron-making blast furnace is usually equipped with several hot blast furnaces, with each hot blast furnace consisting of a combustion chamber, a regenerative chamber, a wind mixing chamber, and a variety of valves and corresponding pipes. The air required for the combustion of a hot blast furnace is provided by a combustion fan. According to the regulations of a hot blast furnace operating instruction, in the normal operating process of a hot blast furnace, a smothered furnace state is necessary between blowing-in and combustion operations. There is no direct transfer between the blowing-in and the combustion state. In short, the production cycle of a hot blast furnace should be combustion – stop – blowing-in – stop – combustion[14](Liu, 2016).

The combustion stage is also called a burning furnace stage. The aim is to heat hot blast furnace lattice bricks to a certain temperature to reserve heat by lattice bricks. The combustion fuel is mainly of blast furnace gas, mixture of blast furnace gas and coke oven, gas or mixture of blast furnace gas and CFG as well as combustion air. Those fuels and air are fed into hot furnace through the burner with a certain ratio between the fuels and the air. The fuels burns in the burner aided with air. The resulting gas is discharged from a flue outlet. At combustion stage, cold air inlet and hot air outlet are both in a closure state. After the combustion process (i.e, lattice bricks storage heat sufficiently), and the operation moved to the next air blowing-in stage.

At the stage of blowing-in, cold air is heated when fed into the blast furnace. The burner and the flue outlet are kept off, while cold air inlet and hot blast air outlet are open. With the heat exchange between cold air and lattice bricks, the temperature of the lattice bricks decrease. Finally, the operation is ceased, waiting for the combustion in the next round.

Because the ratio of air and fuel in the hot blast furnace is different and the inlet pressure and temperature of gas and air are also different, the CO_2 content would be different in the flue gas of hot blast furnace. The residual O_2 is also affected by air-fuel ratio. The general composition of hot blast flue gas is shown in table 7. Although the hot blast flue gas produced by a single hot blast furnace is continuous, in the actual production process, the emission of flue gas at outlet of a chimney is approximately continuous as multiple hot blast furnaces share a flue gas discharge chimney.

Table 7 Composition of a typical hot blast furnace flue gas

Composition	CO_2	N_2	O_2	H_2O	Dust /(mg·m^{-3})
Vol %	28.52	65.15	2.51	3.82	5

3.6. CO_2 emission from power generation unit

The power plant in a steel/iron enterprise is to supply heat and electricity to meet iron/steel making demand. The power plant normally consume the combustible gases produced during iron/steel making processes, including coke oven gas and blast furnace gas, to improve power supply reliability, to reduce power generation cost, and to contribute to   energy conservation and environmental protection of iron/steel industry. The CO_2 concentration of flue gas produced by power and heat generation processes in the power plant is a little low, being about 10-15%.

3.7. Summary of main CO_2 sources in iron/steel industry

There are multiple CO_2 emission sources with huge emissions in an integrated steel/iron plant. The different emission sources correspond to different production processes, thus have different emission characteristics. Among them, the CO_2 content of flue gas of lime kiln, hot blast furnace gas, blast furnace gas and converter furnace gas is higher than that of post-combustion flue gas generated from a typical coal-fired power plant; while, the CO_2 concentration of coke oven flue gas and the self-provided power plant could be lower than that of post-combustion flue gas from coal-fired power plant.

In terms of pressure, except that there is a higher pressure in blast furnace gas before TRT, the pressure of other emission sources is close to an atmospheric pressure. Regarding temperature, the flue gas from hot blast furnace normally has high temperature than other emission sources, thus heat recovery is desired before CO_2 capture. As for discharge way, the discharge of LDG is intermittent, while others are continuously or approximately continuously discharged. Among all gas sources, LDG and BFG are both combustible. Their calorific value can be increased accordingly by capturing CO_2. In general, the different emission characteristics of CO2 enriched gases from iron/steel industry have influence on the technical and economic performance of different capture technologies.

4. Carbon capture technologies for steel/iron industry

The technology development in China's steel/iron industry is unbalanced, although the overall energy consumption is much higher than that of the international community. With the implementation of energy conservation technologies in China's steel/iron industry, the energy consumption level of China's large steel/iron companies is already close to that of international iron/steel enterprises. Therefore, the indirect emission reduction through energy conservation is more and more limited for those large enterprises, resulting in the emission reduction cost through energy conservation is getting higher and higher. It is economically hard for those large steel/iron companies to meet their long-term emission reduction target. As a large-scale CO_2 emission reduction technology with great potential, carbon capture technology can be a cost-effective option to the indirect emission reduction technology. It can benefit large-scale enterprise by achieving a sustainable emission reduction target without changing its already established energy balance system. Therefore, carbon capture technology is increasingly recognized by large steel/iron enterprises in the world.

According to different CO_2 sources, carbon capture technologies are generally categorized into three types: post-combustion capture, pre-combustion capture and oxyfuel combustion capture. Among them, the post-combustion capture refers to the capture of CO_2 from the flue gas of fossil fuel combustion. According to the analysis in Section 2, the most of CO_2 associated with steel/iron production is mainly from post-combustion flue gas, hence, this study focuses on the post-combustion capture technology for iron/steel industry. Based on different separation principles, the post-combustion capture can be further typed into absorption capture technology, adsorption capture technology, membrane capture technology, cryogenic capture technology, hydrate capture technology and mineral carbonation capture technology.

4.1. Absorption capture technology

Absorption capture or separation technology is a technology that uses absorbent solution to separate CO_2 from mixed gases containing CO_2. It can be divided into physical absorption method and chemical absorption method[15](Li, 2014). The absorption technology has been widely used in chemical industry, oil refining, natural gas processing and other fields, and it is proved that it has the application prospect in steel/iron industry [16](IEA, 2010).
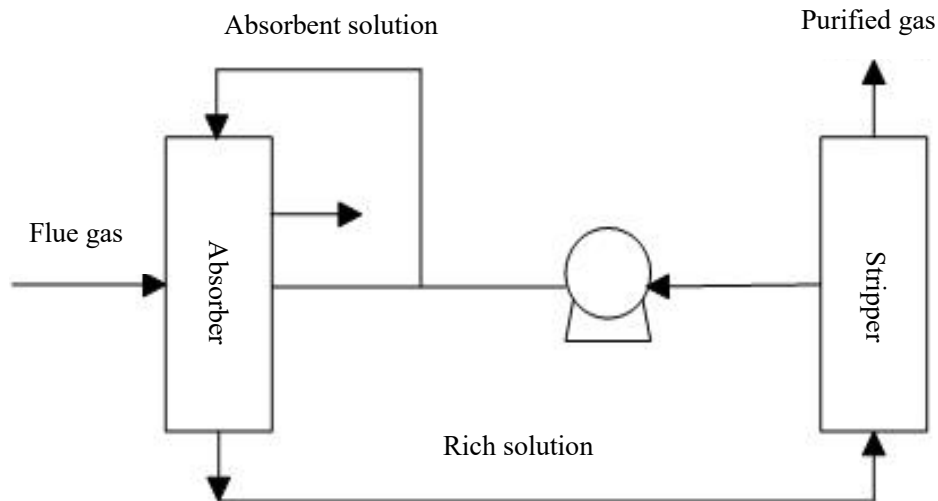
Figure 3-1 Principle of chemical absorption method

The chemical absorption method refers to the use of alkaline chemical absorbent, such as ammonia, to absorb CO_2 in a flue gas by chemical reaction and form unstable salt. Under a certain temperature and pressure condition, the salt can be decomposed in reverse to release CO_2, so as to achieve the aim that removing CO_2 from the flue gas [17](Jiang, 2015). At present, the typical chemical absorbents include mono ethanol amine (MEA), alkyl alcohol amine, ammonium hydroxide, hot potassium carbonate solution, etc. [18](Sun, 2009), the recovery rate of CO_2 can reach 90%, the purity can reach above 99%.

The study of Gielen D (2003)[19] indicated that chemical absorption methods can be used to deal with blast furnace gas (BFG), Linz-Donawitz gas (LDG), and flue gas produced in the process of direct reduction and melting. Tseitlin MA et al[20](1994) used a mono ethanol amine (MEA) solvent to separate CO_2 from blast furnace gas. Tobiesen et al[21](2007) adopted different amine solvents to separate CO_2 from blast furnace gas. In order to separate the CO_2 with the concentration of 30% from hot blast furnace, Cheng et al[22](2010) investigated the performance of different solvents. Yoon et al[23](2011) developed a potassium carbonate/cyclic diamine solvent to separate CO_2 from the flue gas with concentration of 15-20% in the steel/iron industry.

In technology demonstration field, POSCO developed an ammonia absorption technology to separate CO_2 form blast furnace gas. In order to reduce the cost of CO_2 separation, a medium and low temperature waste heat from steel/iron mill was used as the desorption heat of CO_2[24](Kim JY et al, 2009). The first phase of a pilot project was completed in 2008 with processing capacity being $50m^3/h$, CO_2 recovery rate being above 90% and CO_2 volume fraction (concentration) being above 95% [25]. Base on phase one, the second phase of the pilot project was completed in 2011 with blast furnace gas processing capacity being expanded to $1000m^3/h$, CO_2 recovery rate being over 90%, and the concentration of CO_2 exceeding 99.5% [26](POSCO, 2013). In the project of COURSE50, in order to reach the target of 30% emission reduction, Japan

New Energy Industrial Technology Development Organization (NEDO) commissioned the Nippon Steel & Sumitomo Metal and JEF to carry out relevant technology development under the support of the Japan Iron and Steel Federation[27](Li and Lu, 2009).

Nippon Steel & Sumitomo Metal developed ESCAP (energy conversation CO_2 absorption process) low energy consumption CO_2 separation process, which uses the developed new type of amine solvent (RN) to remove CO_2 from blast furnace gas, the desorption heat is low temperature waste heat that has not been utilized in previous iron works [28](TNCSTEEL, 2015). The process required a low regeneration temperature, and the newly developed amine solvent is less corrosive to equipment and devices. For the combined use of the new type amine solvent RN and the waste heat recovery system, CO_2 capture cost was expected to be almost 50% lower than that of MEA method(30%MEA) [29](K Goto et al, 2013). Toshiba International Corp Pty Ltd/Toshiba Corporation in collaboration with Tongfang Environment Co. Ltd proposed an amine solvent absorption method to capture CO_2 in the case of Shougang Jingtang steel plant in China.

The physical absorption method is the absorption of CO_2 by means of physical dissolution. Its advantages include good absorption effect, low energy consumption and high separation recovery rate. Its disadvantages is that it is only suitable for flue gas with high CO_2 content[30](Huang, 2013). Therefore, for low CO_2 content emission sources of steel/iron plant, the physical absorption method may not be technically feasible. The technologies developed by typical physical absorption method include Selexol™ system based on ethylene glycol and Rectisol® system based on methyl alcohol. The Selexol process can operate at an ambient temperature, while the Rectisol process operates as low as -60℃ temperature condition. These systems have been applied in a large scale in the process of syngas purification and natural gas processing.

4.2. Adsorption capture technology

Adsorption capture technology is a technology that utilizes the selectivity of the solid adsorbent for CO_2 and reversible adsorption to separate CO_2 from mixed feed gases containing CO_2. The adsorbent adsorbs CO_2 in a low temperature (or high pressure). The CO2 is de-adsorbed when temperature increasing (temperature swing adsorption, TSA), pressure reduction (pressure swing adsorption, PSA or vacuum pressure swing adsorption, VPSA) or imposing low voltage current (electricity swing adsorption, ESA). Through periodic changes of temperature (or pressure), the CO_2 is separated from a gas stream [31](Han et al, 2009). Currently, pressure swing adsorption process (PSA and VPSA) is more widely applied than TSA [32](Kuramochi T et al, 2011).

The basic principle of pressure swing adsorption (PSA) is that using the difference of adsorption properties of a kind of gas by a solid material and the characteristic that the adsorption capacity varies with pressure. Through a periodic pressure transformation process, the separation or capture of a kind of gas can be realized. The adsorbate adsorb

a specific gas (such as CO_2) at a higher pressure, then the desorbed by reducing pressure. The process of adsorption at high pressure and desorption at normal pressure is normally called pressure swing adsorption (PSA); the process of adsorption at normal pressure or slightly higher than normal pressure, and desorption through vacuum is called vacuum pressure swing adsorption (VPSA).

The performance of adsorbent determines the process and cost of pressure swing adsorption method. The pressure swing adsorption can use carbon-based adsorbent, zeolite and hydrotalcite-like compounds as the adsorbent and is widely applied in purification of hydrogen and CO_2. It can also be used to produce food grade CO_2, purification of CO, purification of natural gas, and oxygen and nitrogen separation.

In the project of COURSE50, JFE steel company developed a two-stage pressure swing adsorption method (zeolite adsorbents) to separate CO_2 from blast furnace gas[33](Qi et al, 2013). The pilot system (ASCOA-3) was developed with CO_2 processing capacity of 3t/d. The system separates the flue gas with CO_2 concentration of 33%, the recovery rate of CO_2 reaching 80% and the CO_2 purity being 99%. In 2011, POSCO developed a pressure swing adsorption technology (PSA) technology to separate the mixture of CO and CO_2. A small pilot with processing capacity of $1Nm^3/h$ and the concentration of captured CO_2 being over 99% was established [26](POSCO, 2013).

4.3. Membrane capture technology

Membrane capture technology can be typed into membrane separation method and membrane-absorption method [34](Guo et al, 2016). Membrane separation method separates mixed gases according to the difference in permeation selectivity of membrane materials for different gases. The driving force of membrane separation is the pressure difference on both sides of the membrane. The gas with high permeability preferentially passes through the membrane and form a permeating airflow. The gas with low permeability forms a residual airflow on the other side. Two streams are led respectively to achieve gases separation [35](FERON P H and JANSEN A E,2002). The ability of this method to separate CO_2 mainly depends on the selectivity of membrane material for CO_2 [34](Guo et al, 2016). The membrane materials for separation of CO_2 are high polymer material, inorganic material, hybrid organic-inorganic materials etc. [36](Wang et al, 2016). The separation process can adopt a single-stage membrane separation or a multistage membrane separation process.
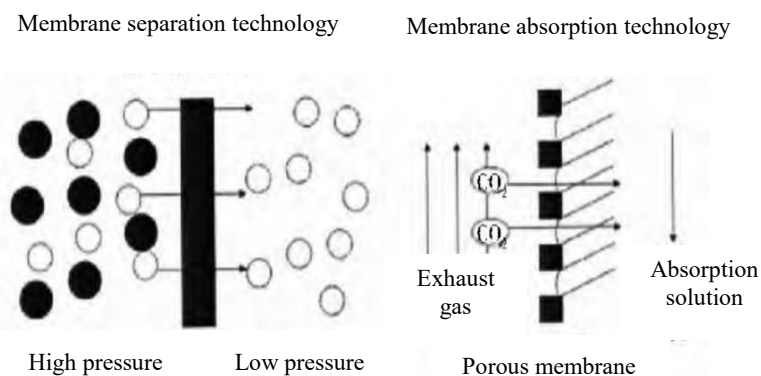
Figure 4-5 Schematic principle of two kinds of membrane separation CO_2

The membrane absorption method is driven by the pressure difference on both sides of membrane, depending on adsorption capacity of each component of gas on the membrane surface and the differences in dissolution and diffusion in membrane (difference of permeation rate), to realize separation. There is no selectivity on the raw gas for membrane itself. The membrane only provides isolation for gas and absorption liquid. The gas and the liquid is not direct contact. They flow on both sides of the membrane [37](Gao et al, 2016). the absorbents play a key role in the selectivity for the composition. The membrane absorption method has overcome some weaknesses of traditional gas (or CO_2) absorption methods. In the case of low CO_2 partial pressure, this method has high selectivity and large separation driving force, which can be modularized for engineering design[38](Zhang and Shu, 2015).

Compared with a traditional tower absorber, membrane-absorption method can increase the contact area of gas and absorption solution, and overcome the entrainment phenomenon caused by the direct contact between two-phase of gas-liquid, it has the advantages, including stable mass transfer interface, large specific surface area, high mass transfer efficiency, low energy consumption, no bubble, no flooding, small equipment size, higher operation flexibility and easy maintenance [39](Gao et al, 2016).

Regarding the demonstration of membrane technologies, there was few demonstration projects had been carried out. Lie JA et al[40] tested the performance of three different types of membranes in capturing CO_2 from the blast furnace gas (BFG). Australia CO_2CRC project developed a new membrane separation technology, which is applied to separate CO_2 for industry gases[41](CO_2CRC).

4.4. Cryogenic distillation capture technology

Cryogenic separation technology refers to compression, liquefaction and distillation of a gas mixture at a low temperature and high pressure operating condition, according to different gas composition with different boiling points. CO_2 could be removed and purified from a mixture gas under a certain temperature and pressure condition. The

purity of extracted CO_2 by this method is high, but it takes a lot of extra energy in the liquefaction and compression process[42](Xiao et al, 2012). In nature, the technology is mainly a gas liquefaction process. Normally, a flue gas is compressed and cooled until a phase change of CO_2, to achieve distillation purpose of separating CO_2 from the flue gas. The advantage of cryogenic separation technology is that the technology can produce liquid CO_2 directly for further transport by truck vehicle, thus avoid further compression and liquefaction of gaseous CO_2 product; the disadvantage of such a technology are in two aspects: one is large energy consumption for cryogenic process, especially for low CO_2 concentration gas stream; the second is blocking issue by water, which will become solid under low temperature. The technology could be more economical for high concentration of CO_2 (above 60%)[43](Wang, 2007) .

The process flow of a cryogenic distillation capture unit is mainly divided into three parts: compression and cooling of feed gas, rectification separation and cryogenic distillation. Practically, a CO_2 enriched feed gas stream is firstly compressed and cooled to about 4.4 Mpa and 40℃, then sent to a cold tank for rectification purification. In the rectification tower, the light component is gradually gathered at the top of the tower, CO_2 is gradually gathered in the tower bottom at high concentration. Finally, the high concentration CO_2 is super cooled to -25℃ and put into storage tanks with a liquid phase after throttling. The liquid CO_2 is then delivered to a CO_2 tank by charging pump, and transported to storage sites or utilization facilities by a vehicle. In the project of top gas recycle of blast furnace (TGRBF) under ULCOS program, CO_2 was captured by pressure swing adsorption (PSA) method, followed by a cryogenic distillation technology to generate liquefied CO_2[44](BJ.P., 2010).

4.5. Summary

For steel/iron industry, carbon capture technology is not only a large-scale CO_2 emission reduction technology with great potential, but also the only technology that can facilitate a large-scale direct emission reduction for steel/iron. It can build the capacity of large-scale enterprises in dealing with sustainable emission reduction without changing their own energy balance system.

A large portion of CO_2 associated with steel/iron production can be sourced from post-combustion flue gas. Correspondingly, post-combustion capture technologies, including absorption separation technology, adsorption separation technology, membrane separation technology, and cryogenic distillation technology can be suitable. Overall, among these technologies, the absorption method is the most mature. In particular, chemical absorption method has already been demonstrated by two large-scale commercial demonstration projects with capacity of one million tonnes per annum CO_2 for each in coal-fired power generation industry. The physical absorption method is demonstrated by commercial application in chemical industry very early. It is relatively mature in carbon capture applications. The membrane separation method is also widely used in gas separation industry. In a steel/iron production process, different kinds of capture technologies have different technical applicability and economic

performance for different gas sources, as different emission sources have different characteristics. It is necessary to provide an insightful analysis on the technical applicability and economic performance of each capture method for each gas source based on different capture requirements.

5. Techno-economic analysis of CO2 capture from different sources

Absorption separation, adsorption separation, membrane separation, cryogenic distillation separation and other capture technologies all have their own features in terms of technology applicability and economic performance. Table 4-1 summarized the overall strength and weakness of each technology (Li, 2014; Han, 2009; Wang, 2016; Huang, 2008). In general, the CO_2 concentration of each emission source in a steel/iron production process is low, thus physical absorption method is obviously unsuitable for its own use. a temperature swing adsorption method may not be suitable for large scale carbon capture because of a slow temperature change. As indicated in Section three, because the composition, pressure and temperature properties of different emission sources in a steel production process are different, the technical and economic may be different when applied to different emission sources.

In China, CO_2 are classified into four different quality specifications, i.e. food grade, industrial grade, internal use, and storage grade. For a concise analysis in this study, industrial grade and food grade are grouped into an industrial grade above category, with CO_2 concentration being greater than 99.9%. The internal use require that CO_2 concentration be greater than 95% and O_2, H_2, and CO be less than 0.5%; while storage grade only expects the 95% of CO_2. Capture scale can be divided into small scale (10,000 tons/year) and large scale (500,000 tons/year).

The captured CO2 has three different use purposes: internal use, large-scale external use by pipeline transportation and small-scale external use by tanker transportation. The internal use only needs to be pressurized to 0.6Mpa to be delivered directly by an internal pipeline; the large-scale external use by pipeline transportation requires the CO2 be transported to designated locations on large scale in a supercritical/dense or a gaseous phase; the small scale external use by tanker requires the captured CO2 been transported in a liquid phase. Both different specification and different use requirements affect technical and economic assessment of carbon capture technologies.

In view of multiple options of capture methods, the technical assessment of a capture method is mainly measured from the perspective of applicability and maturity in CO2 capture field. The criterion can be benchmarked by three levels: good, average and bad. The economic assessment is mainly measured based on current capital cost and operating cost and potential capital cost and operating cost by year 2025, when is the end year of phase 1 of the Plan of China's Coal Clean and High Efficiency Utilization Key Project in Facing 2030 Key Project Program (under developing). The operation time assumed to be 8000 hours/year and the final CO_2 product is in as gaseous at an

atmospheric pressure and temperature of 25℃.

Table 4-1 Characteristics of CO2 separation technologies

Technology		Suitable condition	Strength	Weakness
Absorption	Chemical method	Low CO_2 concentration gas source	High CO_2 recovery rate; commercial demonstration available	Chemical process, produce secondary pollution
	Physical method	High CO_2 concentration gas source	High separation efficiency, low energy consumption	high content CO_2 required
Adsorption	Pressure swing adsorption	High CO_2 concentration gas source	Less corrosion and environmental pollution, high CO_2 recovery rate	Large land use, complex system
	Temperature swing adsorption	High CO_2 concentration gas source	Less corrosion and environmental pollution, high CO_2 recovery rate	Slow temperature change, large land use, complex system
Membrane separation		High CO_2 concentration gas source	Small land use, simple system, easy operation and maintenance	High energy consumption, easy to be contaminated with particulate matter
Cryogenic distillation		High CO_2 concentration gas source	Liquefaction CO_2 can be obtained directly	High energy consumption, high investment, products can only be liquid

5.1 Techno-economic analysis of CO_2 capture from blast furnace gas

Taking a blast furnace gas (BFG) from a Chinese steel/iron mill as a case (Table 4-2), the content of combustible component CO accounts for about 21.8%, the content of CO_2 and N_2 are 23.1% and 51.7% respectively. Pressure is 206Kpa (gauge pressure) and temperature is 150℃. The particulate matter concentration in the gas stream is high containing saturated water moisture. The flue gas adopts a TRT system to recover energy in blast furnace gas. After TRT, pressure of the blast furnace gas is slightly higher than an atmospheric pressure, and the temperature is cooled to room temperature. The content of water is also reduced to a saturated level corresponding to the temperature and pressure. Therefore, there are two different gas sources for capture CO_2 from the blast furnace gas, i.e. flue gases before TRT and after TRT, respectively.

Table 4-2 Composition of typical blast furnace gas in Chinese steel/iron plant

Composition	CO_2	CO	H_2	N_2	O_2	H_2O
Vol %	23.1	21.8	3.2	51.7	0.2	Saturation

5.1.1. Technical performance

After dust removal and purification processes, the blast furnace gas before TRT still has

a temperature of 100℃ and a pressure of 0.2 to 0.3 Mpa. If the purity of the captured CO_2 is required to be industrial grade above for both internal and external uses, chemical absorption method is well technical suitable as it has advantages of high concentration of CO_2 capture through selective absorption and desorption, easy removal of other impurities, and proved by large-scale demonstration project in power-generation industry. It is suitable for the capture of large-scale low concentration CO_2, but the capture process involves chemical process which is complex to iron/steel industry, and the safety and environmental protection requirements for use and storage of absorbent are high. For internal use of small-scale capture, the absorption method is also applicable.

The adsorption method can also be used to produce large-scale high concentration CO_2, however, requiring large land space. The small-scale capture by adsorption is more applicable, due to reduced land use space. In contrast, the cryogenic method is not applicable for CO_2 capture for internal use, because the internal use CO_2 can be delivered through an internal pipeline without liquefaction. With respect to the membrane separation method, it is difficult to guarantee a CO_2 product quality of industrial grade above by membrane technology itself. hence, the applicability of technology only by membrane is poor. However, the combination of membrane separation method and adsorption method (PSA) can overcome the disadvantage of adsorption method (large land use), while ensuring a high quality product by adsorption method. Similarly, the integration of membrane separation with chemical absorption can also ensure a high quality CO_2 product, but it is challenged by complex of membrane separation and chemical reaction process in one system.

For external use of CO_2 with industrial grade above, the demand is normally small. The captured CO_2 needs to be pressurized and liquefied, and temporally stored in a high pressure and low-temperature storage tank. Then, it is transported to the designated site by a truck. Under this circumstance, except chemical absorption and pressure swing adsorption methods, cryogenic method can also be applied. The cryogenic method that combined with membrane separation or pressure swing adsorption can obtain liquefied CO_2 products directly, leading to the improvement of applicability.

Overall, for internal use of food grade or industrial grade above CO_2, absorption method is a mature technology, thus more applicable than other methods without consideration of its environmental impacts; otherwise, the combination of membrane and adsorption technology is more suitable. For external use of food grade or industrial grade CO_2, the scale of project is usually small as market demand is limited. As truck transportation is preferred, membrane separation or pressure swing adsorption combined with cryogenic distillation is also applicable.

In the situation that the captured CO_2 merely needs to meet requirements for general storage or internal use purposes (CO_2 concentration is greater than 95%) (Table 4-4), chemical absorption method is applicable, but the advantages are less obvious than

other technologies. The applicability of pressure swing adsorption method will be improved due to the reduced requirements of CO_2 product, especially for smaller scale, the disadvantage of land use is not so obvious. The use of cryogenic method depends mainly on whether the final CO_2 product needs to be liquefied. Because the concentration requirement of CO_2 product is low, membrane separation method becomes applicable. Through the integration of membrane separation and pressure swing adsorption methods, the weakness of large land use of pressure swing adsorption method will be overcome; integration of membrane and chemical absorption method can further enhance the applicability of absorption method, but the technology is still at early demonstration stage.

After the pressure energy of blast furnace gas is recovered by TRT, gas pressure drops slightly to environmental pressure level and temperature decreases to room temperature. Although the change of pressure will affect absorption, adsorption and membrane separation processes more or less. The effect on adsorption and membrane separation methods are slightly greater than that on absorption method, because the required pressure by adsorption and membrane separation is much higher than that of absorption method. Comparing before and after TRT, for membrane separation and pressure swing adsorption method, the main difference is that the investment of a compressor can be saved in the process as pressure of feed gas before TRT is high. Correspondingly, membrane separation and pressure swing adsorption methods are more suitable before TRT than after TRT.

To summarize, under low concentration requirement of CO_2 products, the applicability of adsorption and membrane separation methods has been improved effectively, especially that of the membrane separation method as its weakness of producing high concentration CO_2 is no longer exist. Further, if membrane separation and pressure swing adsorption are integrated, the applicability of the integrated technology may exceed the absorption method by year 2025, especially in the situation of small-scale CO_2 capture project.

Table 4-3 Technical applicability of technologies for industrial grade above CO2 from BFG prior to TRT

Product requirement	Technology options	Applicability	Advantage	Disadvantage
Internal use	Chemical absorption	Good	Easy to produce high concentration of CO_2, mature technology, less energy loss in feed gas.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2, can use pressure of feed gas before TRT, easy to be modular developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Bad	N/A	Difficult to obtain high purity CO_2 products alone.
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on

				environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Bad	N/A	Product of is in liquid state, not suitable for internal use.
External use	Chemical absorption	Good	Easy to produce high concentration of CO_2, mature technology, less energy loss in feed gas.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2, can use pressure of BFG before TRT, easy to be modular developed; reduced land use and unit size.	High pretreatment requirement, complex system
	Membrane separation	Bad	N/A	Difficult to obtain high purity CO_2 products alone.
	Cryogenic distillation	Average	Product in liquid state, it is suitable for tanker transportation.	Large land use and unit size
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane – cryogenic integration	Good	Product in liquid state, suitable for truck transportation.	Involves two processes of membrane and cryogenic separation and their integration; system is complex.

Table 4-4 Technical applicability of technologies for storage grade CO_2 from BFG prior to TRT

Product requirement	Technology options	Applicability	Advantage	Disadvantage
Internal use	Chemical absorption	Good	Easy to produce high concentration of CO_2, mature technology, less energy loss in feed gas.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2, can use pressure of feed gas before TRT, easy to be modular developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Good	Can produce storage grade CO_2, land use is small; system is simple; easy to modular development.	Lack of project demonstration, rely on membrane development.
	Cryogenic distillation	Bad	Product of is in liquid state, not suitable for internal use.	N/A
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Bad	Product of is in liquid state, not suitable for internal use.	N/A
External use	Chemical absorption	Good	Easy to produce high concentration of CO_2, mature technology, less energy loss in feed gas.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing	Good	Can produce high concentration of CO_2,	High pretreatment requirement,

adsorption		can use pressure of BFG before TRT, easy to be modular developed; reduced land use and unit size.	complex system	
Membrane separation	Good	Can produce storage grade CO_2, land use is small; system is simple; easy to modular development.	Lack of project demonstration, rely on membrane development.	
Cryogenic distillation	Average	Product in liquid state, it is suitable for tanker transportation.	Large land use and unit size	
Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.	
Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.	
Membrane – cryogenic integration	Good	Product in liquid state, suitable for truck transportation.	Involves two processes of membrane and cryogenic separation and their integration; system is complex.	

5.1.2. Economic analysis

a) Cost analysis

Because gas temperature and pressure are different before TRT and after TRT, the economic performance of each capture technology is also different before and after TRT. Under the case of capture rate of 90%, Tables 4-5 and 4-6 respectively illustrate the economics performance of capture technologies for CO_2 products with industrial grade above and storage grade from blast furnace gas before TRT.

For large-scale industrial grade CO_2 before TRT, the economics of chemical absorption method is the best with current technology, especially the investment cost is significantly lower than that of other methods. However, investment cost of membrane separation method will decrease relatively quickly as it is under a quick development in China. It is estimated that by 2025, the investment cost of membrane-pressure swing adsorption integration method might be close to that of absorption method, due to a pressure of 0.2-0.3Mpa before TRT can be utilized; meanwhile, its operating cost has obvious advantages over chemical absorption method. In the case of internal use only need 0.6Mpa compression pressure for CO_2 transportation, it is expected that by 2025, the cost of membrane-pressure swing adsorption method for blast furnace gas could be around $25-27. With the development of membrane absorption technology, its economic performance could keep up with that of chemical absorption method.

For storage grade CO_2, compare to other methods, the advantages of chemical absorption method will be lessened. CO_2 purity requirement has little influence on chemical absorption method in terms of either investment cost or operating cost; while pressure swing adsorption method and membrane separation method are sensitive to product requirements. It is very difficult especially for membrane separation method to satisfy technical requirements of high concentration CO_2. When the purity requirement is reduced, it is technically feasible for membrane separation method. With the funding

support of "membrane method capture CO_2 technology and industrial demonstration project" under the "coal clean and efficient utilization and new energy conversation technology" by Ministry of Science and Technology of China in 2017, it is believed that R&D of membrane technology would be accelerated in the next 5 years. It is expected that by 2025, the investment cost of large scale capture by membrane technology may be just a little bit higher than that of chemical absorption method. The investment cost and operating cost of membrane integrated with pressure swing adsorption technology would be highly possible less than that of chemical absorption method.

Before TRT, as the feed gas contains high pressure, the advantage of this high pressure on membrane separation and pressure swing adsorption method is far superior to the chemical absorption method. One direct benefit is that a large scale compressor for pressurized feed gas can be saved; in the case of after TRT, the investment of the compressor is necessary. The investment cost of a compressor is considerable due to the high volume of feed gas (Table 4-7).

Accordingly, the investment cost of pressure swing adsorption method, membrane separation method and membrane -pressure swing adsorption method after TRT is much higher than that of chemical absorption method. Even if after 2025, the investment cost of membrane separation and pressure swing adsorption methods after TRT is still significantly greater than that of chemical absorption method. Nevertheless, for the operating cost of membrane separation and pressure swing adsorption method, in view that the pressure energy in non-CO_2 airflow can be recycled through the existing TRT system, their operating cost won't be in disadvantageous position compared to chemical absorption method, especially after 2025.

For small scale capture of 100,000 tons/year, the investment cost of membrane separation and pressure swing adsorption technologies before and after TRT are different. The main reason is a high cost associated with a compressor after TRT. The difference of investment cost for chemical absorption method before and after TRT is very small. Hence, for small scale capture after TRT, the economic performance of membrane separation and pressure swing adsorption is far poorer than that of chemical absorption method; while the economics before TRT is just a little inferior to that of chemical absorption method.

Table 4-5 Economic performance of technologies for industrial grade above CO_2 capture from blast furnace gas before TRT (at capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)
Large scale (1.0 mtpa)	Chemical absorption	90-110	30-33	85-105	28-31
	PSA	110-130	29-31	90-110	27-29
	Membrane - absorption	100-120	30-33	90-110	28-31
	Membrane-	120-140	28-30	90-110	25-27

Scale					
	PSAintegration				
Small scale (0.1 mtpa)	Chemical absorption	11-13	30-33	10-12	28-31
	PSA	12-14	29-31	11-13	27-29
	Membrane - absorption	11-13	30-33	10-12	28-31
	Membrane-PSAintegration	13-15	28-30	10-12	25-27

Table 4-6 Economic performance of capture CO_2 of storage grade from blast furnace gas before TRT (at 90% capture rate)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)	Main changes compared with industrial grade above before TRT
Large scale (1.0 mtpa)	Chemical absorption	90-110	30-33	85-105	28-31	Investment and operation costs of chemical absorption method are not sensitive to the requirement of CO_2 products.
	PSA	105-125	28-30	100-120	26-28	Decrease of CO_2 product concentration requirement, lead to the reduction of investment and operating costs.
	Membrane separation	115-135	30-32	100-125	26-28	Membrane separation technology become feasible with reduced CO_2 product requirement; investment cost and operating cost of the membrane reduce significantly.
	Membrane absorption	100-120	30-33	90-110	28-31	Investment and operation costs of chemical absorption method are not sensitive to the requirement of CO_2 products.
	Membrane - PSA integration	110-130	27-29	80-100	24-26	Decrease of CO_2 product concentration requirement, lead to a significant reduction of investment and operating costs of membrane separation - PSA.
Small scale (0.1 mtpa)	Chemical absorption	11-13	30-33	10-12	28-31	Investment and operation costs of chemical absorption method are not sensitive to the requirement of CO_2 products.
	Pressure swing adsorption	11.5-13.5	28-30	10.5-12.5	26-28	Decrease of CO_2 product concentration requirement, lead to the reduction of investment and operating costs.
	Membrane separation	12-14	30-32	10.5-12.5	26-28	Membrane separation technology become feasible with reduced CO_2 product requirement; investment cost and operating cost of the membrane reduce significantly.
	Membrane absorption	11-13	30-33	10-12	28-31	Investment and operation costs of chemical absorption method are not sensitive to the requirement of CO_2 products.
	Membrane separation – pressure swing adsorption	12-14	27-29	9.5-11.5	24-26	Decrease of CO_2 product concentration requirement, lead to a significant reduction of investment and operating costs of membrane separation - PSA.

Table 4-7 Economic performance of technologies for industrial grade above CO_2 capture from blast furnace gas after TRT (capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)	Main changes between prior to TRT and after TRT
Large scale (1.0 mtpa)	Chemical absorption	90-110	30-33	85-105	28-31	Investment and operating costs are unchanged.
	PSA	125-145	30-32	105-115	28-30	Compressor is added, leading to rise of investment and operating costs significantly.
	Membrane - absorption	90-110	30-33	85-105	28-31	Investment and operating costs are unchanged.
	Membrane-PSA integration	135-155	29-31	115-135	26-28	Compressor is added, leading to rise of investment and operating costs significantly.
Small scale (0.1 mtpa)	Chemical absorption	11-13	30-33	10-12	28-31	Investment and operating costs are unchanged.
	PSA	14.5-16.5	30-32	13.5-15.5	28-30	Compressor is added, leading to rise of investment and operating costs significantly.
	Membrane - absorption	11-13	30-33	10-12	28-31	Investment and operating costs are unchanged.
	Membrane-PSA integration	15.5-17.5	29-31	12.5-14.5	26-28	Compressor is added, leading to rise of investment and operating costs significantly.

Table 4-8 Economic of capture CO_2 of storage grade from blast furnace gas before TRT (90% capture rate)

Scale	Technology options	Investment cost (million $)	Operating cost ($/ton)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/ton)	Main changes between prior to and after TRT
Large scale (1.0 mtpa)	Chemical absorption	90-110	30-33	85-105	28-31	Investment and operating costs are unchanged.
	Pressure swing adsorption	130-150	29-31	110-130	27-29	Compressor is added, leading to rise of investment and operating costs significantly.
	Membrane separation	130-150	31-33	115-135	27-29	Compressor is added, the investment cost and operating cost rise significantly.
	Membrane absorption	100-120	30-33	90-110	28-31	Investment cost and operating cost are unchanged.
	Membrane separation – pressure swing adsorption	125-145	28-30	95-105	25-27	Compressor is added, leading to rise of investment and operating costs significantly.
Small scale (0.1 mtpa)	Chemical absorption	11-13	30-33	10-12	28-31	Investment and operating costs are unchanged.
	Pressure swing adsorption	14-16	29-31	13-15	27-29	Compressor is added, leading to rise of investment and operating costs significantly.
	Membrane separation	14.5-16.5	31-33	12.5-14.5	27-29	Compressor is added, leading to rise of investment and operating costs significantly.

Membrane absorption	11-13	30-33	10-12	28-31	Investment cost and operating cost are unchanged.
Membrane separation – pressure swing adsorption	14.5-16.5	28-30	12-14	25-27	Compressor is added, leading to rise of investment and operating costs significantly.

b) Benefit analysis

On the one hand, capturing CO_2 from blast furnace gas (BFG) can reduce emission CO_2, while the captured CO_2 can be used to place nitrogen in iron/steel making processes; on the other hand, removal of CO_2 from BFG will increase the calorific value of BFG. In case that CO_2 is used to replace nitrogen. Supposing one cubic meter of CO_2 is equivalent to one cubic meter of nitrogen, the benefit of one tonne CO_2 is about US$15.0/ton when internal price of nitrogen is US$0.03/m^3. If the captured CO_2 can be sold to oil companies for enhancing oil recovery, the price of CO_2 can reach US$20/tonne in China. In fact, when CO_2 concentration meets industrial grade or food grade requirements, market sale price can be as high as US$60.0/ tonne.

Because of its low calorific value of raw BFG, before CO_2 removal, BFG needs to be mixed with coke oven gas which has high calorific value. Take a mixing ratio of 9:1 as an example, (i.e., nine blast furnace gases mix with one coke oven gas). Based on a case of Chinese iron/steel plant, the unit price of blast furnace gas (BFG) and coke oven gas (COG) is assumed to be US$0.02/Nm^3, respectively. Consequently, the unit price of original gas mixture will be US$0.046/Nm^3. The benefit of blast furnace gas with CO_2 removal is mainly due to the rise of its calorific value in response to the reduced use of coke oven gas. Under different capture rate, the extent of CO_2 removal is different, thus the extent of calorific value increase is also different. Accordingly, the ratio requirement between blast furnace gas and coke oven gas is also different, leading to the cost of mixed gas is also different. The unit cost and benefit of mixed gas with CO_2 removal are shown in Table 4-9. It is indicated that the higher the capture rate, the more the calorific value increases, the higher the benefit.

Although more CO_2 can be removed with high capture rate, resulting in the rise of the combustion calorific value of blast furnace gas, both investment cost and operating cost of capture technologies may be more expensive under high capture rate. For chemical absorption method, it is easy to achieve 90% capture rate, while for membrane separation and PSA methods, when capture rate reaches 90%, the investment cost and operating cost could be very high. In case that the capture rate is reduced to 85%, the investment cost and operating cost of membrane separation and PSA methods could be significantly reduced. Therefore, it is necessary to comprehensively justify the costs and the benefits of CO_2 based on a real specific business case,

Table 4-9 Caloric value benefit of CO_2 capture from BFG under different capture rate

Item	Capture rate	BFG proportion	COG proportion	Original cost of mixed gas at ratio of 9:1 of BFG and COG (US$/Nm3)	Unit cost of mixed gas after CO2 removal (US$/Nm3)	Benefit of CO2 capture from BFG (US$/Nm3)
1	100%	0.988	0.012	0.046	0.023	0.023
2	95%	0.984	0.016	0.046	0.024	0.022
3	90%	0.98	0.02	0.046	0.025	0.021
4	85%	0.976	0.024	0.046	0.026	0.020
5	80%	0.973	0.027	0.046	0.027	0.019
6	70%	0.966	0.034	0.046	0.029	0.017
7	60%	0.959	0.041	0.046	0.031	0.15

5.2. Techno-economic analysis of CO_2 capture from lime kiln flue gas

5.2.1. Technical performance

The CO_2 in lime kiln flue gas is directly sourced from the calcination of lime. The composition of lime kiln flue gas is similar to that of coal-fired power generation flue gas. CO_2 concentration is about 15-20% in lime kiln flue gas, which is only a little higher than 11-15% concentration of flue gas of coal-fired power plant, therefore, most of the methods and processes of post-combustion CO_2 capture used by coal-fired power plant basically can be used as a reference to CO_2 capture from lime kiln flue gas by iron/steel industry. Tables 4-10 and 4-11 show the technical performance of capture methods for lime kiln flue gas. Compared to blast furnace gas, the CO_2 concentration of lime kiln flue gas is slightly lower; thus, applicability of chemical absorption method for capturing industrial grade above CO_2 is further improved compared to PSA and membrane separation methods. For the capture of storage grade CO_2, due to the lack of hydrogen and other impurities in lime kiln flue gas, the applicability of membrane separation CO_2 could also be improved, however, the applicability is still at an average level due to the low CO_2 concentration in flue gas. The cryogenic method could be more applicable in case that CO_2 product is required to be transported in liquid phase.

Compared to blast furnace gas, another difference is that the nitrogen composition in lime kiln feed gas is high. After the pressurized feed gas pass through membrane or adsorption adsorbents, the nitrogen content in the gas stream is increased due to removal of CO_2. Without further pressurized, the gas stream with higher nitrogen content can directly generate high purity nitrogen by other nitrogen separation

technologies such as membrane and thus produce nitrogen by-product with low costs. Regarding to chemical absorption method, the separation of nitrogen from gas stream still requires additional pressure and pretreatment.

From the perspective of technical maturity, a 100 kilo tonnes per year demonstration project by PSA technology for capturing CO_2 from lime kiln flue gas was carried out by Shougang Jingtang steel plant located in Tangshan, China.

Although there is no demonstration projected reported on chemical absorption method, it can be directly applied to lime kiln flue gas with no doubt as it plenty of experience of post-combustion capture demonstration in coal-fired power plant which can certainly referred. Currently membrane separation method lacks technical demonstration, so the maturity of this technology is poor. However, with the accomplishment of the MOST funded "membrane method capture CO_2 technology and industrial demonstration project" under the "coal clean and efficient utilization and new energy conversation technology" by 2022. It can be reasonably estimated that the maturity of membrane method could have a significant improvement by year 2025.

Table 4-10 Technical of capture methods for industrial grade CO_2 from lime kiln flue gas

Product requirement	Technology options	Applicability	Advantage	Disadvantages
Internal use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2; can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Bad	N/A	Poor system reliability, lack of technology demonstration; difficulty to produce high concentration CO_2
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system reliability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Bad	N/A	Product of is in liquid state, not suitable for internal use.
External use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2; can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system

	Membrane separation	Bad	N/A	Poor system reliability, difficult to obtain high purity CO_2 products alone.
	Cryogenic distillation	Bad	N/A	CO_2 concentration is too low.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Good	Product of is in liquid state, suitable for external use by small scale.	Not suitable for pipeline transportation in super-critical phase.

Table 4-11 Technical of capture methods for storage grade CO_2 from lime kiln flue gas

Product requirement	Technology options	Applicability	Advantage	Disadvantages
Internal use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Average	Can produce storage grade CO_2 and can be modularly developed.	Poor system reliability, lack of technology demonstration.
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Bad	N/A	Product of is in liquid state, not suitable for internal use.
External use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Average	Can produce storage grade CO_2 and can be modularly developed.	Poor system reliability, lack of technology demonstration.
	Cryogenic distillation	Bad	N/A	CO_2 concentration is too low.

	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Good	Product of is in liquid state, suitable for external use by small scale.	Not suitable for pipeline transportation in super-critical phase.

5.2.2. Economic analysis

Comparatively, because the CO_2 concentration in lime kiln flue gas is slightly higher than in coal-fired power generation flue gas, investment and operating costs of the corresponding technology are slightly lower than post-combustion CO_2 capture in the coal-fired power plant, while also lower than capture technologies applicable to blast furnace gas capture. When considering nitrogen recovery, the investment cost will increase more. Tables 12 and 13 give the economic performance of CO_2 products by industrial above grade and storage grade, respectively.

For the capture of industrial grade above CO_2, the investment cost of chemical absorption method is far below that of pressure swing adsorption and other methods; even by 2025, it is still the case. For operating cost, chemical absorption method is lower than that of other methods under current technical condition, however, it might be at the same level as other methods by 2025. Because membrane method and pressure swing adsorption method are easy to produce high purity nitrogen as a by-product, the economics of membrane and pressure swing adsorption methods can be greatly improved, and can probably be higher than chemical absorption method, when this nitrogen benefit is included, At an internal price of nitrogen being USD0.03/Nm^3, the benefit of nitrogen product could be as high as USD22.0/tonne. Take a lime kiln flue gas with 17% CO_2 and 72% nitrogen as an example, capture one tonne CO_2 can generate about \$53 of nitrogen benefit under scenario of CO_2 capture rate being 90%, and nitrogen capture rate being 80%.

Table 4-12 Economic performance of technologies for industrial grade above from lime kiln flue gas (at capture rate of 90%)

Scale	Technology options	Investment cost (million \$)	Operating cost (\$/ton)	Investment cost by 2025 (million \$)	Operating cost by 2025 (\$/ton)
Large scale (1.0 mtpa)	Chemical absorption	100-120	32-35	95-115	30-33
	PSA	140-160	33-35	120-140	30-33
	PSA & N_2 recovery	150-170	36-38	140-160	33-35
	Membrane	100-120	32-35	95-115	30-33

	absorption				
	Membrane-PSA integration	145-165	32-34	120-140	29-31
	Membrane-PSA integration & N$_2$ recovery	155-175	35-37	130-150	32-34
Small scale (0.1 mtpa)	Chemical absorption	13-15	32-35	13-15	30-33
	PSA	16-18	33-35	14-16	30-33
	PSA & N$_2$ recovery	17-19	36-38	16-18	33-35
	Membrane absorption	13-15	32-35	13-15	30-33
	Membrane-PSA integration	16-18	32-34	13-15	29-32
	Membrane-PSA integration & N$_2$ recovery	18-20	35-37	16-18	32-35

Table 4-13 Economic performance of technologies for storage grade from lime kiln flue gas (at capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/ton)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/ton)
Large scale (1.0 mtpa)	Chemical absorption	100-120	32-35	95-115	30-33
	PSA	130-150	32-34	110-130	29-32
	PSA & N$_2$ recovery	140-160	35-37	130-150	32-34
	Membrane absorption	100-120	32-35	95-115	30-33
	Membrane separation	135-155	33-35	105-125	29-32
	Membrane- & N$_2$ recovery	145-165	36-38	105-125	32-35
	Membrane-PSA integration	135-155	31-33	110-130	28-30
	Membrane-PSA integration & N$_2$ recovery	145-165	34-36	120-140	31-33
100,000 tons/year	Chemical absorption	13-15	32-35	13-15	30-33
	pressure swing adsorption	15-17	32-34	13-15	29-32
	Adsorption + N$_2$ recovery	16-18	35-37	15-17	32-34
	Membrane absorption	13-15	32-35	13-15	30-33
	Membrane separation	15-17	33-35	13-15	29-32
	Membrane separation + N$_2$ recovery	16-18	36-38	15-17	32-34
	Membrane separation – pressure swing adsorption	15-17	31-33	12-14	28-31
	Membrane separation – pressure swing adsorption + N$_2$ recovery	17-19	34-36	15-17	31-34

5.3. Techno-economic analysis of CO_2 capture from for hot blast furnace flue gas

5.3.1. Technical analysis

Hot blast furnace is one of the important facilities in the process of iron-making. Although the flue gas produced by a single hot blast furnace is generated intermittently, in the actual production process, multiple hot blast furnaces share one flue gas discharge pipeline; therefore, at the end of the pipeline, the discharge of flue gas is almost continuous. The temperature of hot blast furnace flue gas is usually high, being about 250-300°C; on the one hand, the high temperature has influence on some carbon capture technologies; on the other hand, the high temperature waste heat can also be recycled to offset the energy consumption of carbon capture.

The composition of a typical hot blast furnace flue gas in Chinese steel/iron plant is shown in Table 4-14. The CO_2 concentration is 28.52%, which is much higher than that of blast furnace gas, lime kiln flue gas and other major CO_2 emission sources in a steel plant. This high concentration of hot blast flue gas can not only benefit the applicability of chemical absorption method, but also pressure swing adsorption method and membrane separation method (Table 4-15). However, the high temperature of flue gas could affect the chemical absorbent consumption and the use of pressure swing adsorption. The advantages of absorption method and pressure swing adsorption method are able to play well when the temperature is reduced; for the membrane separation method, by using high temperature resistant membrane materials, such as zeolite membrane, it can be operated at high temperature; while for pressure swing adsorption method, the high temperature has a negative effect.

Specifically, capture CO_2 with industrial grade above by large scale for internal use, the chemical absorption method is more applicable, although there is a negative effect of high temperature. Due to the higher CO_2 concentration in feed gas, the applicability of pressure swing adsorption method is improved. Similarly, the applicability of the pressure swing adsorption method integrated with membrane separation will also be more enhanced than that of a simple adsorption method. For the storage grade capture, both absorption and pressure swing adsorption methods can be applied when the temperature is reduced, compared to lime kiln flue gas and blast furnace gas, membrane separation method is more applicable. The applicability of pressure swing adsorption integrated with membrane separation will be further improved.

Similar to lime kiln flue gas, the nitrogen composition of hot blast furnace gas is high. After the pressurized feed gas passes through membrane material or pressure swing adsorption unit, the nitrogen content in the gas stream is increased due to removal of CO_2. Without further pressurized, the gas stream with higher nitrogen content can directly generate high purity nitrogen by other nitrogen separation technologies such as membrane and thus produce nitrogen by-product with low costs. While for the chemical absorption method, the gas stream rich in nitrogen still requires further high energy

consumption to separate nitrogen. It is difficult for chemical absorption method itself to obtain high purity nitrogen as a by-product.

From the perspective of technology maturity, the maturity of chemical absorption method is higher than that of membrane separation and pressure swing adsorption. The composition of flue gas from a hot blast furnace contains high concentration CO_2, hence, the experience of industrial gases separation by membrane separation method and pressure swing adsorption method can be referred, although there is still lack of direct technical demonstrations of these two methods.

Table 4-14 Composition of hot blast furnace flue gas of a typical China's steel/iron plant

Composition	CO_2	N_2	O_2	H_2O	Ash/(mg·m^{-3})
Hot blast furnace flue gas	28.52	65.15	2.51	3.82	5

Table 4-15 Technical performance of technologies for hot blast furnace flue gas

Product requirement	Technology	Applicability		Disadvantages
Industrial grade	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	pressure swing adsorption	Average	Easy to be modularly developed, can produce by-product nitrogen.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Bad	N/A	Poor system reliability, lack of technology demonstration.
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Average	Product is in liquid state, suitable for external use by small scale.	Product of is in liquid state, not suitable for internal use.
Storage grade	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressure swing adsorption	Good	Easy to be modularly developed, can produce by-product nitrogen.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Good	Can be modularly developed, can produce by-product nitrogen.	Poor system reliability, lack of technology demonstration.
	Cryogenic distillation	Bad	N/A	CO_2 concentration is too low.
	Membrane –	Average	Can guarantee high	Involves integration of membrane

	absorption integration		concentration of CO_2; can reduce land use.	and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Average	Product is in liquid state, suitable for external use by small scale.	Not suitable for pipeline transportation in super-critical phase.

5.3.2. Economic analysis

The CO_2 concentration in hot blast furnace flue gas is higher than that in blast furnace gas. It is nearly double the CO_2 concentration in lime kiln flue gas. The investment and operating costs of the corresponding capture technologies are far less than that of hot blast furnace gas and blast furnace gas. When considering the recovery of nitrogen, the investment cost will increase. Tables 4-16 and 4-17 give the economics of CO_2 product of industrial grade and storage grade, respectively.

For capture of industrial grade above CO_2, the investment cost of chemical absorption method is still lower than that of PSA and other methods, even by 2025. However, compared with blast furnace gas, this gap is much smaller. The operating cost of PSA method is low. By 2025, the operating cost of pressure swing adsorption method may be lower than that of absorption method. In particular, membrane-PSA integration method is very likely to be lower than absorption method. If considering the benefit of by-product nitrogen, the cost of membrane-PSA integration method can be greatly improved, and will be lower than that of chemical absorption method.

For CO_2 capture of storage grade, the economics of chemical absorption method is slight lower than that of industrial grade capture. The investment cost and operating cost of PSA method will be further declined. The cost of membrane separation is also close to the cost of absorption method and PSA method. It may likely be lower than the cost of PSA method in 2025. The cost of membrane-PSA integration method could be further reduced than that of single membrane separation method and single PSA method. At an internal price of nitrogen being USD0.03/Nm^3, the benefit of nitrogen product could be as high as USD22.0/tonne. Take a lime kiln flue gas with 28% CO_2 and 65% nitrogen as an example, capture one tonne CO_2 can generate about $30 of nitrogen benefit under scenario of CO_2 capture rate being 90%, and nitrogen capture rate being 80%. Compared with the capture of lime kiln flue gas, although the cost of CO_2 capture decreases, the benefit of nitrogen also decreases.

Table 4-16 Economic performance of technologies for industrial grade above from hot blast furnace flue gas (at capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)

Scale	Technology options	Investment cost (million $)	Operating cost ($/ton)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/ton)
Large scale (1.0 mtpa)	Chemical absorption	80-100	28-30	75-95	27-29
	PSA	110-130	28-30	100-120	26-28
	PSA & N_2 recovery	125-145	31-33	115-135	29-31
	Membrane absorption	80-100	28-30	75-95	27-29
	Membrane-PSA integration	120-140	27-29	110-130	25-27
	Membrane-PSA integration & N_2 recovery	135-155	33-35	120-140	30-32
Small scale (0.1 mtpa)	Chemical absorption	11-13	28-30	10-11	27-29
	PSA	13-15	28-30	12-14	26-28
	PSA & N_2 recovery	15-17	31-33	14-16	29-32
	Membrane absorption	11-13	28-30	10-11	27-29
	Membrane-PSA integration	14-16	27-29	13-15	25-27
	Membrane-PSA integration & N_2 recovery	16-18	33-35	16-18	30-32

Table 4-17 Economic performance of technologies for storage grade above from hot blast furnace flue gas (at capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/ton)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/ton)
Large scale (1.0 mtpa)	Chemical absorption	80-100	28-30	75-95	27-29
	PSA	100-120	27-29	90-110	25-27
	PSA & N_2 recovery	110-130	30-32	100-120	28-30
	Membrane absorption	80-100	28-30	75-95	27-29
	Membrane seperation	105-125	28-30	90-110	25-27
	Membrane- & N_2 recovery	115-135	31-33	100-120	28-30
	Membrane-PSA integration	110-130	28-30	95-115	25-27
	Membrane-PSA integration & N_2 recovery	120-140	31-33	105-125	28-30
Small scale (0.1 mtpa)	Chemical absorption	11-13	28-30	10-11	27-29
	PSA	12-14	27-29	11-13	25-27
	PSA & N_2 recovery	14-16	30-32	13-15	28-30
	Membrane absorption	11-13	28-30	10-11	27-29
	Membrane seperation	13-15	28-30	11-13	25-27
	Membrane- & N_2 recovery	15-17	31-33	13-15	28-30
	Membrane-PSA	13-15	26-28	12-14	24-26

	integration				
	Membrane-PSA integration & N$_2$ recovery	15-17	29-31	14-16	27-29

5.4. Techno-economic analysis of CO$_2$ capture for Linz-Donawitz gas

In a Linz-Donawitz steel-making process, under high temperature, carbon in molten iron reacts with blown oxygen to generate a mixture of carbon monoxide and a small amount of carbon dioxide. The recovered Linz-Donawitz gas (LDG) contains about 60% of CO, 15~20% of CO$_2$, as well as nitrogen, hydrogen and trace oxygen. Capturing CO$_2$ from Linz-Donawitz gas is not only the need for carbon reduction, but also anti-corrosion of gas pipe caused by the presence of CO$_2$. Because the amount of Linz-Donawitz gas is not generated at a stable level in a smelting process, the gas usually needs to be stored in a gas cabinet temporarily after full dusting and cooling. The capacity of the gas cabinet determines the gas buffer time in the gas cabinet. With the gas cabinet storage, "intermittent producing, continuous use" of the gas can be realized. CO$_2$ in the gas stream can be captured either before the gas stream enters the cabinet or after the gas stream enters the cabinet. Capturing CO$_2$ before the cabinet can reduce the volume of the gas stream, and increase the buffer efficiency of a cabinet; on the other hand, the dissolution of CO$_2$ is reduced at a water sealing process through removing CO$_2$ in the gas stream, thereby, the corrosivity of the gas stream is further undermined. When capturing CO$_2$ after the gas cabinet, the corresponding gas volume can be continuous and stable which is particularly helpful to some capture technologies.

5.4.1. Technical analysis

For capture CO$_2$ from a LDG stream before a gas cabinet, whatever the captured CO2 product is at industrial above grade or storage grade, whatever it is by large scale or small scale, overall, the technical applicability of chemical absorption method and membrane-absorption method is obviously better than that of other methods. The main reason is that the intermittence of Linz-Donawitz gas before a cabinet storage has less influence on a chemical absorption process, while greater influence on membrane separation and pressure swing adsorption processes that require compression operation of a compressor. Especially for a centrifugal compressor, a gas stream without stable volume can result in many technical problems (Table 4-18).

However, when capture CO$_2$ from LDG stream after a gas cabinet, if capturing CO$_2$ for internal use, pressure swing adsorption method and membrane separation method can also be applicable since feed gas stream can be adjusted at stable level with the cabinet. Another technical advantage of membrane and PSA separation methods is that the CO2 removed gas stream can be directly transported through pipeline without further pressure because the feed gas has been pressurized for removal the CO$_2$. The integration of membrane separation and PSA can further enhance the advantage. If capturing CO$_2$ for industrial grade above, absorption method is more applicable (Tables 4-19 and 4-

20).

Table 4-18 Technical performance of technologies for Linz-Donawitz gas before cabinet

Technological options	Technical applicability	Main reasons	Disadvantages
Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
Pressured swing adsorption	Bad	Compressor is difficult to operate under an intermittent condition.	High pretreatment requirement, large land use and unit size, complex system
Membrane separation	Bad	Compressor is difficult to operate under an intermittent condition.	Poor system reliability, lack of technology demonstration.
Cryogenic distillation	Bad	Compressor is difficult to pressurize the intermittent gas.	N/A
Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.

Table 4-19 Technical performance of technologies for industry grade above CO_2 from Linz-Donawitz gas after cabinet

Product requirement	Technology options	Applicability	Advantage	Disadvantages
Internal use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressured swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Bad	N/A	Poor system reliability, lack of technology demonstration; difficulty to produce high concentration CO_2
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane–cryogenic integration	Bad	N/A	Product of is in liquid state, not suitable for internal use.
External use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves a chemical process, the system is complex, negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed.	High pretreatment requirement, large land use and unit size, complex system

	Membrane separation	Bad	N/A	Poor system reliability, difficult to obtain high purity CO_2 products alone.
	Cryogenic distillation	Bad	N/A	CO_2 concentration is too low.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Good	Product of is in liquid state, suitable for external use by small scale.	Not suitable for pipeline transportation in super-critical phase.

Table 4-20 Technical performance of technologies for storage grade CO_2 from Linz-Donawitz gas after cabinet

Product requirement	Technology options	Applicability	Advantage	Disadvantages
Internal use	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on environment.
	Pressure swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed, LDG after CO_2 removal can enter pipeline without addition pressure	High pretreatment requirement, large land use and unit size, complex system
	Membrane separation	Average	Can be modularly developed. LDG after CO_2 removal can enter pipeline without addition pressure	Poor system reliability, lack of technology demonstration.
	Cryogenic distillation	Bad	N/A	Product of is in liquid state, not suitable for internal use.
	Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
	Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability. LDG after CO_2 removal can enter pipeline without addition pressure.	Involves two processes of membrane and PSA and their integration; system is complex.
	Membrane– cryogenic integration	Bad	N/A	Product of is in liquid state, not suitable for internal use.
External use of storage grade	Chemical absorption	Good	Capable of producing high concentration CO_2, mature technology.	Involves chemical process, complex system and negative effect on

			environment.
Pressure swing adsorption	Average	Can produce high concentration of CO_2 and can be modularly developed. LDG after CO_2 removal can enter pipeline without addition pressure	High pretreatment requirement, large land use and unit size, complex system
Membrane separation	Average	Can be modularly developed; LDG after CO_2 removal can enter pipeline without addition pressure	Poor system reliability, lack of technology demonstration.
Cryogenic distillation	Bad	N/A	CO_2 concentration is too low.
Membrane – absorption integration	Average	Can guarantee high concentration of CO_2; can reduce land use.	Involves integration of membrane and chemical absorption; complex system, and negative impacts on environment; immature technology.
Membrane – adsorption integration	Good	Can produce high concentration CO_2; reduced land use and facility size; enhanced system stability; LDG after CO_2 removal can enter pipeline without addition pressure	Involves two processes of membrane and PSA and their integration; system is complex.
Membrane– cryogenic integration	Good	Product of is in liquid state, suitable for external use by small scale; LDG after CO_2 removal can enter pipeline without addition pressure	Not suitable for pipeline transportation in super-critical phase.

5.4.2. Economic Analysis

Before a Linz-Donawitz gas enters a cabinet, chemical absorption is cost-effective to capture CO_2 of industrial grade above and storage grade. For the project of million tonnes/year scale (large scale), because of the intermittency of feed gas, the investment cost of such a large-scale project will be greater than that of post-combustion capture project with the same concentration in a coal-fired power plant. The operating cost of a project is only slightly higher than that of the post-combustion capture project in coal-fired power plant, because the costs mostly depend on energy consumption of absorption and desorption processes, which are less affected by the intermittency of feed LDG stream. Removing CO_2 from a Linz-Donawitz gas can not only increase the calorific value of the gas, but also increase the efficiency of gas storage cabinets and reduce the corrosive effect of the gas on the subsequent device and equipment. In addition, the capture process can also contribute partially to cool the gas, thus save the capital and operating costs of cooling equipment.

Regarding the CO_2 from LDG stream after a gas cabinet, a chemical absorption method is also cost effective. The investment cost is further reduced significantly while the operating cost also reduces as the feed gas has a stable volume. However, the feed gas before cabinet has a high corrosivity to the cabinet, and the utilization efficiency of the cabinet is also poor. Currently, the investment cost of PSA and membrane separation methods that are applicable to storage grades are far higher than that of chemical

absorption method, however, after 2025, the investment cost could decrease significantly. When considering the energy consumption saved in the subsequent compressing process that ensure the gas transported through a pipeline under high pressure, the operating cost may further decrease. Considering this cost saving, by 2025, the overall cost of the technology that integrates membrane separation with PSA is probably close to the cost of chemical absorption method (Table2 4-21 and 4-22).

Table 4-21 Economic performance of technologies for industrial grade above CO_2 from Linz-Donawitz gas after cabinet (at capture rate of 90%)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)
Large scale (0.1 mtpa)	Chemical absorption	110-130	33-36	100-120	31-34
	adsorption	160-180	35-37	140-160	32-34
	Membrane absorption	130-150	33-36	120-140	31-34
	Membrane separation – pressure swing adsorption	160-180	36-38	140-160	32-34
Small scale (0.1 mtpa)	Chemical absorption	15-17	33-36	14-16	31-34
	Pressure swing adsorption	18-20	35-37	16-18	i
	Membrane absorption	16-18	33-36	15-17	31-34
	Membrane separation – pressure swing adsorption	18-20	36-38	16-18	33-34

Table 4-22 Economic of capture CO_2 of storage grade after Linz-Donawitz gas enters the gas cabinet (90% capture rate)

Scale	Technology options	Investment cost (million $)	Operating cost ($/tonne)	Investment cost by 2025 (million $)	Operating cost by 2025 ($/tonne)
Large scale (0.1 mtpa)	Chemical absorption	110-130	33-36	100-120	31-34
	Adsorption	150-170	34-36	130-150	31-33
	Membrane absorption	110-130	33-36	100-120	31-34
	Membrane separation	150-170	35-37	130-150	32-34
	Membrane separation – pressure swing adsorption	150-170	35-37	130-150	31-33
Small scale (0.1 mtpa)	Chemical absorption	15-17	33-36	14-16	31-34
	pressure swing adsorption	17-19	34-36	15-17	31-33
	Membrane	15-17	33-36	14-16	31-34

absorption				
Membrane separation	17-19	35-37	15-17	32-34
Membrane separation – pressure swing adsorption	17-19	35-37	15-17	32-34

5.5. Techno-economic analysis of CO_2 capture for flue gas from coke oven and power generation unit

The coke oven flue gas in a steel/iron plant is sourced from combustion for heating a coke oven. It is the combustion product of fossil fuel in a coke oven and discharged through a coke oven chimney. The flue gas sourced from power generation unit mainly comes from combustion of fuel, such as BFG, COG, coal, natural gas. The sources and the compositions of flue gases from coke oven and power generation unit are similar, with the CO_2 concentration being between 10% and 15%. Therefore, a technology that is applicable to one is roughly applicable to the other.

For capturing storage grade CO_2 from a post-combustion flue gas stream with low concentration CO_2, the chemical absorption method is the most suitable among current available capture technologies. So far, there have already been large-scale post-combustion capture demonstration projects in operation in Canada and US, respectively. The technologies and experiences leant from those two projects can be referred to capture of flue gas from a coke oven and a power generation unit in a steel/iron plant. Although the PSA method and membrane separation method are also suitable for carbon capture of storage grade, however, it is still in a technological demonstration stage for flue gas from power-generation processes. Even by 2025, it is estimated that it is difficult for large-scale commercial application mainly because the CO_2 concentration in the flue gas is very low. By 2025, membrane-absorption integration method may become gradually technical mature.

As for economic performance, whatever investment cost or operating cost, chemical absorption method is mostly dominant over other methods, such as PSA method and membrane separation method. By year 2025, membrane-absorption method that integrates chemical absorption with membrane separation would further reduce its investment cost and operating cost. It is likely that its economic is getting better than an absorption method. Membrane separation method and PSA method as well as their integration are unlikely to be economically superior to the chemical absorption method by 2025.

5.6. Discussions

In a typical production process of steel/iron in China, main CO_2 emission sources include: lime kiln flue gas, hot blast furnace gas (HBFG), blast furnace gas (BFG), Linz-Donawitz gas (LDG), and flue gas from coke oven and power generation unit.

CO$_2$ concentration as well as temperature, pressure and impurity content of these emission sources are different; therefore, technical applicability and economic performance of capture technologies are also different when applied to different emission sources. Generally, chemical absorption method is suitable for low concentration gas and PSA, membrane separation and cryogenic distillation methods are suitable for high concentration gas, while membrane separation, PSA and cryogenic methods and their integration are also suitable for gas stream with pressure over ambient environment level, such as blast furnace gas before TRT.

The different demands on captured CO$_2$ product also affect technical applicability and economic performance of capture technologies. In general, chemical absorption method is more suitable for obtaining CO$_2$ of industrial level above than other methods. Membrane separation and PSA methods and their integration are also suitable for storage grade CO$_2$. capture; while cryogenic distillation method is not suitable for large-scale capture of low CO$_2$ concentration gas in steel/iron plant, but it is applicable when integrated with membrane separation or PSA method for capture small-scale CO$_2$ product with liquefaction requirement.

The technical applicability and economic performance of capture technologies are also affected by by-product opportunity associated with the removal of CO$_2$. For instance, the value of blast furnace gas can be raised by CO$_2$removal; flue gas of hot blast furnace and lime kiln can produce a by-product of nitrogen; corrosivity of Linz-Donawitz gas can be lessened after CO$_2$ removal.

The technical applicability and economic performance of capture technologies are also depended on capture rate. Chemical absorption method is less influenced by capture rate than that membrane separation and PSA methods. Under a low CO$_2$ concentration condition, membrane separation and pressure swing adsorption technologies are difficult to achieve a capture with rate of 90%. Even if it can be achieved through their integration, investment and operation costs would be increased significantly. It is good for membrane separation and PSA methods and their integration to improve their technical applicability and economic performance by acceptance of a capture rate as low as 85%. The optimal capture rate should be identified through a comprehensive analysis of capture cost and benefit in a system framework.

For China's steel/iron industry, take technical applicability and economic performance of various technologies into consideration comprehensively, it is recommended that capture on blast furnace gas, hot blast furnace gas and flue gas from lime kiln be prioritized due to the following main reasons: (1) high concentration of CO2 in those gas stream; (2) calorific value of BFG can be significantly improved by removal of CO$_2$; (3) nitrogen gas, which is highly demanded by iron/steel industry, can be obtained as a co-benefit to the capture. Though the CO$_2$ concentration of lime kiln flue gas is lower than hot blast furnace gas, by-product nitrogen benefit is higher than that gas.

In fact, if taking all major carbon emission sources into account in a whole, carbon

capture for iron/steel industry could be another different case, in view of interactions among carbon capture from various sources, For example, high temperature feature of hot blast furnace gas and Linz-Donawitz gas can be used for absorbent regeneration by chemical absorption method; as the result of CO2 capture, calorific value increasing of blast furnace gas can reduce the amount of feed gas for hot blast furnace heating, coke oven heating and power generation, thus could increase the CO_2 concentration in their flue gases. It is then beneficial to improve the economic performance of further capture from those gases. In short, the technical applicability and economic performance of carbon capture technologies for a steel/iron industry could be affected by multiple factors and their interactions under different conditions, it is necessary to carry out future research with a real-world business case to assess the technical applicability and economic performance of CO_2 capture for China iron/steel industry based on individual gas source and overall gas system, respectively

6. Conclusion

Carbon capture technology is not only a large-scale CO_2 emission reduction technology with great potential for China's iron/steel industry, but also the only technology that can deliver a large-scale direct emission reduction for steel/iron industry, while enable large-scale iron/steel companies to achieve a sustainable emission reduction with less effect on their own established energy balance system. This study provided a comprehensive techno-economic analysis of major CO2 capture technologies for China's steel/iron industry. Based on a typical iron/steel making process of China's iron/steel industry, main CO2 emission sources including blast furnace gas, Linz-Donawitz gas, hot blast furnace flue gas, lime kiln flue gas and flue gases of coke oven and power generation within an iron/steel plant were characterized. It was indicated that CO_2 concentration of lime kiln flue gas, hot blast furnace gas, blast furnace gas and Linz-Donawitz gas is higher than that of post-combustion flue gas of normal coal-fired power generation industry; CO_2 concentration of flue gases from coke oven and power generation unit within an iron/steel plant is lower than that a post-combustion flue gas from normal coal-fired power generation industry. In general, hot blast furnace flue gas has the highest CO_2 concentration, blast furnace gas ranks the second, followed by Linz-Donawitz gas and lime kiln flue gas.

Various post-combustion capture methods, including chemical absorption, pressure swine adsorption (PSA), membrane separation, cryogenic distillation methods and their integrations, are identified and analyzed from the perspective of their technical applicability and economic performance based on features of individual gas sources. Overall, chemical absorption is the most mature technology and have been demonstrated by two large-scale to post-combustion capture projects. It is particularly applicable and cost-effective to emission source with low CO_2 concentration. Regarding PSA, membrane separation and cryogenic distillation methods, they are more applicable and cost-effective to high concentration CO_2 source and have excellent technical and economic performance on gas stream with high pressure.

It is recognized by this study, that many factors could affect technical and economic performances of carbon capture technologies. Different temperature, pressure, impurity content and CO_2 concentration of each emission source in steel/iron production process would lead to different technical applicability and economic performance of capture technologies; different demands for CO_2 product also affect technical applicability and economic performance of capture technologies; in addition, co-benefit or by-product associated with CO_2 removal affect technical applicability and economic performance of capture technologies. Specifically, calorific value of blast furnace gas can be significantly improved by CO_2 removal; hot blast furnace flue gas has the highest CO_2 concentration and high concentration nitrogen, lead to the lowest capture cost and an opportunity to produce by-product nitrogen with membrane technology, PSA or membrane-PSA integration technologies; Though the CO_2 concentration of lime kiln flue gas is lower than hot blast furnace gas, by-product nitrogen benefit is higher than that gas.

In view of interactions among carbon capture from various sources, the technical applicability and economic performance of carbon capture technologies for a steel/iron industry could be affected by multiple factors and their interactions under different conditions, it is necessary to carry out future research with a real-world business case to assess the technical applicability and economic performance of CO_2 capture for China iron/steel industry based on individual gas source and overall gas system, respectively

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Review of Current Status of Iron/Steel Sector CCUS Including Options for CO$_2$ Transport and Storage

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Contents

1. Review of typical iron and steel plant layout

Steel production consists of both a long process and a short process. The long process consists of mineral processing, sintering, ironmaking, steelmaking, and the steel rolling process. The short process begins with steel. It refers to compact production process of the combination electric arc furnace, continuous casting and continuous rolling. The main performance is the compact process of raw materials preparation, electric arc furnace melting, refining, continuous casting and rolling Current steel technology gives priority to the long process. The primary technological process in producing steel is shown in Figure 1. The following sections will describe the long process which includes raw material preparation, ironmaking, steelmaking and steel rolling.

Figure 1. Main Technological Processes in Producing Steel
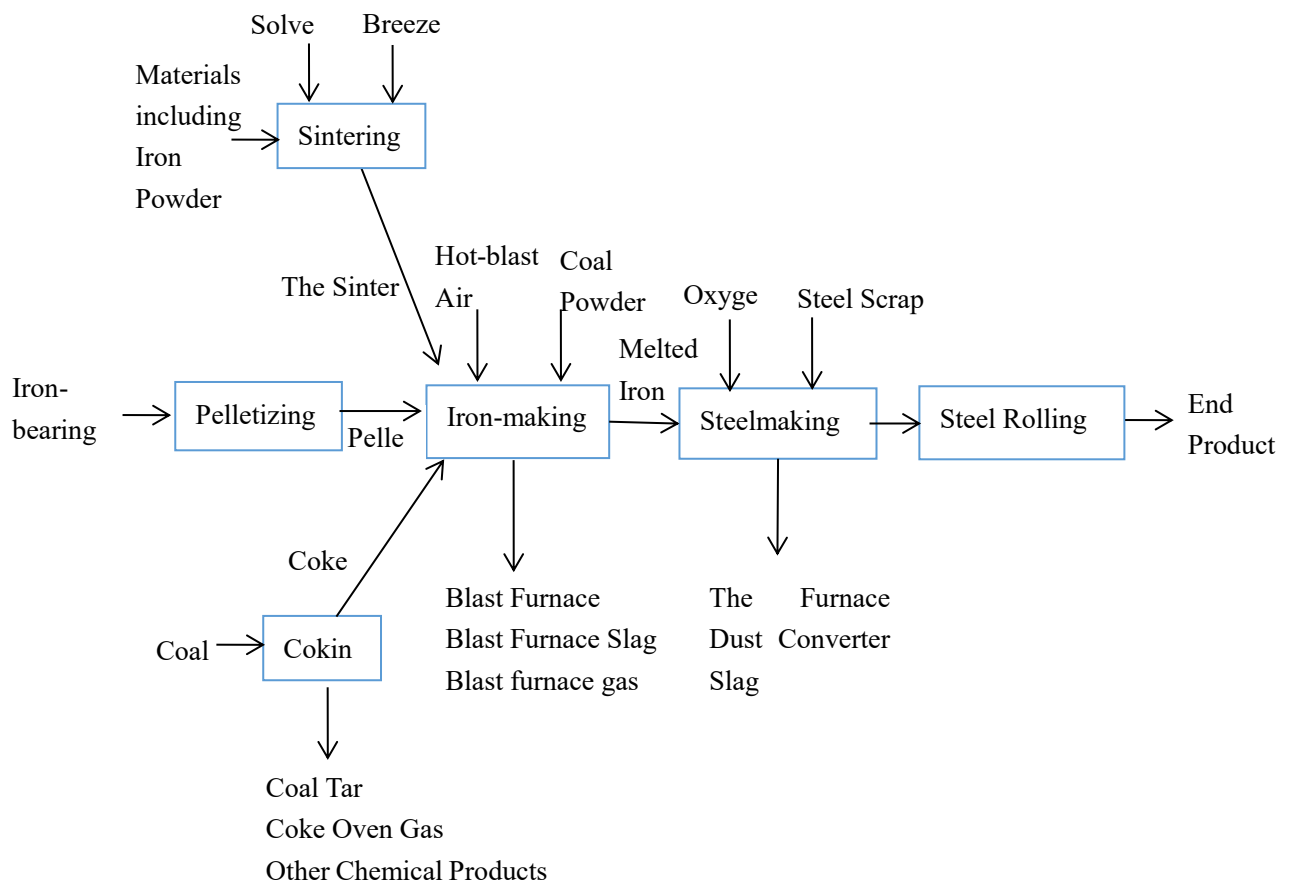
1.1 The preparation of the raw material

1.1.1 Mineral processing

Mineral processing of low-grade raw ore occurs via the processes of magnetic separation, flotation and re-election, followed by high grade iron concentrate in preparation for the next step of smelting. Main production processes include: crushing iron ore, grinding, mineral processing, drying, and ore concentrate powder.

1.1.2 Sintering and pelletizing

Sintering production is the process of mixing iron powder, solvent and fuel in specific proportion and then tiling the mixture to a sintering car and ignition. This process results in the evaporation of the solution water and causes a series of chemical reactions to occur, ultimately resulting in a partial liquid phase bonding with sufficient strength and granularity. Finally, after crushing, cooling and screening, we produce the finished sinter. Main production processes include burden, first-mixing, second-mixing, sintering, crushing, sieving, cooling and the finished sinter. The production of sintering produces a large amount of sulfur-containing flue gas, which will need to undergo desulfurization process.

1.1.3 Coking

Coke oven gas is a primary fuel type that is produced by sintering, coking, ironmaking, steelmaking and steel rolling processing and is used for blast furnace smelting. Coking production is the process of mixing and crushing specific coal types, and placing them in a coke oven to produce both hot and crude coke gas through the retorting process. The coking process will produce both coking gas and various other chemical products.

The coke is produced through the carbonization process, in which clean coal is heated in the vacuum-sealed carbonization chamber of the coke oven. The red-hot coke is then sent to a coke quenching tower to be cooled, crushed, sieved and classified. Following this procedure, we are able to get different particle sizes of the coke products.

1.2 Ironmaking

Blast furnace ironmaking is used to make iron ore or iron-bearing materials into the qualified liquid iron by using a reducing agent (such as coke, coal, etc.) at high temperature.

The production process for blast furnace ironmaking is mainly composed of a blast furnace stack and a number of auxiliary systems. The body of blast furnace consists of a furnace throat, stack, bosh, belly, and hearth (moving from top to base of the structure). The auxiliary system consist primarily of feeding, air-supply, coal powder injection control, blast furnace cooling, iron slag and gas purification systems.

The blast furnace ironmaking process begins with the mixing of sinter, pellets, raw ore and other materials in prescribed proportions, sending the mixture to the top of a charging device via a belt or car, and keeping the material surface at a specific height. In this environment, the materials will form ore and coke in alternating layers within the furnace. The coke with then reacts with oxygen, forming carbon monoxide and hydrogen by blowing high-pressure, hot air from the tuyere around hearth. Descending furnace charge and rising coal gas will transfer heat, resulting in reduction, melting, decarburization of the coke to generate the raw iron and slag.   Both the molten iron and slag are alternatively expelled from the base of the hearth.   The slag and iron are then separated by the skimmer. Molten iron is poured into torpedo ladles or hot metal packages and are sent to steelmaking plants. After a water quenching treatment, blast furnace slag can be used as the raw material in cement.   After various processing steps (gravity precipitation, bag dedusting and TRT power generation), the coal gas formed at the top furnace can be incorporated into a gas pipe network.

1.3 Steelmaking

The steelmaking process is divided into four processes: molten iron pretreatment, converter steelmaking, refining outside the furnace and continuous casting. The basic tasks of the steelmaking process requires the removal of a number of elemental compounds (carbon, phosphorus, sulfur, nitrogen and hydrogen) and the removal the non-metallic inclusions. After this purification process, the material is then heated and molded.

1.3.1 Molten iron pretreatment

Molten iron pretreatment is the preparation process for the molten iron of the blast furnace before it is sent to the steel furnace. Without an additional heat source, active substances in the treatment agents will react rapidly with sulfur, phosphorus and silicon. Thus, these elements are removed from the molten iron to form a stable slag phase separate from the molten iron. This process simplifies the steelmaking process and improves the quality of steel.

1.3.2 The converter steelmaking

The oxygen converter allows high-speed oxygen to oxidize with the carbon, phosphorus, sulfur, nitrogen and hydrogen in steel to produce slag. The oxidation process also removes non-metallic elements and provides a heat source. The process of steel tapping includes charging and converting the material, deoxidizing steel tapping, slag-splashing for furnace protection and, finally, pouring the slag.

1.3.3 Refining outside the furnace process

Steel refining outside the furnace begins by converting the molten steel produced from

primary smelting and pouring the converted steel into ladles. The steel proceeds to undergo deoxidization, desulphurization, decarbonization, and degassing. Non-metallic inclusions are then removed and liquid steel compositions are exposed to high temperatures and undergoes further smelting.

1.3.4 Continuous casting process

The continuous casting process is the process of converting the molten steel into solid steel via the use of molds during solid-state phase transformation. The liquid - solid phase change occurs when cool water reacts with the surface of the casting billet, causing the molten steel to undergo the processes of crystallization and casting. In the continuous casting process, the steel will undergo phase transformation and the ingot may experiences bending, correction and some other changes.

1.4 Steel rolling

The process of steel rolling places rolled pieces of steel into a high-speed roller to generate a desired shape. According to the product types of steel rolling, it can be divided into shaped steel, wire rod, sheet metal and pipe steel. According to production methods, it can be divided into hot rolling and cold rolling.

During the hot rolling process, steel is rolled at temperatures above the recrystallization temperature. This process includes: heating, dephosphorization, roughing rolling, top cutting, precision rolling, laminar cooling, crimp, finishing and plate cutting or heavy rolling.

Cold rolling is steel rolling that occurs at temperatures below the recrystallization temperature. This process includes: dephosphorization with acid pickling, cold rolling, degreasing, annealing, leveling, skin rolling, classifying and packaging.

2. Review of most appropriate carbon capture and utilization technology

2.1 Carbon capture technology

The most appropriate technologies used to capture CO_2 from the various gaseous streams can be divided into (Carpenter A. 2012):

- Adsorption using solid adsorbents;
- Chemical or physical absorption, or combined chemical and physical absorption (hybrid system);
- Physical separation via membranes or molecular sieves;
- Phase separation by cryogenics and gas hydrates;
- Chemical bonding via mineral carbonation.

2.1.1 Adsorption capture technology

Adsorption involves passing the CO_2-containing gas through a bed of solid sorbent (such as zeolites or activated carbon) which adsorb the CO_2. Once the bed is fully loaded, the gas is passed through a second adsorbent bed. The bed, now loaded with CO_2, is regenerated by reducing the pressure (pressure swing adsorption (PSA) or vacuum pressure swing adsorption (VPSA)), increasing the temperature (temperature swing adsorption, TSA) or applying a low voltage electric current (electric swing adsorption, ESA). Only PSA and VPSA will be discussed in the subsequent sections as they are commercially used in the iron and steel industries, and other industrial facilities.

PSA and VPSA processes typically operate at near ambient temperature. The higher the pressure during adsorption, the more CO_2 is adsorbed. The bed is desorbed (CO_2 is removed) by reducing the pressure to above one atmosphere (0.1 MPa) (PSA) or below atmospheric pressure (VPSA). Using two adsorbent vessels allows near-continuous operation and also enables the depressurized gas leaving the vessel to be used to partially pressurize the second vessel. This results in significant energy savings (Carpenter A. 2012).

2.1.2 Absorption capture technology

Separation of CO_2 from gas streams can be achieved by chemical or physical absorption or by a combination of the two (hybrid method). CO_2 is removed by a chemical or physical solvent in one reactor (absorption column), and the solvent is regenerated in a second reactor (stripping column).

The CO_2 is stripped from the chemical solvents by applying heat (steam) and from physical solvents by heating, pressure reduction, or a combination of both. The CO_2 is then cleaned and dried, if necessary, before it is compressed for transport and storage.

Absorption processes are widely used in the chemical, refinery and gas processing industry and could potentially be applied in the iron and steel industry (Carpenter A. 2012).

2.1.2.1 Chemical absorption

Chemical solvents are most suitable for the deep removal of CO_2 from gas streams with low CO_2 concentrations and a low partial pressure less than or equal to 0.5 MPa (Gielen, 2003). Thus chemical absorption is being investigated for BFG (blast furnace gas), BOF (basic oxygen furnace) gas, natural gas DRI (direct reduced ion) process gases, fluidised bed DRI production gases, smelting offgases and others.

The most common chemical solvents used for CO_2 capture are amines and the most widely used amine is monoethanolamine (MEA). Amine solvents have a high capture efficiency and selectivity. However, disadvantages include equipment corrosion,

solvent degradation, low CO_2 loading capacity, high thermal energy consumption during solvent regeneration, large footprint, and removal and disposal of solvent degradation products (Davidson, 2007). Corrosion and solvent degradation is due to O_2 and SO_x in the offgas and has occurred in the context of power plant flue gas. Offgases in the iron making processes generally have lower O_2 and SO_x content than power plant flue gas, and so corrosion may be less problematic. If the SO_x level is a problem, it can be easily removed before the gas enters the CO_2 capture unit (Carpenter A. 2012).

New amine solvents and blends are being developed to mitigate some of the above-stated disadvantages, and to reduce the cost of absorbent regeneration that presently results in around half of the CO_2 capture costs. Blending existing solvents can exploit the desirable characteristics of the different solvents.

2.1.2.2 Physical absorption

Absorption in most current physical solvent systems occurs at high CO_2 partial pressures and low temperatures. The solvents combine less strongly with CO_2 than chemical solvents and therefore require less energy for separation and regeneration. Capacity can be higher since the physical solvents are not limited by the stoichiometry of the chemical system. Physical absorption is usually the preferred method at CO_2 concentrations greater than 15% (IEA, 2008b).

2.1.3 Membranes capture technology

Gas separation membranes (such as polymers, ceramics, metals and zeolites) rely on differences in physical and chemical interactions between gases and a membrane material, allowing one component to pass through the membrane faster than another. Membrane processes can achieve over 80% CO_2 separation efficiency. The main advantages of membrane processes are that no regeneration energy is required, no waste streams are generated, and the separation units are small and simple to operate. But membranes are sensitive to sulphur compounds and other trace elements, and particulates must be removed from the gas feed prior to passing through the membranes.

Membranes usually cannot achieve a high degree of separation and consequently, multiple stages and/or recycle of one of the streams is necessary. This leads to increased complexity, energy consumption and costs (CSLF, 2010). New membrane materials are being developed to mitigate these handicaps. For example, sas absorption membranes are hybrid systems that combine a membrane with the selective absorption of a solvent, such as amines, improving on both.
Development of a membrane capable of separating oxygen and nitrogen in air could play an important, indirect role in CO_2 capture (CSLF, 2010). Lower cost oxygen is important for O_2-blown BFs (blast furnaces) and coal gasification processes producing syngas for DRI processes.

Membranes are used commercially for CO_2 removal from natural gas at high pressure and high CO_2 concentrations, and therefore could be applied to BFG and other high concentration CO_2 streams in steelworks. Lie and others (2007) compared the performance of three types of membranes for capturing CO_2 from BFG. Bench-scale tests with single gases found that the fixed site carrier membrane (a polymeric membrane with amine groups) showed superior selectivity for CO_2 over CO, N_2 and H_2 and had a higher CO_2 performance (productivity) than the adsorption selective carbon and carbon molecular sieving membranes. In addition, H_2 is retained on the high pressure side (as opposed to the carbon membranes), requiring no extra H_2 separation unit. Water in the feed gas is an advantage instead of a problem since the polymer membrane must be humidified during operation.

2.1.4 Cryogenics capture technology

CO_2 can be separated from other gases by cooling and condensation. While cryogenic separation is used commercially for gas streams with a high CO_2 concentration (typically >90%), it is not used for more dilute CO_2 streams because of the high energy requirements (CSLF, 2010). However, the purified gas, with a low temperature, can be easily compressed to the pressure required for the combustion chamber of a gas turbine (Lampert and others, 2010). Some components, such as water, have to be removed before the gas stream is cooled to avoid blockages in the cryogenic flow lines (CSLF, 2010). Cryogenic separation, though, does have the advantage that it produces liquid CO_2 ready for shipping or pipeline transport to the storage site. It also has a low temperature and could be used as a cooling agent (Lampert and others, 2010).

The most promising applications for cryogenic separation are expected to be for the separation of CO_2 from high pressure gases or from offgas produced from O_2-blown BFs. In the planned demonstration of the TGR-BF (top gas recycling and blast furnace) (O_2-blown) under the ULCOS programme, the CO_2 captured by the PSA unit will be further purified by cryogenics to produce liquid CO_2 ready for underground storage. The cryogenic unit also generates an extra reducing gas stream for recycling to the BF. A cryogenics unit could be used on its own in the HIsarna process, which is designed to generate nitrogen-free and CO_2 rich offgas (Birat, 2010b). The oxygen for the BF or HIsarna reactor could be supplied by cryogenic separation of air, a technology already applied commercially in other industries.

2.1.5 Gas hydrates capture technology

Hydrate-based CO_2 separation is in the research and development phase. In this technology CO_2 molecules are trapped in the cages, or clathrate hydrates, formed by water molecules under high pressure and low temperatures. The CO_2 is recovered from the hydrates either by heating or depressurization in a second reactor, and the separated water is recycled back to the hydrate crystallisation reactor. Processes being developed for the power generation industry (for flue gas and syngas) use one or more hydrate crystallisation reactors. Compressing the gaseous stream to the required hydrate

formation pressure is expensive. Therefore compounds, such as tetrahydrofuran, are added to lower the hydrate equilibrium pressure. Impurities in the gaseous stream may adversely affect the process, and agglomeration of hydrate crystals can create barriers to efficient gas/water contacts. Duc and others (2007) investigated a continuous hydrate process for capturing CO_2 from BF gases utilising tetra-n-butyl ammonium bromide ($C_{16}H_{36}NBr$, TBAB) as the hydrate promoter.

2.1.6 Mineral carbonation capture technology

Slags generated during the iron and steel making processes have a high alkaline earth metal oxide content (in the form of silicates, free lime and other minerals) and could potentially be utilised to capture and permanently store CO_2 via mineral carbonation. Calcium oxide and magnesium oxide in the slags react with CO_2 to form stable calcium carbonate (calcite).

Carbonation processes under development can be classified (Baciocchi and others, 2010) as:

  ● direct, where the reactions with CO_2 occur either in the aqueous phase such as the two-stage slurry reactor developed at the Missouri University of Science and Technology in the USA (Richards and others, 2008) or at the gas-solid interface;
  ● indirect, in which the alkaline metal is first extracted from the slag matrix and is then precipitated as carbonate. Extraction agents investigated include acetic acid (Eloneva and others, 2008; Teir and others, 2007), nitric acid (Doucet, 2010), hydrochloric acid (Kunzler and others, 2011), hydroxides and ammonium salts (Fogelholm and others, 2009).

In both routes, the slag is first ground. This activates the surface of the mineral to increase its effective carbonation rate and yield, and also improves the recovery of iron currently lost to the slag. CO_2 uptake is influenced by the slag composition, which is highly variable, and operational parameters, such as pressure, temperature and particle size distribution (Uibu and others, 2011). A carbonation reactor could be retrofitted in a steel mill and will most likely be installed after a gas cleaning system to prevent contamination with dust (Rawlins and others, 2006).

The energy requirements of the processes and/or solvent regeneration costs can be high (Doucet, 2010). In addition, carbonation processes generate their own CO_2 emissions. Producing marketable carbonate products that are suitable for polymer fillers, agricultural and construction applications could lower the costs. Precipitation of high quality calcium carbonate would enable its sale to the paper industry (Fogelholm and others, 2009). Leaching of potentially harmful constituents from steel slag is reduced after its carbonation (Comans and others, 2010), allowing its use in civil engineering applications. Utilising carbonated slag blocks in the ocean promotes the growth of algae which will further absorb CO_2 through photosynthesis (Baoshan Iron and Steel, 2008).

These methods can also be used to help buffer ocean acidification, particularly in endangered reef areas.

2.1.7 Carbon capture recommendation

A drawback for some CO_2 capture technologies is the high energy consumption and, where used, steam consumption. The capture process could be optimised by utilising waste heat from other on-site processes to regenerate the capture solvents for those technologies which use solvents. CCS is expensive, and the high cost could inhibit its widespread commercial deployment. CO_2 capture is generally cheaper for the direct reduction and smelting reduction processes than for air or oxygen-blown blast furnaces.

The commercial viability of CCS partly depends on the price of carbon emissions which is set by government policy. More large-scale demonstration projects, such as the Florange project in France could lead to lower costs in the future. If all technical, financial and cost barriers are overcome, then CCS could be more widely deployed in the steel industry. Developing new technologies, such as the HIsarna process, that are designed to generate a nitrogen-free and CO_2 rich off gas which will make CO_2 capture easier and cheaper, is another way forward. Innovative iron and steel making processes that avoid the use of carbon-based reducing agents are a long-term prospect.

Processes still at the research stage include the use of hydrogen or electrons (molten oxide electrolysis and electrowinning) as the reducing agents. These technologies will depend on a cheap CO_2-free hydrogen production process being developed and the availability of cheap CO_2-free electricity respectively. To conclude, no single option can yield the necessary CO_2 emission reductions but a combination of technologies are available that can be retrofitted to achieve significant reductions. If CCS is fitted then steel plants could become near zero emitters of CO_2.

2.2 Carbon utilization technology

Millions of tonnes of CO_2 are used in industry each year, and the idea that combining CO_2 utilization with CCS is quite appealing. Instead of disposing CO_2 as a waste, delivering it to willing buyers is a better way on an economic analysis. However, CO_2 utilization could only act as a driving force to develop CCS but cannot replace geological storage. The reason is that the uses are rather limited when considered to be applied to CCS. For example, the global beverage industry uses around 8 Mt CO_2/yr, which is only 0.5% of the CO_2 need to be captured and stored by 2030. Therefore, the CO_2 demand of different approaches should be considered in order to match the capture capacity. The emission reductions and financial contribution should also be analyzed.

2.2.1 CO_2 used for enhanced oil recovery

Enhanced oil recovery is the largest source of CO_2 utilization, with 70Mt CO_2 used

annually. It is also called tertiary oil recovery. CO_2-EOR technology is injecting CO_2 into an underground geologic zone that contains hydrocarbons to produce the oil. The CO_2 is produced along with oil and then recovered and re-injected to recover more oil.

The United States has been using CO_2-EOR for several decades and has sequestrated millions of tonnes of CO_2 underground. However, about two-thirds of quantities of CO_2 are from natural sources. Additionally, at present the main purpose of CO_2-EOR is to increase oil production. Therefore, EOR technology should be improved when used either primarily or secondarily for CCS. For example, incorporating monitoring and validation systems into EOR could help ensure the long-term retention of CO_2.

Storing CO_2 in oil and gas reservoirs can not only enhance oil and gas recovery, but could have the added benefit of reducing CO_2 emission. However, when we use numerical models to simulate the process of CO_2-EOR, a problem arises when CO_2 sequestration and EOR should be co-optimized at the same time. Jahangiri and Zhang (2012) proposed the ensemble-based optimization (EnOpt) method to co-optimize CO_2 sequestration and enhanced oil recovery.

This study takes both CO_2 storage and oil production into account and uses NPV (net present value) of the CCS project as the optimization objective function. The proposed methodology presented in this work can be readily used with any reservoir simulator and thus could be used to design and co-optimize the coupled CO_2 sequestration and EOR

2.2.2 CO_2 used in iron making process

Hong (2012) from Northeastern University China applied CO_2 as a desiliconizing agent for hot metal. The experiments were carried out in a laboratory induction furnace, with 1kg of material prepared using a pig iron with iron silicide with silicon content around 0.745wt%. CO_2 is injected into hot metal through a quartz tube for desiliconizing under different temperatures ranging from 1300 to 1500°C, and different gas flow rates ranging between 0.2 to 0.6 L min^{-1}. The results showed that the mass transfer of gas is the rate-limiting step of desiliconizing reaction with CO_2. Under constant temperature, higher gas flow rate will give better desilication.   On the contrary, at certain gas flow rate, higher temperature leads to lesser desilication. This is in conformity with thermodynamic analysis since desilication is an exothermic reaction and lower temperature would favour desilication.

Guo et al. (2010) patented the use CO_2 as the transmission medium for pulverized coal injection into a blast furnace (BF) instead of N_2 or compressed air.   Pulverized coal was first transferred by CO_2 from bins to pipes then injected into BF with CO_2 as the carrier. This was expected to enhance the proportion of CO in the BF gas, hence increase the quality and reducing the coke rate. This is in part due to CO_2 concentrations around tuyeres being very high, and the reaction $C(s) + O_2(g) = CO_2(g)$ will be restrained while the reaction $CO_2(g) + C(s) = 2CO(g)$ will be promoted. One should notice that it is essential to control the CO_2 proportion in the mixed gas, because higher

CO$_2$ will increase the potential energy of the coke reaction. This will result in large amounts of cracks and pores within the coke, decreasing the coke strength. In this case, it will deteriorate the permeability of stock column during the descending process.

Almost at the same time in 2010, Fu et al. (2010) invented a method of injecting carbon dioxide into BF with the aim to reduce the coke ratio. CO$_2$ is produced from the exhaust gas of the hot blast stove or other exhaust gases which contain CO$_2$. Replacing the O$_2$-rich gas stream with CO$_2$ will result in drastic decreases in temperature, hence the temperature of the injecting gas needs to be increased when introducing CO$_2$ into the BF. There is no industrial application being reported for the above two patents, maybe because it is difficult to operate.

2.2.3 CO$_2$ used in steel making process

2.2.3.1 CO$_2$ used in converter process

2.2.3.1.1 Decarburization

The use of CO$_2$ for decarburization has a history of around 30 years in China. Back in 1985, Jin (1985), an industrial researcher from Shanghai's No. 1 steel plant, reported the positive effects of N$_2$–CO$_2$ bottom blowing in a 15 t converter. It was reported that this application can enhance the decarburization efficiency and decrease the total iron oxide concentrations (Σ^{FeO}) in the final slag. However, the corrosion of the refractory around tuyere was found to be severe.

Wang (1986, 1989) carried out a series studies during 1986–1989 on the bottom blowing of CO$_2$ bearing gases. The high temperature experiments were carried out and the result showed that with CO$_2$ bottom blowing, the decarburization rate is larger than other gases in the middle period of decarburization. Similar work was carried out elsewhere (Hara et al. 1986; Paules 1987), aiming to investigate the effect of CO$_2$ during bottom blowing. The results of these studies showed that CO$_2$ is an effective alternative for N$_2$/Ar bottom blowing, since it will not increase the nitrogen content in liquid steel. This would also be a superior alternative to bottom blowing O$_2$/C$_x$H$_y$ in converter as the dissolved hydrogen content would not increase during the operation. The mechanism of bottom blown CO$_2$ in the bath of combined blown converter was investigated in later stage (Guo & Chen 1993) by Chinese researchers and the industrial test of CO$_2$ bottom blowing was carried out in a 180 t converter in Anshan Steel Plant (Li & Han 1996). However, this technology could not be applied in the industry initially due to the short lifetime of the purge plug.

During the experiment, it is found that the corrosion of the tuyere is severe just as Shanghai No. 1 steel's practice (Jin 1985). It was suggested that, during the progress of decarburization, the carbon content in the melt would be very low and, consequently, the carbon in refractory around tuyere will dissolve into the melt.

Anshan Steel Plant carried out further research to solve the refractory problem and increase the lifetime of tuyere to 1500–2000 times of use. CO_2 bottom blowing in converter had been used widely in this plant until the paper of (Li & Han 1996) was published. Sodium carbonate (Na_2CO_3) solution absorption method was adopted by Anshan Steel Plant for CO_2 production but the cost of CO_2 preparation has not been reported.

Utilization of CO_2 in metallurgical processes in China has been studied by Jin et al. (2007) and Yi et al. (2009). They started the work around 2004–2005 and named the new process the COMI (CO_2 and O_2 Mixed Injection) process. In 2007, experimental study of steelmaking with CO_2– O_2 mixture was carried out by a 10 kg induction furnace, with the initial carbon content of around 2.5wt%. The result showed that it is feasible to decarburize the melt with CO_2–O_2, and they pointed out that the maximum amount of CO_2 introduction in converter is 13% (Jin et al. 2007).

The process was implemented in 2009 in industrial experiments (Yi et al. 2009) with CO_2 addition ratio of around 7%, and the results were very positive. The consumptions of lime, iron ore as well as oxygen with COMI process were all lower than that with conventional process. Additionally, the Total iron (T_{Fe}) content in slag was decreased by 1.79wt% compared to the conventional method.

2.2.3.1.2 Dust reduction

One of the important achievements in Chinese research with regards to the benefit of using CO_2 in the converter process is that it can reduce the generated amount of converter dust. The characteristics and mechanism of dust generation was also investigated by Bi et al. (2010). Both laboratory and industrial experiments have been carried out in China (Ning et al. 2009; Yin et al. 2009; Zhu et al. 2010) and the results showed that, with an increase in the CO_2 ratio in the mixture gas, the dust generation is decreased.

Evaporation was considered as the main reason for fine (micro size) dust formation, which constitutes more than 60% of converter dust. The main content of the converter dust is FeO_x (around 50% of total dust). With the oxygen injecting into hot metal, a fire zone forms with temperature higher than 2500°C (maximum 3000°C). As the boiling point of iron is 2750°C, iron will be oxidized and evaporate to form dust at lower temperatures. If one can decrease the temperature of the oxygen jet fire zone, dust generation is expected to decrease. Based on the endothermic nature of the Boudouard reaction, namely the reaction of CO_2 and C, if CO_2 is mixed with O_2 to form the oxidizer gas mixture, the temperature of the fire zone will be lowered so as to decrease the oxidation evaporation of Fe.

The result obtained by Yin et al. (2009) has shown that, compared to the conventional steelmaking process, when CO_2 volume ratio is 5%, the dust amount is decreased by 25%, while at the same time, the T_{Fe} content in the dust is reduced by about 15.3wt%.

2.2.3.1.3 Dephosphorization

The dephosphorization of BOF with the introduction of CO_2 has been widely studied (Lv et al. 2011a; Lv et al. 2011b; Zhu et al. 2012). The dephosphorization of hot metal with high-Si and high-P in the converter is a serious technical problem during the steelmaking process. Normally, in order to enhance the dephosphorization efficiency, solid coolant is added during dephosphorization with the aim to control the temperature increase rate. However, solid coolant will lead to a partial-cooling of the bath. Consequently, the cooling effect would be non-uniform. Additionally, the impurity in solid coolant will affect the quality of steel production. In this case, CO_2 could be a better choice as a temperature controlling agent. A 30 t converter was adopted for carrying out the CO_2 cooling experiments (Yi et al. 2009).

The industrial trials showed that, with the introduction of CO_2 (namely COMI process), the temperature of the dephosphorization period has been controlled better compared to the conventional process and CO_2 bottom blowing is found to be beneficial for dephosphorization. The temperature of semisteel is around 1330-1350°C, and the phosphorous content in semisteel is lower than 0.050wt%. The average dephosphorization efficiency for semisteel using conventional processes is 53.10%, while it is 66.49% with COMI process. The P content for the first tapping is also decreased by 23%, from 0.030 to 0.023wt%.

To summarize the effects of CO_2 used in converter process, the introduction of CO_2 in the proper amount will be favourable to decarburization, dust reduction, reduction of materials consumption and dephosphorization. However, the amount or ratio of CO_2 mixing must be calculated carefully, as too much CO_2 can lead to skull of slag because of the endothermic reaction between CO_2 and C.

2.2.3.2 CO_2 used in AOD process

The application of CO_2 in stainless steel making is extremely interesting. Currently, stainless steel is mostly produced through the argon oxygen decarburization (AOD) process. For ordinary stainless steel production, the Ar consumption is 11-12m^3/t, O^2 consumption is 14-24m^3/t, while, Ar consumption is 18-23m^3/t in the case of smelting extra-low carbon stainless steel (Chen et al. 2008). It has economical profit if Ar could be replaced by cheaper gases, like N_2, steam, CO_2 etc. However, N_2 will bring N and steam and will take H into the melt, both of which are harmful for certain steel grades. The use of CO_2 could be ideal considering this aspect. The present authors have

investigated the feasibility of CO_2 application in the stainless steel making process, both in Sweden and in China.

Wang et al. (2009, 2010) have carried out induction furnace experiments at the Royal Institute of Technology Sweden (KTH) during 2007-2010 and the results show that CO_2 is effective for decarburization without the loss of chromium. After that, Zhu et al. (Li et al. 2015) have carried out basic study of thermodynamics of CO_2 applied for stainless steel smelting, and pointed out the maximum CO_2 used in AOD process is 9.13%. They stated that for carbon content over 0.5wt%, it is possible to use $CO_2 + O_2$ mixture, while, at carbon level lower than 0.5wt%, it is better to use Ar to decrease partial pressure of CO (P_{CO}). They also implemented experiments in China (Bi et al. 2012) and found when the ratio of CO_2 increased from 0 to 50%, the carbon content will decrease by 12% while Cr content will increase by 19.93%. These authors have suggested the use of 5-11m^3 CO_2 for one ton stainless steel production. The price of Ar is around 5-8 times that of CO_2. Consequently, the production cost will be decreased by 3-7 US$/t.

Anderson et al. (1990) have shown, from their corresponding trials at a steel plant in U.S. with production capacity of 1.0 million tons per year, that adopting a similar practice as proposed in Bi et al. (2012), 20 Million to 45 Million RMB could be saved per year. In 2011, Anshan Iron and Steel Co., Ltd. (Tang et al. 2011) invented an AOD process with injection of CO_2 to produce stainless steel and they found it is suitable for smelting steel with carbon content from 0.001 to 0.3wt% using the new process. They also found with CO_2 injection, oxygen lance can be cooled and its life improved by 20%.

2.2.3.3 CO_2 used in EAF process

Electric arc furnace (EAF) steel takes up around 10.1% of the steel production in China in 2012, which is far lower than the international average and it is related to the lack of scrap and energy in China. However, with the development of the country, the ratio of scrap is expected to increase and the EAF process would be comparable to developed countries. The use of CO_2 in EAF would have a great impact in future steel production in China. CO_2 was introduced as the bottom blowing gas instead of Ar in the EAF process, in order to enhance the stirring ability of the bath for promoting the slag-metal reaction, homogenize the bath temperature and composition, and increase the yield of valuable metal (He et al. 1992; Van Wijngaar den & Pieterse 1994; Zhao 1995; Gulyaev & Filippov 2001). The materials and heat balances were calculated by Wang et al. (2012) for the introduction of CO_2 in EAF process with hot metal charging.

These authors concluded that, with the CO_2 addition in the oxidization gas, the hot metal ratio charged into EAF could be enhanced, resulting in energy savings. Recently, the industrial experiments for CO_2 application in the EAF process were carried out in a 65t EAF with the product of 45# steel (Wang et al. 2014) compared to Ar bottom stirring.

The results show that with CO_2 bottom blowing, the stirring effect was reinforced and the FeO content in slag was lowered, which offers good desulphurization conditions. The desulphurization ratio could be increased by 7% compared to that with Ar bottom blowing. However, with CO_2 bottom blowing, the end point carbon content will increase slightly, and a small amount of Cr will be oxidized because CO_2 oxidizes Cr in the melt, while Ar has no effect on Cr oxidation.

To conclude, with CO_2 bottom blowing in EAF instead of Ar, the production cost will be decreased because the expensive Ar is replaced and the quality of the steel will not be affected, even enhanced at times.

2.2.3.4 CO_2 used in secondary refining process

The use of CO_2 as protection gas in a ladle furnace (LF) during heating can be traced back to 1986, with the aim to form a CO_2 gas layer. This could reduce the possibility of steel melt absorbing nitrogen as well as re-oxidation. American and French plants have applied this technology successfully to decease the N content in the liquid steel by 63-75% (Hara et al. 1986). The research work by Bruce et al. (1987a) showed that bottom blowing CO_2 in LF did not influence the quality of molten steel.

Unfortunately, there is little further study on applying CO_2 as a bottom stirring gas in LF refining process due to its characteristic of weak oxidation. Because of this background, the current group, Gu et al. (2014) and Dong et al. (2014) have studied the CO_2 application in LF both experimentally and theoretically. The experiments were carried out in a 70 ton LF with CO_2 as bottom blowing gas for 45# grade steel production. Compared with bottom blowing Ar, types and compositions of inclusions have no significant change in steel.

On the other hand, it is observed that the yield density of inclusions has decreased and the cleanness of steel was improved. But one should also take note of the fact that CO_2 is a weak oxidizer, and it's use may lead to the increase of oxygen content in the liquid steel. A slight increase of oxygen in steel has been observed by Gu et al. (2014) and Dong et al. (2014) when blowing 1/3 and 2/3 CO_2 compared with pure Ar blowing.

This result is in accordance with the experimental results obtained by Paules et al. (1987) and Bruce et al. (1987b), who demonstrated that, when the carbon content is less than 0.20wt% in the melt, the dissolved oxygen in liquid steel is higher with CO_2 stirring than with Ar stirring, but for steel grades with higher carbon content, there is no difference of dissolved oxygen content by blowing these two gases.

2.2.4 CO_2 used in continuous casting process

CO_2 was applied in casting as shield gas, replacing Ar for special steel rod production in America 1989 (Anderson et al. 1989). Almost at the same period, researchers from UK (Normanton & Wang 1990) also tested the utilization of CO_2 on ladle slide gate as shield gas during 1986-1988. The conclusion from these experiences was that, with the protection of CO_2, the steel quality was similar to that when Ar is used. The utilization of CO_2 in the casting process came into popularity rather late in China. Until 2015, Li et al. (2015b) have carried out the industrial experiments on CO_2 applied as a protective gas during continuous casting process instead of Ar/N_2.

When CO_2 is used as stirring gas or shielding gas for production, the quality of steel is similar or even the same to that using Ar gas. The nitrogen content in the melt is slightly lower with CO_2 blowing than with Ar blowing since 1 volume CO_2 reacting with C will generate 2 volumes of CO and large amounts of gas benefit from removing nitrogen. The oxygen content, hydrogen content and the content of oxide inclusions in the liquid steel are comparable with that stirred by Ar.

2.2.5 CO_2 used in ferroalloy production

Converter refining for ferrochrome (FeCr) and ferro manganese (FeMn) production is the trend of medium and low carbon (MLC) product smelting in China. Because the submerged arc furnace used for high carbon ferroalloy production is getting larger in size and the tapping size is very large. The conventional way for medium and low carbon ferroalloy production is not suitable because of its limited size and very high energy consumption. But the current converter technology used for M-LCFeCr and M-LCFeMn production has defects of a short lifetime of linings and low yield of Cr/Mn. In this case, current authors (Yu 2015; Yu et al. 2015) introduced CO_2 into the converter process for M-LCFeCr and M-LCFeMn production. Laboratory scale experiments show that it is feasible to use CO_2 for producing these two alloys and it can enhance the yield of Cr/Mn by using $CO_2 + O_2$ mixtures, especially when the carbon content in product is higher than 3.0wt%. However, calculations indicate that it is not beneficial to produce ferrochrome with carbon content lower than 1.0wt% with the introduction of CO_2.

Additionally, the refining of silicon and ferrosilicon with the outfurnace method has also considered using CO_2 as a medium; the results, however, are not very encouraging (Suzuki et al. 1992; Wu et al., 2009, 2014) and would require further study.

2.2.6 CO_2 used in other areas in steel process

CO_2 was also used as the protection media, as a substitute for hydrocarbon, for side-blown oxygen lance in a converter to successfully limit dissolved hydrogen in liquid

steel (Liu 1983). As an acidic gas, CO_2 could also be used to fix active basic substances in slag to get stable carbonate. Dong et al. (2008) have used CO_2 to stabilize the converter slag and found that the best reaction temperature was 700°C. Slag splashing in a converter is widely used in China and CO_2 is being tested as a replacement for N_2 by researchers at the Chinese Academy of Sciences (Yuan et al. 2007; Zhao et al. 2010). During these trials with slag splashing, coke fines or pulverized coal with additives were added into the converter. The basic idea was that CO_2 would react with C to form CO. In this case, CO + CO_2 mixed gas will be recycled using this process. After separation, the CO_2 could be utilized for slag splashing again, while CO could be reused in other places in plant.

2.2.7 CO_2 used in microalgae cultivation

CO_2 used in microalgae cultivation is another promising way of sequestering CO_2. On one hand, microalgae could fix carbon in a very efficient way with zero carbon emissions. On the other hand, it helps to realize the transformation of solar energy to biomass energy. Microalgae has broad applications. It can be used to produce biodiesel which has many advantages over traditional fuels. Advantages include better combustion and safety behavior, and higher environmental performance. Another microalgae application is in food industry. Microalgae is used to produce products with high industrial added value, such as DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid).

The broad geographical distribution of microalgae and its extraordinary environmental tolerance make large-scale microalgae cultivation possible. China is the largest microalgae breeding country in the world and has great potential for microalgae development. Therefore, microalgae technology should be perceived as an important development direction of carbon fixation and should receive more attention. Currently, technical challenges include the low quality of microalgae, less efficiency of large-scale cultivation, and high energy cost.

2.2.8 Carbon utilization recommendation

Significant research efforts have been made on CO_2 used as stirring gas, reacting medium as well as protecting source in metallurgical processes. This covers almost all the fields of ferrous metallurgy. In most cases, the results observed are positive. However, despite the positive impacts, the negative effects of CO_2 also need to be considered. For example, when it is used in converter and EAF processes, it may prolong the tap-to-tap time hence increase the production cost somehow, and it is difficult to decide the proper introduction amount. While, when it is used in LF (ladle furnace) and CC (continuous casting) processes, it may lead to re-oxidation of the melt for clean steel production.

Till now, the experiments on application of CO_2 in the metallurgical processes in China

are limited to laboratory scale and pilot scale. The lack of enthusiasm in industrial implementation could be attributed to (1) method of CO_2 preparation leads to the cost of CO_2 currently is not low, and it is not economical to use CO_2; (2) there is lack of sufficient research results with regard to the optimal amount of CO_2 to be used. These problems need to be addressed by researchers in the near future. Recently, the new methods for CO_2 separation from the off-gas in iron making and steelmaking plants reported by researchers from South Korea (Kim et al. 2015) provided an economic solution of CO_2 preparation (62 USD/t CO_2 separated), which will make CO_2 cyclic utilization in the metallurgical processes closer to the industrial production.

3. Review of appropriate CO_2 transport and storage options

3.1 Options for CO_2 transport

Generally, a CCS system has three separate elements: capture, transport and storage. As the intermediate process in the CCS chain, CO_2 transport is needed to link CO_2 sources and storage sites and thus plays a significant role in the successful deployment of CCS. Hence, it is important to have a thorough consideration of CO_2 transportation approaches and corresponding cost. However, transport is considered as the least challenging element of CCS and has been less studied (Aspelund and Jordal, 2007).

In industry, CO_2 is transported by pipelines, ships, railway tankers, and tanker trucks. Sevensson et al. (2004) performed an economic analysis on these four alternatives and concluded that water carriers (offshore), pipelines (offshore and onshore) and a combination of these are appropriate transport options for CCS. Figure 2 shows the cost and capacity for transportation alternatives at a distance of 250 km. It clearly shows that pipeline and water carriers have a large capacity and low cost. Nevertheless, other options still have the potential to be applied to small-scale CCS projects. For example, Yanchang integrated a CCS demonstration project in China that adopts tanker trucks and pipelines as its CO_2 transport method (GCCSI, 2017a). For large-scale CCS projects, due to the low capacity and high transportation fares, railway tankers and tanker trucks are not cost effective. Therefore, this portion of the review will focus on pipeline and shipment transport and gives a brief introduction of transport technology as well as cost analysis.

Figure 2. Cost and capacity for transportation alternatives at 250 km
(Sevensson et al., 2004)
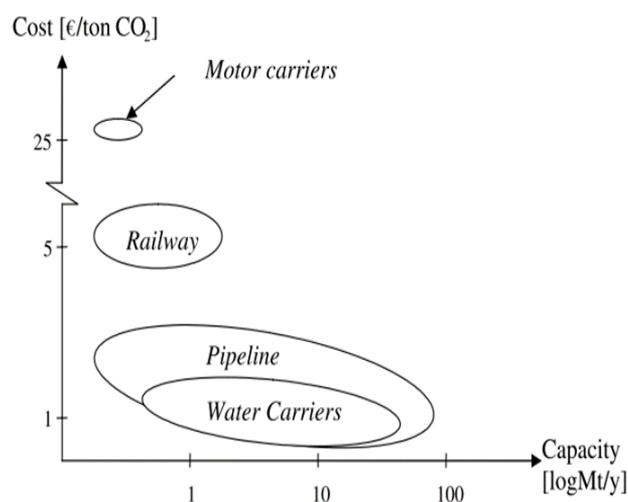
3.1.1 CO_2 pipeline transport

The use of CO_2 pipelines is well established to be the most economical way of transporting CO_2 (Zhang et al, 2006). At present, 14 of 16 global large-scale CCS projects use pipeline transport. Carbon dioxide pipelines extend over more than 2500 km in the western USA (2005), where they carry 50 $MtCO_2$/yr from natural sources to enhanced oil recovery projects in west Texas and elsewhere. There is no indication that the problems for carbon dioxide pipelines are any more challenging than those set by hydrocarbon pipelines in similar areas. So, we can use the learning from the use of hydrocarbon pipelines, i.e. system design, construction, risk monitoring, to develop pipelines for CO_2 transport.

Table 1. Transportation of global large-scale CCS project in operation
(adapted from GCCSI, 2017b)

Project name	Capacity (Mtpa)	Operation date	Transport type	Length (km)
Val Verde Natural Gas Plants	1.3	1972	Pipeline	316
Enid Fertilizer CO_2-EOR Project	0.7	1982	Pipeline	225
Shute Creek Gas Processing Facility	7.0	1986	Pipeline	Multiple, maximum of 460 km
Sleipner CO_2 Storage Project	0.85	1996	N/A	Not applicable
Great Plains Synfuel Plant and	3.0	2000	Pipeline	329

Weyburn-Midale Project				
Snøhvit CO$_2$ Storage Project	0.7	2008	Pipeline	153
Century Plant	8.4	2010	Pipeline	64 to 240
Air Products Steam Methane Reformer EOR Project	1.0	2013	Pipeline	158
Coffeyville Gasification Plant	1.0	2013	Pipeline	112
Lost Cabin Gas Plant	0.9	2013	Pipeline	374
Petrobras Santos Basin Pre-Salt Oil Field CCS Project	Approx. 1.0	2013	N/A	Not applicable
Boundary Dam Carbon Capture and Storage Project	1.0	2014	Pipeline	66
Uthmaniyah CO$_2$-EOR Demonstration Project	0.8	2015	Pipeline	85
Quest	Approx. 1.0	2015	Pipeline	64
Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries (ESI) CCS Project)	0.8	2016	Pipeline	43
Petra Nova Carbon Capture Project	1.4	2017	Pipeline	132

N/A means no transport required (direct injection)

3.1.1.1 Transport technology and system design

Broadly speaking, the CO$_2$ pipeline transport chain includes gas conditioning, compression and pipeline transport. Gas conditioning is referred to as the required processing for CO$_2$ to achieve transport specification. Normally, it includes two steps: removal of water and other liquids, and the removal of volatile gases. Liquids should be ensured not to enter CO$_2$ compressors in order to avoid the formation of gas hydrates, the freezing of water and corrosion. Volatiles gases, like nitrogen, would be transported later and would increase the energy requirement and cost. However, gas conditioning is often times considered as the interface between CO$_2$ capture and transport.

Figure 3. The CO$_2$ transport chain (Aspelund and Jordal, 2007)
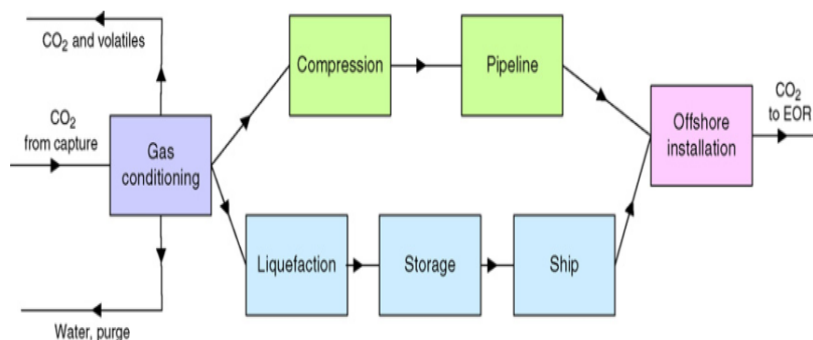
The most economic way of transporting CO_2 is as a dense phase (Vandeginste and Piessens, 2008). The dense phase pipeline was 20% cheaper than a low-pressure CO_2 gas pipeline. Generally, the pressure should be kept above 9.6 MPa to remain in a dense phase state no matter the temperature change. In addition, high pressure CO_2 is advantageous in the injection process. Compressors not only offer the pressure at the starting point, but also operate at some points along the pipeline, at areas called booster stations, to overcome the pressure loss caused by friction. These stations are not necessarily equally spaced. When pipeline length is short, they may lack compressor stations.

The diameter of the pipeline is the crucial parameter in pipeline design. Based on the mechanical energy balance, a model was developed to calculate the pipeline diameter required for a given pressure drop (Mohitpour et al., 2003). The diameter is also influenced by mass flow rate, fanning friction factor and pipeline length. The solving process is iterative, so an initial guess is needed.

A monitoring system is essential as high concentrations of CO_2 can be fatal for humans and animals. Pipelines can be monitored internally by pigs, which are piston-like devices moved along the pipeline by pressure, and can also be monitored externally by leak detection systems.

3.1.1.2 Economic analysis of pipeline transport

The cost of CO_2 transport includes three items: construction costs, operation and maintenance and other costs. Construction costs, also called capital costs, measure the initial investment costs. It contains material/equipment costs, and labor costs. Figure 4 shows construction costs for pipelines in different contexts. This data clearly shows the relationship between diameter and the capital cost. It is also obvious that booster stations increase the capital cost. O&M costs include monitoring costs, maintenance costs and energy costs. Other costs are miscellaneous, including design, project management and right-of –way costs, etc. Levelized cost takes all the costs in the whole lifetime of a project into account, and it represents the cost of per tonne CO_2 transported by pipeline (McCollum and Ogden, 2006).

Figure 4. Construction costs for pipelines from various information sources. Costs exclude booster stations. (IPCC, 2005)
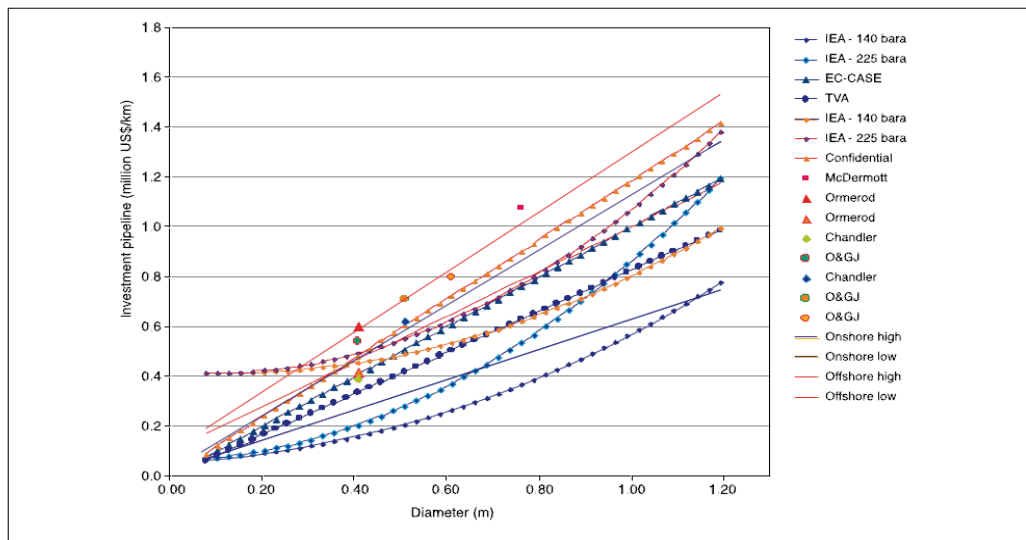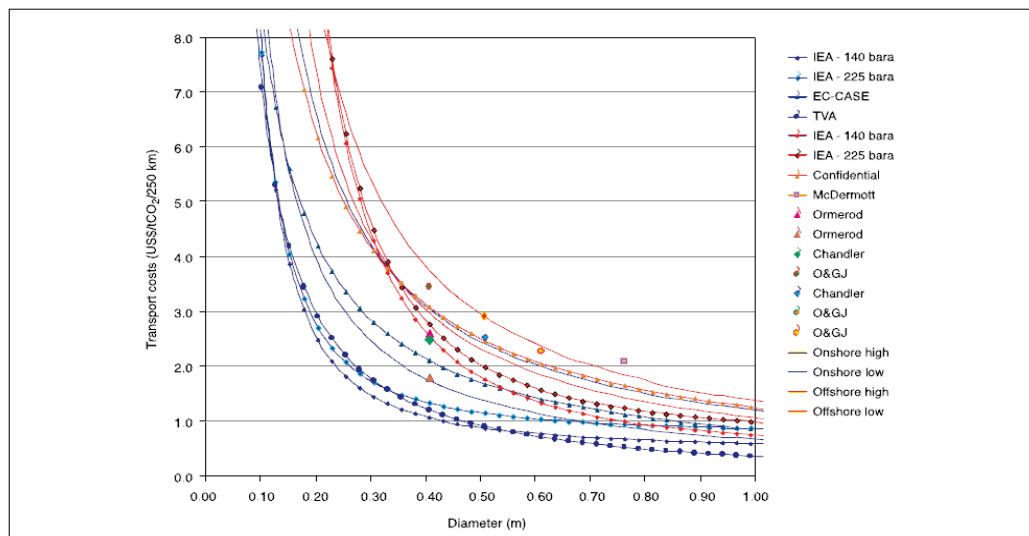

Figure 5. Levelized cost of pipeline transport from various information sources. (IPCC, 2005)

Based on natural gas pipelines experience, Mccoy and Rubin (2008) developed a model to calculate the pipeline capital cost in the U.S. For an illustrative example (five million tonnes of CO_2 transported over 100km), the capital cost was US$1.16 per tonne of CO_2. An engineering-economic model based on China-specific condition was also developed (Liu and Gallagher, 2011). For five illustrative case studies with a pipeline length of 100km, the levelized costs are US$1.84-3.06 per tonne of CO_2 , about two-thirds that of the developed countries.

3.1.2 CO₂ transport by ship

CO_2 transport by ship is more flexible compared to pipeline transport, and it is more competitive for ocean CO_2 storage or marine oilfield EOR. CO_2 transport by ship is very similar to LPG transport by ship. However, the number of CO_2 marine tankers is rather limited because of the low demand. Currently, there are no existing experienced CO_2 transport ships for CCS. Only four small-scale semi-pressurized CO_2 ships operate in western Europe, the CO_2 of which is used for the food industry. Korean-CCS 1 and 2 may become the first two projects using shipment transport for CO_2, as the storage site is offshore Korea. Now they are under evaluation and the operation date is in the 2020's.

3.1.2.1 Transport technology and system design

The CO_2 ship transport process is rather different to the pipeline transport process. The ship transport chain of CO_2 includes liquefaction and gas conditioning, an intermediate storage, a loading system, shipping and a loading system. At the onset of the transport process, CO_2 is liquefied around its triple point. The density of CO_2 will range from 1200 Kg/m^3 at the triple point to 600 at the critical point. Higher density means more CO_2 can be transported for the same size ship. In addition, since CO_2 is captured continuously, but the cycle of ship transport is discrete, the system must include an intermediate storage part. The CO_2 is stored at the bubble point in semi-pressurized storage tanks before being loaded on board.

There are three types of ships for transporting CO_2: fully pressurized ship, semi-pressurized ship and fully refrigerated ship. Semi-pressurized ships are recommended by ship designers and the best transport condition is at 0.65MPa and -52°C (Bock et al., 2003). LPG ships can be rebuilt for CO_2 transport. However, some difficulties may arise because the CO_2 is transported at a little higher pressure and lower temperatures. It is noteworthy that CO_2 leakage during ship transport is inevitable. The total loss is estimated between 3 to 4% per 1000km (IPCC, 2005).

3.1.2.2 Economic analysis of CO₂ transport by ship

Costs of shipment system comprise many elements. Capital costs involve investments for ships, loading and unloading facilities, intermediate storage and liquefaction units. O&M costs include ship fuel costs, electricity costs etc. There are also miscellaneous costs. However, there is very little information on the costs of a CO_2 shipment system as there are no large-scale CCS projects at present. Hence the cost estimates from different literature may vary widely.

Aspelund et al. (2006) performed a cost, energy and CO_2 emission analysis on transport chain within the North Sea. The total cost is US$20-30 per tonne of CO_2 for volumes larger than 2Mt per year. The energy requirement is 142 KWh per tonne of CO_2, where the liquefaction process accounts for 77%. Total CO_2 emissions are estimated to be 1.4% of the inlet CO_2. By comparison, a case study in China gives the levelized cost of shipment transport as US$7.09 per tonne of CO_2 with a ship transport distance of 300km and pipeline length of 25km (Gao, 2011). The ship capacity and travel distance are sensitive factors and will have large impact on cost. The relationship between travel distance and the levelized cost is non-linear. Therefore, ship transport is a more cost-effective transport solution with distance over 1000km (Aspelund, Molnvik, & Dekoeijer, 2006). Figure 5 clearly shows ship transport is more cost-effective with a larger distance.

Figure 6. Comparison of costs of onshore and offshore pipelines, and ship transport. (IPCC, 2005)
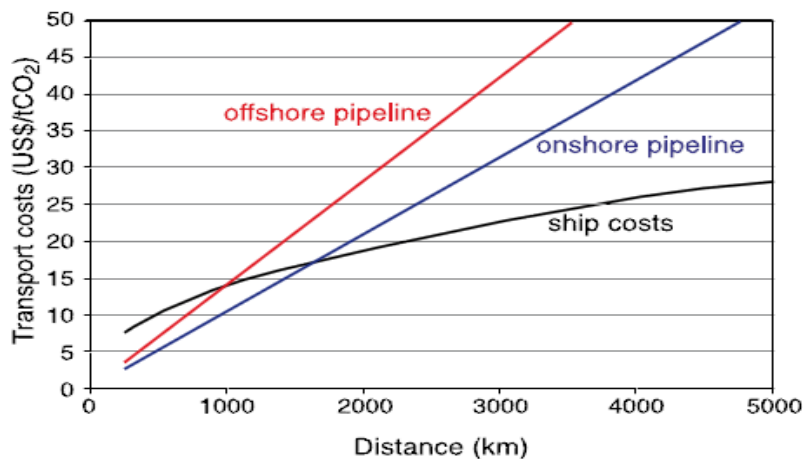
3.1.3 Proximity study

Broadly speaking, any place that releases CO_2 into the atmosphere is a CO_2 source. In contrast, any place that sequestrates CO_2 from the atmosphere is a CO_2 sink. However, in this context sources and sinks refer to those related to CCS project. Therefore, CO_2 sources include power plants, steel mills, cement factories, etc. CO_2 sinks include oil reservoirs, deep saline aquifers, coal beds and the ocean.

Proximity study is indispensable in CCS system. It is necessary to spot the geo-location of CO_2 sources and sinks and specify their capacity so as to evaluate the CCS potential in an area. In addition, the geological information can be used to calculate the transportation cost. The availability of CO_2 sources data is relatively easy, but things are not easy for sinks. The sinks are always underground which means geological exploration method should be used. In this case, the accuracy is compromised. In most

cases, CO_2 sources and sinks do not coincide. So proximity study is needed to deploy CCS transport lines wisely to optimize the NPV.

Proximity study of China is at an early stage, though several studies have estimated CCS potential of China. Bai et al. (2006) performed a preliminary study on CO_2 industrial point sources and their distribution in China. Liu et al. (2005) estimated the CO_2 storage capacity of coalbeds in China. Li et al. (2006) studied the deep saline aquifers in China and ranked their potential for CCS application. At present, proximity study of China is at national scale which is not meaningful considering a specific CCS project. Also the lack of integrated study of sources and sinks undermines the integrity of CCS system. Therefore, proximity should be performed at regional scale and be more holistic in future.

### 3.1.4 CO_2 transport recommendation

CO_2 transport approaches should be determined based on proximity study and the quantity of CO_2 to be sequestrated. For the existing alternatives, pipeline transport is the most cost-effective and stable method for onshore storage. However, for some special cases, i.e. CO_2 capture from marine natural gas production, ship transport can be an alternative option. In summary, pipeline transport is our recommendation for CO_2 transport. We should focus on building of pipeline networks.

3.2 Trapping mechanisms of geological storage of CO_2

The Carbon Sequestration Leadership Forum (CSLF) described mechanisms of CO_2 geological storage in great detail. Trapping mechanisms of CO_2 can be classified into five types: structural trapping, capillary trapping, solubility trapping, mineral trapping and hydrodynamic trapping. The relative importance of these processes is expected to change over time as CO_2 migrates and reacts with the rocks and fluids, as illustrated conceptually in Figure 7 (Benson & Cole, 2008). With the extension of time, the storage security of CO_2 sequestration increases. The trapping mechanism determines the contribution of each trapping approach. At the beginning, structural trapping and hydrodynamic trapping play an important role. After hundreds of years, the effect of capillary trapping, solubility trapping and mineral trapping increases in importance. These main trapping mechanisms are summarized in the subsections below.

For scientific research on caprock-sealing mechanisms of CO_2 sequestration, Song and Zhang (2013) presented a comprehensive overview of the CO_2 caprock-sealing mechanisms, where the problems related to CO_2 leakage are defined, and major research gaps and additional study areas are identified.

Figure 7. A general representation of the evolution of trapping mechanisms over time
(Metz, Davidson, De Coninck, Loos, & Meyer, 2005)
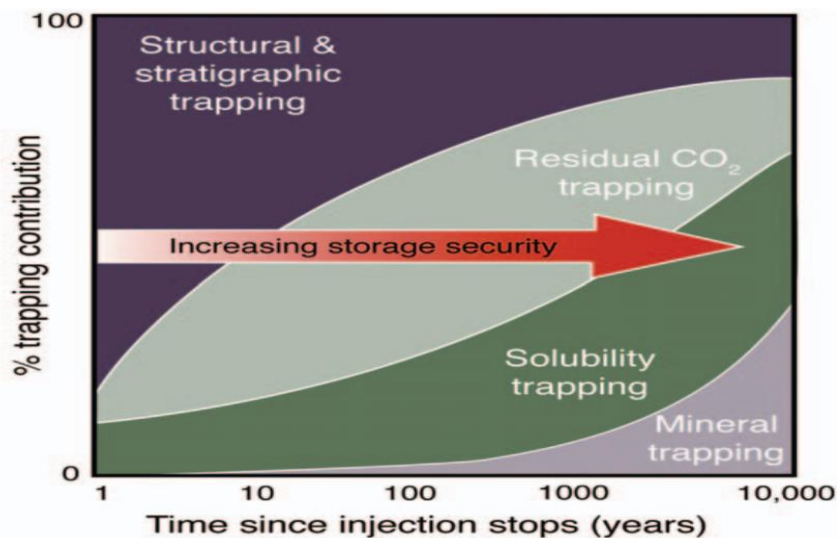
3.2.1 Structural trapping

When a thick and fine-textured rock serves as a seal above the sequestration reservoir, the migration of CO_2 is vertically restricted. Though CO_2 has high buoyancy, the sealing effect of an impermeable layer impedes the upward migration of CO_2. In addition, the seal is supposed to provide an effective permeability and capillary barrier for upward migration (Benson & Cole, 2008). Geological structures capable of forming a sealing trap include anticlines (a type of fold that is an arch-like shape), fault blocks (bedrock broken up into blocks of rock by faults) and pinch outs (a subsurface pool of hydrocarbons trapped by overlying rock formations with lower permeability). In most cases, the structure originally contains oil and gas, or groundwater. Structural trapping works immediately after the injection.

3.2.2 Capillary trapping

During CO_2 migration within a reservoir unit, CO_2 can be trapped in the pore space due to tensional forces at the gas-liquid interface. When large quantities of CO_2 pass through porous media, CO_2 is usually isolated in the pore as spherical droplets. Therefore, the more CO_2 passing through the porous media, the more CO_2 is trapped in the rock pore. Normally, this process can last for several decades after CO_2 has been injected into the formation. This process traps CO_2 primarily after injection stops and water begins to mix with the CO_2 plume.

3.2.3 Solubility trapping

When CO_2 migrates into the pore spaces of rock, it will come into contact with water and crude oil, into which CO_2 can dissolve. This process leads to solubility trapping. The amount of CO_2 that can dissolve depends on several factors, most notably pressure, temperature, and salinity of the brine (Benson & Cole, 2008). The chemical composition of formation water and crude oil, and the contact rate between CO_2 and unsaturated formation water and crude oil will also determine the amount of dissolved CO_2. Because of the gravity, CO_2-saturated formation fluids will move downwards towards the center of the basin over time. Due to this effect, this trapping mechanism has more storage potential compared with structural trapping. The time-scale of solubility trapping is from 100-1000 years.

3.2.4 Mineral trapping

This mechanism occurs when dissolved CO_2 reacts directly or indirectly with minerals in the geologic formation, promoting the precipitation of carbonate minerals (Oelkers, Gislason, & Matter, 2008). Although mineral trapping is considered as the most reliable for the reason that it can trap the CO_2 over very long time scales, the process is very slow and the overall efficiency may not be realized for hundreds of years or longer. The main factors which can influence the speed of mineral trapping include mineral composition, fluid type and the type of chemical reaction. For example, chemical reaction rate is high when the mineral being formed is carbonate. In contrast, the chemical reaction rate is low or even negligible when the formation is sandstone.

3.2.5 Hydrodynamic trapping

The groundwater flow pressure will impede and accumulate CO_2 when its direction is opposite to that of CO_2 buoyancy and of approximately equal force. This mechanism works when the CO_2 is injected into the deep saline aquifers within a closed formation. Like the structural trapping, hydrodynamic trapping works immediately after the injection. The difference is that the lateral movement of CO_2 is not blocked in hydrodynamic trapping. The groundwater migration velocity is measured in centimeters per year, whereas the CO_2 migration distance is measured in kilometers. So it will take thousands of years for the injected CO_2 to migrate to the shallower geologic sections. Other trapping mechanisms will likely also contribute and, consequently, no free CO_2 will reach the surface. Thus the integrity of the CO_2 storage is guaranteed.

3.3 Options for CO_2 storage

Following the capture and transport processes, it's necessary to sequester CO_2. There are many options available for the long-term storage of CO_2. CO_2 can be stored into geological formations, such as deep saline aquifers and depleted oil reservoirs which

additionally have economic benefits. Geological storage is at present considered to be the most viable option for the storage of the large CO_2 quantities needed to effectively reduce global warming and related climate change (Leung, Caramanna, & Maroto-Valer, 2014). A typical geological storage site can hold several tens of million tonnes of CO_2 trapped by different physical and chemical mechanisms (Doughty, Freifeld, & Trautz, 2008).

Suitable geological sites for CO_2 storage need to be carefully selected. General requirements for geological storage of CO_2 include sufficient porosity for large volumes, the thickness and permeability of the reservoir rock (permits injection at high flow rates without requiring overly high pressure), a cap rock with good sealing capability, and a stable geologic environment (Solomon, Carpenter, & Flach, 2008). Additional factors should also be taken into account, such as the distance between storage sites and source of CO_2. Bachu (2000) describes the criteria and approaches for selecting suitable geological sites for storing CO_2, including the tectonic setting and geology of the basin, its geothermal regime, hydrology of formation waters, hydrocarbon potential and basin maturity. In addition, economic aspects related to infrastructure and socio-political conditions will also have an impact the site selection.

It is considered that three different geological formations are suitable for CO_2 storage: depleted oil and gas reservoirs, saline aquifers, and coal beds (Figure 8). The Earth's oceans cover over 70% of its surface with an average depth of about 3800 meters. The storage of CO_2 within marine sediment at sufficient pressure and temperature is also a feasible option for CO_2 storage. It is estimated that CO_2 storage potential can reach 400-10000GT for deep saline aquifers compared with only 920 GT for depleted oil and gas reservoirs and >15 GT in coal beds (Ghg, 2004). Different options for CO_2 storage have their advantages and disadvantage as discussed below.

Figure 8. Types of geological formations and reservoirs that can be used for storage (Benson & Cole, 2008)
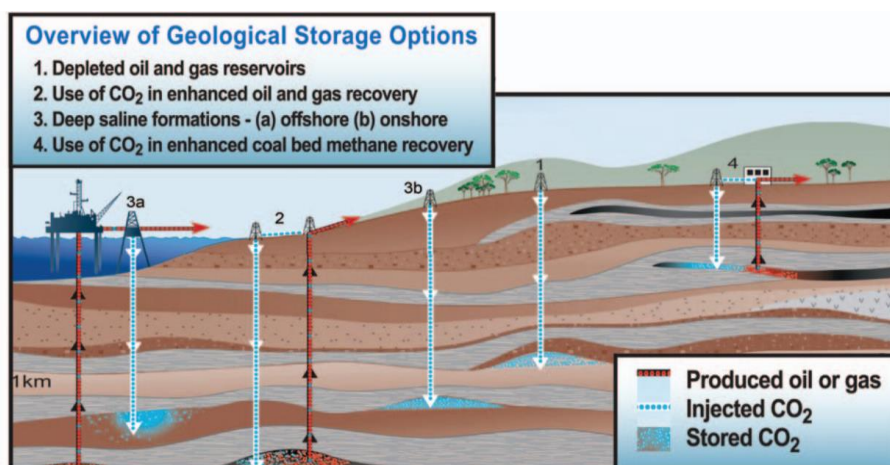
3.3.1 Depleted oil and gas reservoirs

Much of the oil remaining in a reservoir at the end of primary or secondary recovery may be trapped by capillary forces as discrete droplets, surrounded by water, or as a continuous phase at low saturation with gas occupying the larger fraction of the pore space (Bondor, 1992). Injecting CO_2 into depleted oil and gas reservoirs can maintain pressure and effectively enhance oil recovery. The displacement of oil by gas can be classified as immiscible and miscible processes, depending on the properties of the gas injected and the reservoir fluids at reservoir conditions (Gozalpour, Ren, & Tohidi, 2005). Immiscible flooding occurs at pressures below a minimum miscible pressure (MMP) of the oil, in which there is less interchange of components or mixing zones between the CO_2 injected and the reservoir fluid. On the contrary, the CO_2 injected and hydrocarbons are completely miscible and form a single-phase fluid at miscible conditions. Mechanisms of miscible flooding range from oil swelling and viscosity reduction for injection of immiscible fluid (at low pressure) to completely miscible displacement in high pressure applications.

In these applications, more than 50% and up to 67% of the injected CO_2 returns with the produced oil and is usually separated and re-injected into the reservoir to minimize operating costs (Metz, Davidson, de Coninck, Loos, Meyer, et al., 2005). Thus, storing CO_2 in depleted oil and gas reservoirs can not only sequester CO_2, but also enhance oil recovery.

3.3.2 Saline aquifers

Saline formations are deep sedimentary rocks saturated with formation waters or brines containing high concentrations of dissolved salts (Solomon et al., 2008). Deep aquifers at 700-1000m below ground level often host high salinity formation brines (Singh, 2008). Deep saline aquifers almost have no commercial value but can be used to store CO_2. The biggest difference between this option and others is that mechanisms are much more complex and the quantities of CO_2 stored in saline aquifers change over time. Its efficiency depends on pressure, temperature, salinity and interaction rates of CO_2, formation water and formation minerals. For this option, the following criteria for selecting a sequestration site should be considered: (1) Depth of storage should be greater than 800m; (2) The whole saline aquifer must be sealed; (3) Formations should have appropriate porosity and permeability. Although there is high uncertainty in the estimated potential of saline aquifer storage sites, arising from the minimal knowledge of deep-seated saline aquifers, sequestrating CO_2 in saline aquifers has potential in terms of storage capacity.

3.3.3 Coal beds

CO_2 can be injected into coal beds for enhanced coal bed methane (ECBM) which is trapped in the porous structure of coal seams. The adsorption capacity of CO_2 is greater than that of methane in coals, thus, CO_2 injected into coal beds will sorb to the coal inner surface and it can efficiently replace part of the methane at the same time. One of the first ECBM micro-pilot field tests was set up in Alberta, Canada. Several years later, similar tests were performed in China. It is estimated that 79Tcm of CBM are potentially recoverable globally:29 Tcm from conventional CBM, and 50Tcm from the ECBM. This would facilitate the potential storage of nearly 448Gt of CO_2 (Godec, et al., 2014). However, methane is also one kind of greenhouse gases and it can intensify the greenhouse effect more than CO_2. As a result, capturing methane replaced by injected CO_2 is crucial. Besides, one of the main problems associated with developing ECBM is the low permeability of most un-minable coals (Lokhorst & Wildenborg, 2005).

3.3.4 Deep-sea sediments

CO_2 can be injected below the ocean floor at the ocean depth >3000m. High pressure and low temperature provide an ideal environment which compresses CO_2 to a liquid phase that is denser than seawater. In this condition, a layer of more buoyant pore fluid will prevent the upward flow of CO_2. In addition, the formation of hydrate will also guarantee the stability of CO_2 storage. It has been suggested that the double cap of this approach will enable CO_2 to be stored without any monitoring or verification investment (House et al., 2006). The storage capacity for this approach is vast considering 71% of the earth is covered by ocean. Therefore, deep-sea sediments storage can be considered along with other storage options.

3.3.5 CO_2 storage recommendation

In light of the large quantities of coalbeds and oilfields in China, ECBM and EOR are recommended. On the one hand, the CO_2 storage potential is large. On the other hand, the increase in coal gas and oil production could be profitable. It is also necessary to improve the techniques for CO_2 storage to lower the cost and leakage risk. For example, a new monitoring system is needed. Finally, we should attract more and more enterprises to participate in the CCS projects. It is very beneficial to expand the scale of CCS and increase the public awareness.

3.4 Case studies

3.4.1 CCS projects in the world

As the world's first commercial CO_2 storage project, Sleipner operated at 1996 and around 15.5 million tonnes of CO_2 have been injected until June 2015. The Sleipner area gas development is located in the middle of the Central North Sea. Covering an area of about 26000 km^2, the shallow sands in Utsira Formation at Sleipner were deposited as basin-restricted marine lowstand deposits. A sand-rich succession in the Sleipner area is 200-300 m thick and has a net-to-gross ratio of 95%, interbedded with thin (<1 m) shale stringers. Porosities are 35-40% and permeabilities are above 1 Darcy. High porosity and large permeability make Utsira Formation an extraordinary place for CO_2 storage. It is estimated that the Utsira Formation is capable of storing 600 billion tons of CO_2.

From table 2, we can see that most of world's operating large-scale CCS projects use CO_2 to enhance oil recovery. The other three projects inject CO_2 into deep saline aquifers for storage.

Table 2. Primary capture & storage type of global large-scale CCS project in operation (adapted from GCCSI, 2017b)

Project name	Country	Operation date	Industry	Capture type	Primary storage type
Val Verde Natural Gas Plants	UNITED STATES	1972	Natural gas processing	Pre-combustion capture	Enhanced oil recovery
Enid Fertilizer CO_2-EOR Project	UNITED STATES	1982	Fertiliser production	Industrial separation	Enhanced oil recovery
Shute Creek Gas Processing Facility	UNITED STATES	1986	Natural gas processing	Pre-combustion capture	Enhanced oil recovery
Sleipner CO_2 Storage Project	NORWAY	1996	Natural gas processing	Pre-combustion capture	offshore deep saline formations
Great Plains Synfuel Plant and Weyburn-Midale Project	CANADA	2000	Synthetic natural gas	Pre-combustion capture	Enhanced oil recovery
Snøhvit CO_2 Storage Project	NORWAY	2008	Natural gas processing	Pre-combustion capture	offshore deep saline formations
Century Plant	UNITED STATES	2010	Natural gas processing	Pre-combustion capture	Enhanced oil recovery

Air Products Steam Methane Reformer EOR Project	UNITED STATES	2013	Hydrogen production	Industrial separation	Enhanced oil recovery
Coffeyville Gasification Plant	UNITED STATES	2013	Fertiliser production	Industrial separation	Enhanced oil recovery
Lost Cabin Gas Plant	UNITED STATES	2013	Natural gas processing	Pre-combustion capture	Enhanced oil recovery
Petrobras Santos Basin Pre-Salt Oil Field CCS Project	BRAZIL	2013	Natural gas processing	Pre-combustion capture	Enhanced oil recovery
Boundary Dam Carbon Capture and Storage Project	CANADA	2014	Power generation	Post-combustion capture	Enhanced oil recovery
Uthmaniyah CO_2-EOR Demonstration Project	SAUDI ARABIA	2015	Natural gas processing	Pre-combustion capture	Enhanced oil recovery
Quest	CANADA	2015	Hydrogen production	Industrial separation	onshore deep saline formations
Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries (ESI) CCS Project)	UNITED ARAB EMIRATES	2016	Iron and steel production	Industrial separation	Enhanced oil recovery
Petra Nova Carbon Capture Project	UNITED STATES	2017	Power generation	Post-combustion capture	Enhanced oil recovery

3.4. CCS projects in China

In China, demonstrations of both CCS and CCUS have been implemented. Shenhua Group's saline aquifer storage demonstration project in Ordos has been operational since 2011. China's National Petroleum Corporation (CNPC) and Sinopec have successively launched CO2-EOR campaigns in the oil fields of Jilin, Zhongyuan, Shengli, Jiangsu, Daqing, Changqing, etc., and have gained notable research achievements (Wu, 2014). China Huaneng Group and China Power Investment Corporation have built prototypes to capture CO2 from flue gas in Beijing, Tianjin, Shanghai, and Chongqing. China United Coalbed Methane Co., Ltd. has been conducting CO2-ECBM pilot experimental projects in two wells. The Yanchang Integrated Carbon Capture and Storage Demonstration Project has been progressing into the execution stage. Between 0.4 and 0.5 Mtpa of CO2 would be captured from gasification facilities at chemical plants in Shaanxi Province, with the CO2 used for EOR.

3.4.3 The next wave of projects

The Paris Agreement sets a goal of limiting global temperature increase below 2 Celsius degrees by 2050, and CCS plays a key role for achieving this target. However, the overall trend of CCS is not promising. The number of CCS projects that have failed to reach a financial investment decision outnumbers the successful projects by a factor of two to one. By 2016 the large-scale CCS projects had shrunk to 38 from 77 large-scale CCS projects in 2010. Given the shrinking number of projects in the early to mid-stages development, there is significant potential for stagnation in global project development. IEA (2016) concludes that CCS is not on track for Paris targets and picking up the pace of CCS deployment is urgent. Accelerating the pace of CCS deployment needs more policy support, economic investment, advanced technology, and global cooperation.

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