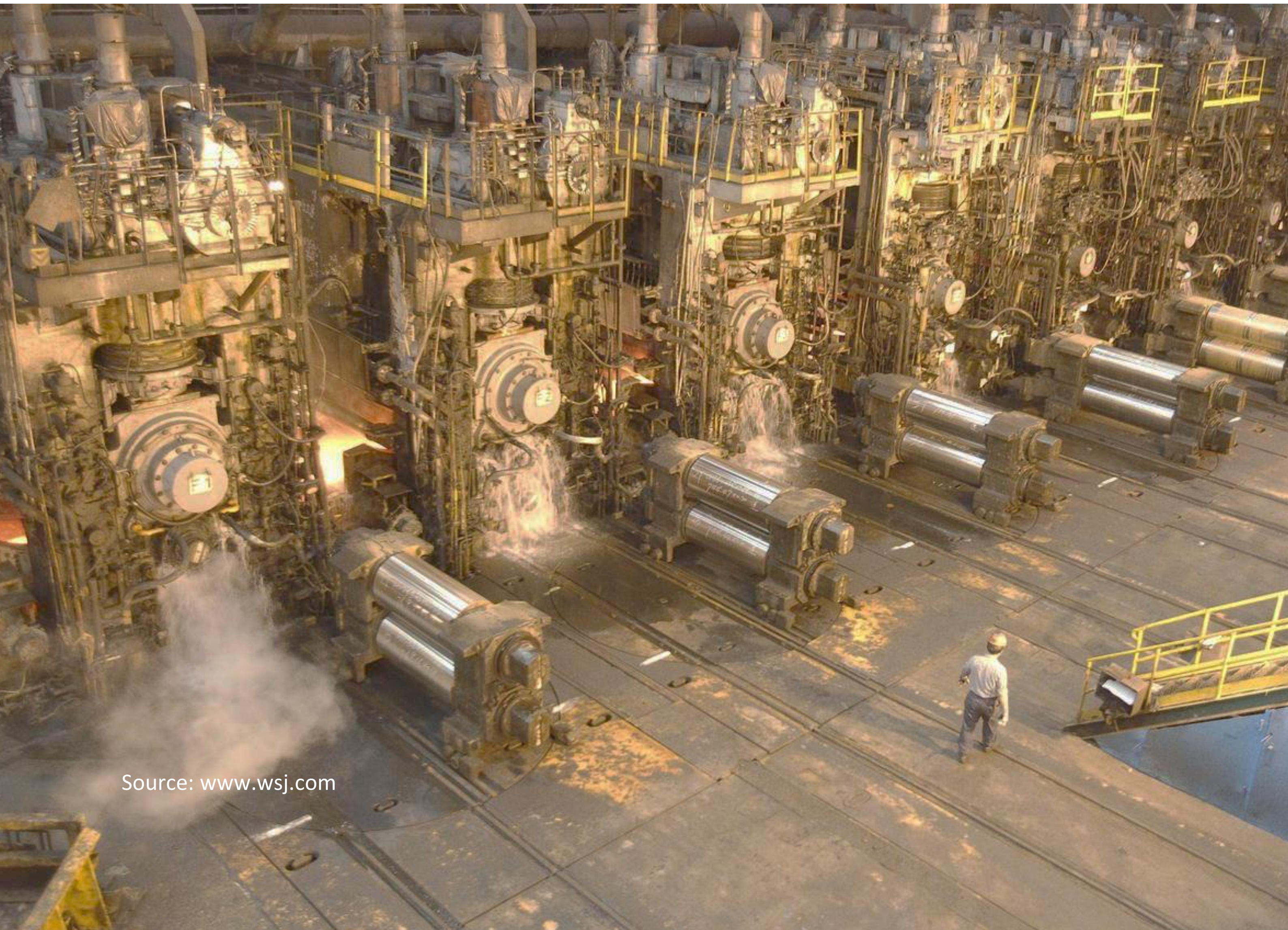
Carbon Capture, Utilisation and Storage in China's Iron/Steel Sector

CONSIDERATIONS FOR MAKING STEEL PLANTS CCS-READY IN CHINA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Considerations for Making Steel Plants CCS-Ready in China

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Acronyms

ADB	Asian Development Bank
ASPEN Plus	Advanced System for Process Engineering
BF-BOF	Blast Furnace – Basic Oxygen Furnace
BFG	Blast Furnace Gas
BoP	Balance of Plant
CAPEX	Capital Expenditure
CAPPCCO	Chinese Advance Power Plant Carbon Capture Option
CCR	Carbon Capture Readiness
CCS	Carbon Capture and Storage
CCSR	Carbon Capture and Storage Readiness
CCUS	Carbon Capture Utilisation and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COG	Coke Oven Gas
DCS	Distributed Control System
DECC	Department of Energy and Climate Change
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EOR	Enhanced Oil Recovery
FEED	Front-End Engineering Design
FGD	Flue Gas Desulphurisation
GCCSI	Global CCS Institute
GDCCUSC	UK-China (Guangdong) CCUS Centre
GIS	Geographic Information System
HAZOP	Hazard and Operability
HMB	Heat & Mass Balance
ID	Induced-draft
IGCC	Integrated Gasification Combined Cycle
LP	Low Pressure
LDG	Linz-Donawitz Gas
MAC	Marginal Abatement Cost
MCC	Motor Control Centre
MEA	Monoethanolamine
MDEA	N-Methyldiethanolamine
MVR	Mechanical Vapor Recompression

NO_x	Nitrogen Oxides
NRDC	National Resources Defense Council
OPEX	Operational Expenditure
PSA	Pressure Swing Adsorption
R&D	Research & Development
SO_x	Sulphur Oxides
UKCCSRC	UK CCS Research Centre
ULCOS	Ultra-Low CO_2 Steel Making
WHB	Waste Heat Boiler
WWT	Waste Water Treatment

1. Executive Summary

- The steel sector is one of the largest industrial sources of CO_2 emissions, contributing around 28% of the global industry sector's direct greenhouse gas emissions. Since 2012, China has accounted for approximately half of global steel production, rendering it critical to explore ways to decarbonise the Chinese steel sector. One important technological option for doing so is carbon capture and storage (CCS).
- 'CCS readiness' or 'CO_2 Capture Readiness' (CCR) is a design concept requiring minimal up-front investment in the present to maintain the potential for CCS retrofit in the future. As such, capture readiness avoids a carbon lock-in effect in the steel industry. This report outlines the key technical and design requirements to ensure that a steel plant is capture-ready.
- A hypothetical case study is undertaken to develop a conceptual CCR design for a project capturing 0.5 million tonnes of CO_2 from the off-gas of a steel plant hot stove at a capture efficiency of 90%, using a generic amine solvent (30 wt% MEA) as a base-case scenario.
- The general requirements for CCR include but are not limited to: **1)** the **choice of the geographic location** of the steel plant: after the addition of the capture plant, the captured CO_2 needs to be transported for geological storage and/or enhanced oil recovery, hence it is important to ensure proximity to a CO_2 storage site and to address health and safety issues; **2)** the **choice of capture technology**: CCR for steel plants should not be limited to a single technology pathway, but should take into account the demands of different technological options that may become viable in the future; and **3)** ensuring **sufficient space** exists to accommodate the additional CO_2 capture equipment and the required connections to it, as well as an extension of balance of plant (BoP) equipment to cater for the additional requirements (e.g. cooling water, auxiliary power distribution) of the capture equipment.
- This research indicates that **51 out of 142 steel plants with production capacity higher than 1 million tonnes per year in China are within a 200km radius of a potential EOR CO_2 storage sit**e.
- For the CCR design of the modelled project, a rectangular area of 4,000 m^2 (100m x 40m) needs to be reserved when the plant is constructed to accommodate, in the

future, the equipment of the pre-treatment unit, amine unit, the CO_2 compression unit for CO_2 transportation and storage, as well as a building complex including the control centre, analytical laboratory and the electrical switching rooms, etc. Additional space may be required for utilities supply facilities, estimated at around 1,200 m^2 (30m x 40m).

- **Cooling water** of around 12,500t/h in total will be required for cooling equipment (assuming a supply and return temperature of 32/40^{o}C respectively). The precise amount of cooling water required may vary with local weather conditions, as well as with water cooling system types.
- Modifications and additions to the **wastewater treatment plant** are expected to be required for capture retrofit in order to enable the plant to treat and safely dispose of the additional effluent from the capture equipment.

Key words: Steel, CCS, Capture Ready, CCS Readiness, China

2. Introduction

The steel sector contributes approximately 28% of the global industrial sector's greenhouse gas emissions (IEAGHG, 2018: 15), and since 2012, China has accounted for approximately half of global steel production (World Steel Association, 2018). This renders it critical to explore how to decarbonise the steel sector, in China in particular. The average carbon dioxide (CO_2) emissions from steel production using the blast furnace route, which is the dominant steel-making technology in China, is approximately 2-3 tonnes CO_2 per tonne of steel produced (ULCOS, 2013).[1]

A number of low-carbon technologies and plant upgrade options exist for steel plants. Figure 1 shows that the application of all possible negative (i.e. cost-saving, or 'no regrets') marginal abatement cost (MAC) technologies could contribute to a reduction of 0.45 tonne CO_2 per each tonne of crude steel produced. Put differently, deployment of all of these technologies put together would be able to reduce CO_2 emissions in crude steel production by no more than about 20-25%. Carbon capture and storage (CCS) is one of the few options available to reduce the remaining 75-80% of emissions, but its immediate large-scale deployment remains a challenge, due to its high positive abatement cost.

As time passes, however, lower MAC opportunities will be exploited and therefore no longer available, and a lower emission performance standard or a higher carbon pricing scenario, which would incentivise higher cost abatement, could be applicable in the future. A steel plant built today could operate for 25 to 40 years, therefore, establishing carbon capture and storage readiness (CCSR)[2] at steel plants can be a low-cost technical approach to ensuring plants could be retrofitted with CCS to achieve deep cuts in greenhouse gas emissions in the future.

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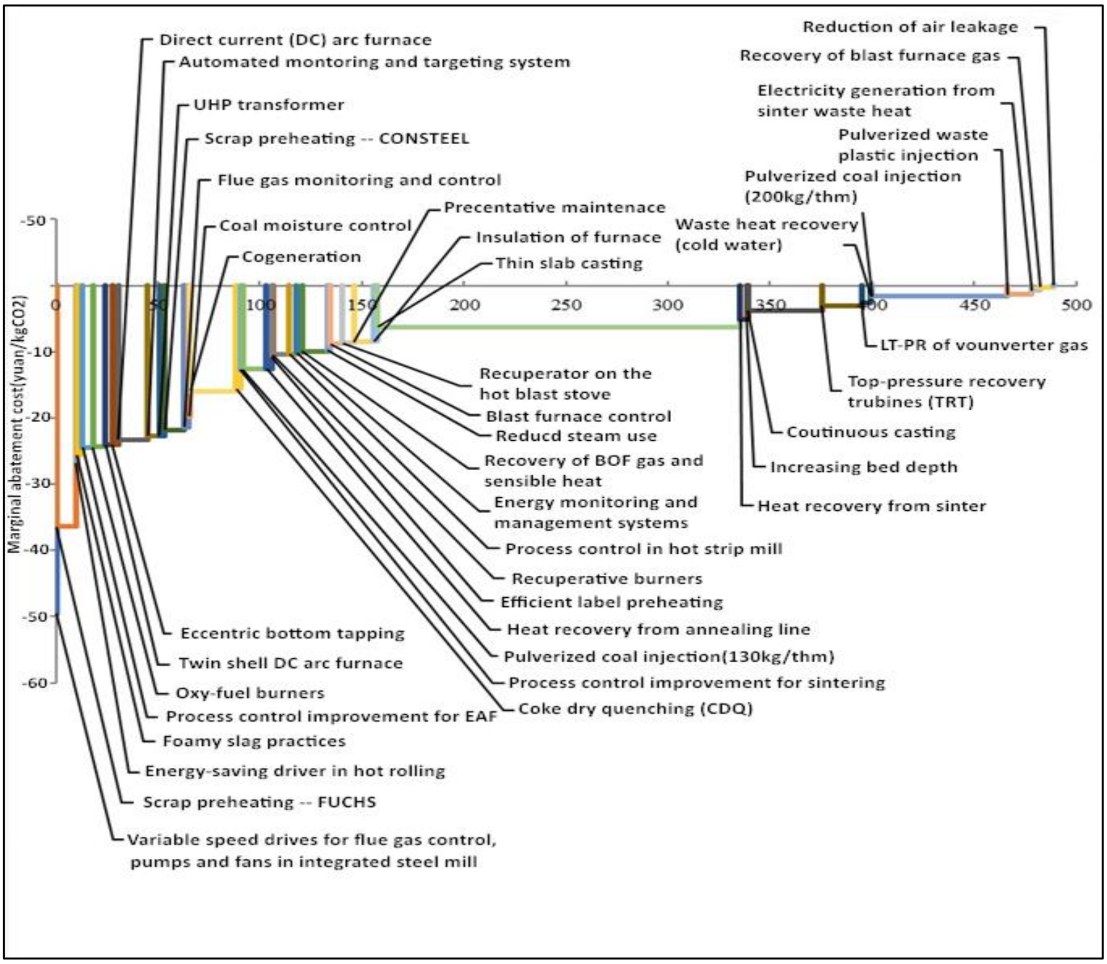
[1] This value can vary from as low as 0.4 tCO_2/t to up to 2.5 tCO_2/t of steel produced depending on the production technology and route adopted. The IPCC (2007) reported that the sector's emissions vary significantly between countries, where average emissions in Brazil are around 1.25 tCO_2/t steel, 1.6 tCO_2/t steel in Korea and Mexico, 2.9 tCO_2/t steel in the US, and 3.1-3.8 tCO_2/t steel in China and India.

[2] Hereinafter, the term CCSR, sometimes referred to as CCR (Carbon Capture Readiness), is used in the context of a power or industrial plant and refers to the fact that the consenting authority has concluded at the time the consent was granted that it will be technically feasible to retrofit CCS to that power station/industrial plant in the future.

Figure 1. Marginal abatement cost curve for negative-cost emission reduction technologies in the steel sector (Unit for y-axis: Yuan/kgCO_2; Unit for x-axis: kgCO_2/tonne crude steel production)



Source: Lu et al., 2018

The next section of the report explores the evolution of the concept of capture readiness, including how it has been applied in the Chinese power sector. Section 4 outlines design considerations for CCSR, including storage options for steel plants in China or ‘storage readiness’. Section 5 presents a case study for a hypothetical CCSR project for capturing 0.5 million tonnes of CO_2, and is followed by discussion and conclusions in section 6.

3. Evolution of the concept of 'capture readiness'

Gibbins (2004) defined capture readiness as a '*plant designed to have CO_2 capture added at some time in the future with minimal impact on lifetime economic performance*'. Aside from the technical design, a critical element in any capture readiness proposal is the need for physical space to accommodate the additional plant needed. The concept was further developed in the subsequent years (IEAGHG, 2007; Gibbins et al., 2006).

The idea has also become popular among some environmental groups. In December 2004, the US environmental group Natural Resources Defense Council (NRDC)'s China Clean Energy Project listed '*the development of capture readiness in China for coal gasification based poly-generation*' (co-production of electricity and chemicals) as one of their national initiatives (NRDC, 2004). Wilson and Gibbins (2005) raised a broader concept of 'capture readiness' in early 2005. Their suggestions included:

a) Making sure that new fossil fuel plants of all types are built so that, within the limits of the best current understanding, they can have a capture facility retrofitted in the future with the minimum additional cost and performance penalty;

b) Improving the technologies that will be needed to convert these capture-ready plants (and other existing plants) to capture CO_2, and feeding experience from this back into the capture-readiness plant design;

c) Making sure that any additional technologies that may not be as competitive until CO_2 capture becomes the norm are also developed for rapid deployment when they will be needed; and

d) Developing proven- and socially-acceptable CO_2 storage options.

Capture readiness should not be restricted to capture alone, in the sense that a CCS project will need to be integrated across capture, transportation and storage. The concept of capture readiness should ideally incorporate plant siting to allow as much of the captured CO_2 as possible to be transported to the storage site in order to lower the total cost of the CCS process. Moreover**, 'capture readiness' does not entail a specific plant design, but rather a spectrum of investments and design decisions that a plant owner would undertake during the design and construction of the plant** (Bohm et al., 2007: 114).

The GCCSI (2010) with support from ICF Consulting further developed the capture readiness concept and promoted CCS readiness with more consideration of storage and transport readiness. Capture readiness was adopted by the UK Government in the revision of the Electricity Act 1989. The concept was brought to China in 2006 through stakeholder consultations in the Chinese Advance Power Plant Carbon Capture Option (CAPPCCO) project (Li et al., 2012; 6-7) and an option value concept was introduced by Liang et al. (2009) for a hypothetical case study of a power plant in China to enable stakeholders to understand the intrinsic value of making a new plant capture-ready.[3] The concept of capture readiness was also promoted by multilateral banks in China, and the Asian Development Bank (ADB, 2014) made a recommendation for capture-ready plants' design in 2014. The Chinese industry incorporated the capture readiness concept in the 2014 feasibility study of China Resources Power Haifeng Project's Units 3 & 4 coal-fired power plant (GDCCUSC, 2014: 30).

In summary, the concept of capture readiness has evolved over time, from a narrow appreciation of the basic physical requirements for future retrofit of capture technologies, to a broader understanding of the need to anticipate and support a variety of future CCS-related needs. The concept should not be restricted to 'capture' alone, as a CCS project will need to be integrated across the full chain of capture, transportation and storage. Accordingly, the concept of capture readiness should ideally incorporate plant siting to allow as much of the captured CO_2 as possible to be transported to the storage site in order to lower the total cost of the entire CCS process.

[3] To understand the economic value and investment characteristics of making new plants CCR in China, Liang and his team examined a typical 600MW pulverised coal-fired ultra-supercritical power plant, located in Guangdong province.

4. Technical and design requirements for CCS-ready steel plants

4.1. Locational considerations

The geographic location of the plant plays a major role in determining its suitability for CO_2 capture as, after the addition of the capture plant, the captured CO_2 needs to be transported for geological storage and/or enhanced oil recovery (EOR). Factors relevant to a plant's geographic location include:

- ***Proximity to a CO_2 storage and/or utilisation location***: this will enable ease of transport and reduction in transportation cost.
- ***Proximity to other existing or planned carbon capture facilities***: this could enable sharing of CO_2 infrastructure leading to lower CO_2 transport costs (the potential for shared CO_2 pipelines, shared road transport facilities or ship transport for coastal sites). Furthermore, risks associated with public opposition to building new plants are generally lower for sites with an established industrial presence;

Table 1. Potential EOR storage sites in proximity to large steel plants in China

Potential EOR Storage Sites	Number of Steel Plants within 200km radius	Number of Steel Plants within 500km radius
Shengli Oil Field	4	30
Jidong Oil Field	16	17
Jianghan Oil Field	1	14
Jiangsu Oil Field	8	11
Jingan Oil Field	7	10
Changqing Oil Field	0	8
Zhongyuan Oil Field	5	7
Sichuan Basin	2	7
Liaohe Oil Field	3	6
Pearl River Mouth Basin	2	4
Beibuwan Basin	1	3
Daqing Oil Field	0	3
Yanchang Oil Field	1	1
Zhungeer Basin	1	1
Tadamu Basin	0	1
Total	**51**	**123**

A preliminary GIS analysis undertaken by the project team indicated that 51 out of 142 steel plants in China with production capacity higher than 1 million tonnes per year are within a 200km radius of a potential EOR CO_2 storage site, as shown in Table 1 and Figure 2 below. First, we investigated the distribution of existing steel plants based on the data from China Steel Yearbook (2017) and marked those plants with annual steel production higher than 1 million tonnes. Then we marked main potential CO_2-EOR sites in China (Dahowski et al., 2009) and only took into account those sites that are within 500km radius of each steel plant. A separate report developed by this study's researchers will focus on non-EOR CO_2 storage opportunities for steel plants.

Figure 2. Location of large steel plants (red) and potential storage sites (blue) in China

4.2. Carbon capture technology options for different flue gas streams

An iron- and steel-making plant has a complex flue gas emission system – unlike a coal-fired power plant which has a unified centralised discharge from a stack. The emission source locations of iron/steel plants are relatively dispersed and the contents and components of the different flue gases are not the same. Therefore separate carbon capture units must be considered for different parts of the steel plant.

4.2.1. Iron/steel making processes and CO_2 emission sources

In general, making steel involves two stages: 1) **the iron-making process**, where pig iron is extracted from iron ore; and 2) **the steel-making process**, where pig iron is purified into rough steel. The two processes can be further split into four parts:

- Raw material preparation, including iron ore sintering/pelleting, lime kiln, and coal coking;
- Iron smelting (iron ore transformation into molten iron or direct reduced iron (DRI) through a carbonaceous device, and solidification of the product), including two main routes: 1) the blast furnace – basic oxygen furnace (BF-BOF) route and 2) the electric arc furnace (EAF) route. The BF-BOF route, which utilises iron ore and scrap, uses between 70% and 100% of iron ore, with the balance made up of steel scrap. The EAF route, which utilises DRI, scrap, and cast iron, uses between 70% and 100% scrap material, with the balance made up of ore-based materials;
- Steelmaking (conversion of molten iron or DRI into liquid metal); and
- Iron and steel casting, heating, rolling and forming.

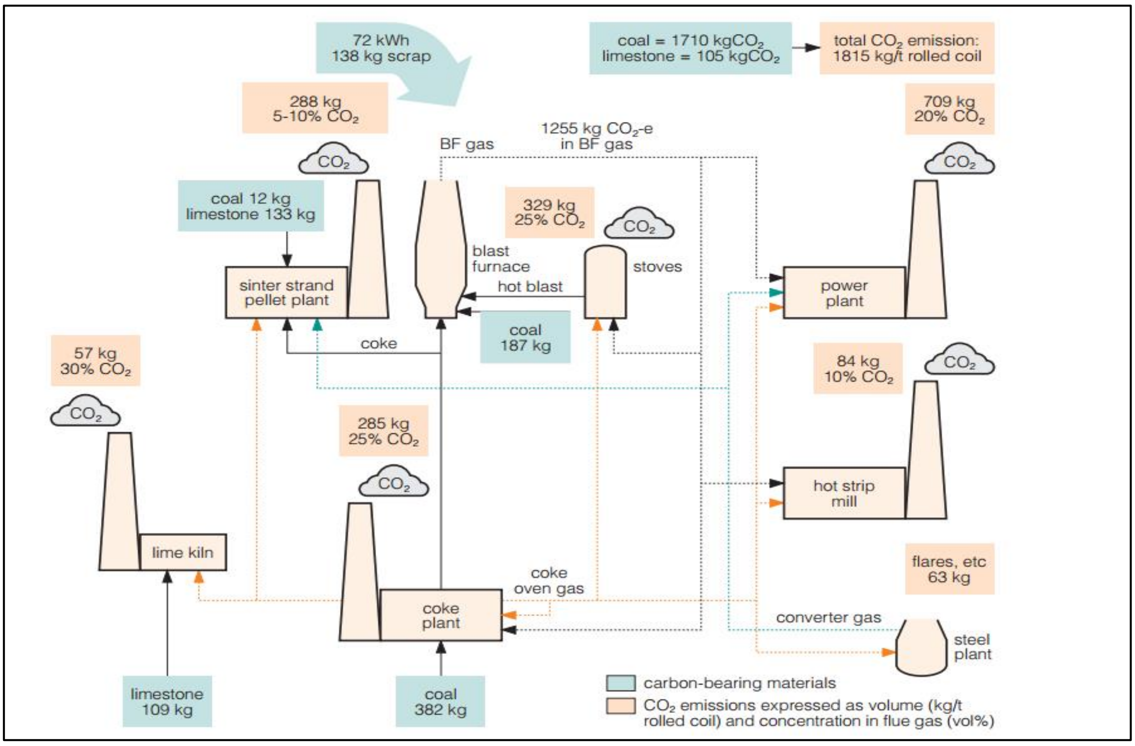
Other auxiliary facilities include the power plant, which uses the gaseous fuels from various iron- and steel-making processes, including mostly by-pass gas products such as coke oven gas, BF gas, and converter gas.

The typical CO_2 emission sources of a steel-making plant are illustrated in Figure 3, featuring CO_2 concentration ranges and emission indices per tonne of rolled-coil steel produced.

The CO_2 emission sources of Chinese iron and steel plants are identified according to 'The Guidelines to Ironmaking and Steelmaking Enterprises for Accounting Methods and Reporting of Greenhouse Gas Emissions in China' which was issued by the Chinese National Development and Reform Commission (2013).

In contrast with conventional blast furnace (BF) and basic oxygen furnace (BOF) processes, new steelmaking process designs have emerged with the aim of lowering the energy and carbon intensity of the manufacturing process. IEAGHG (2018: 16) identified a number of emerging manufacturing technologies including electrolysis based steelmaking, advanced DRI-EAF, TGRBF (top-gas recirculated blast furnace), advanced smelting reduction (HIsarna, HIsmelt) and solid-state reduction (Corex). These new processes should be further investigated in future CCS-readiness studies.

Figure 3. Typical CO_2 emission sources of a steel-making plant



Source: UNIDO, 2010

4.2.2. Carbon capture technology options

There has been significantly more research on post-combustion CO_2 capture technologies than on other approaches and they are at a mature stage of development in the form of commercially-available amine-based solvents (commercial pre-combustion technologies are also available). However, the large-scale implementation of a post-combustion carbon capture project still faces various challenges, such as its high energy consumption, amine degradation, amine loss and other environmental issues, and the subsequent rise in the cost of capture. However, post-combustion, since it captures from the flue gas (which minimises the interruption of the exiting process), can benefit from reduced complexity at the plant interface (Progressive Energy Limited, 2015: 33). Emerging technologies that address these issues are under development, including new solvents, physical and chemical solid sorbents, membranes and cryogenic processes.

Due to the possibility of new technologies becoming commercially viable in future, capture readiness also involves ensuring that any such technologies may also be rapidly deployed when they become available and competitive. As such, CO_2 capture technologies are screened from a diverse range of gas separation technologies based on their current capacity for capture, but other potential technologies are also included in the scope of concept design for capture readiness. The characteristics of the main CO_2 emission sources and potential capture technologies are presented in Table 2, including the basic requirements for a capture-ready steel plant. This provides a long list of options which can subsequently be refined, and which will be continually reviewed to follow the progress of emerging capture technologies.

4.3. Essential requirements for a capture-ready plant

As per IEAGHG's (2007) definition of capture readiness, developers of capture-ready plants are responsible for ensuring that all known factors under their control and which could prevent the installation and operation of future CO_2 capture are identified and eliminated. This includes:

- Conducting a study of options for CO_2 capture retrofit and potential pre-investments;
- Inclusion of sufficient space and access for the additional facilities that would be required; and
- Identification of reasonable route(s) for the storage of CO_2.

Pre-investment in these essential capture-readiness features is expected to be relatively inexpensive. Further optional pre-investments could be made to reduce the cost and downtime for CO_2 capture retrofit.

4.3.1. Additional space for CCS in steel plants

A prime requirement for the construction of capture-ready steel plants that utilise amine capture technology is the allocation of sufficient additional space at appropriate locations onsite to accommodate the additional CO_2 capture equipment, plus the ducts and pipes for connections to it and points where the necessary connections to the existing plant can be made. A further requirement is to allow for the extension of BoP equipment to cater for the additional requirements (cooling water, auxiliary power distribution, etc.) of the capture equipment. The space required is also discussed in the context of individual systems and equipment and includes the following:

Table 2. Capture technology options for different CO_2 emission sources

Emission source	Off-Gas Features (CO_2 concentration in vol%)		Possible CO_2 Capture Technical Options		CO_2 capture-readiness steel plant requirement[1]								
					DeNO$_x$ DeSO$_x$	Pre-treatment	Space	Utilities Supply: Electric Power	Utilities Supply: Steam	Utilities Supply: Cooling water	Utilities Supply: Others	Chemical storage	WWT[7]
Sinter Strand Pellet	CO_2 5-10% 120-150 ℃	Low CO_2 conc., Complex compositions, High CO conc., Dioxin, Fluoride, SO_x, NO_x and dust	Post-combustion	Chemical absorption	Yes	Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	Yes
				Physical adsorption		Yes	***	***		*	Instru. air		
Flue gas from Coke Plant	CO_2 25% 130 ℃	High CO_2, Complex compositions, High content of NO_x, SO_x and dust	Post-combustion	Chemical absorption	Yes	Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	Yes
				Physical adsorption		Yes	***	***		*	Instru. air		
Coke Oven Gas[2] (COG)	H_2 45-64% CH_4 20-30% CO 5-10% CO_2 2-5%	High heat value, High add-value feedstock (High H_2 and CH_4 conc.)		Chemical absorption									
				Physical adsorption									
Lime kiln	CO_2 15-30% 110℃	High CO_2 and high dust	Post-combustion	Chemical absorption		Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	Yes
				Physical adsorption		Yes	***	***		*	Instru. air		
				Calcium-Looping CO_2 Capture[3]									
Blast Furnace Gas[4] (BFG)	CO_2 20-25% CO 20-25% H_2 3% 80-150℃	High CO conc. Fuel gas with low heat value	Pre-combustion	Chemical absorption		Yes	***	*	***	***	Raw water Demin water Instru. air [5]	Yes	Yes
				Physical absorption		Yes	***	**	*	**	Raw water Demin water Instru. air	Yes	Yes
				Physical adsorption		Yes	***	***		*	Instru. air		
				Membrane separation		Yes	*	****		**	Raw water Instru. air		
				Membrane + Physical adsorption		Yes	**	**		**	Raw water Instru. air		

Emission source	Off-Gas Features (CO_2 concentration in vol%)		Possible CO_2 Capture Technical Options		CO_2 capture-readiness steel plant requirement[1]								
					DeNO$_x$ DeSO$_x$	Pre-treatment	Space	Utilities Supply				Chemical storage	WWT[7]
								Electric Power	Steam	Cooling water	Others		
Hot Stove Flue Gas	CO_2 25-28% 155 ℃	High CO_2 conc.	Post-combustion	Chemical absorption	Yes	Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	Yes
				Physical adsorption		Yes	***	***		*	Instru. air		
				Membrane separation		Yes	*	****		**	Raw water Instru. air		
				Membrane + Physical adsorption		Yes	**	**		**	Raw water Instru. air		
Converter[6]	CO_2 15-20% CO 60-70% 100℃	Low CO_2 conc, High CO conc.	Pre-combustion	Chemical absorption		Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	Yes
				Membrane + Physical adsorption		Yes	**	**		**	Raw water Instru. air		
Power Plant Boiler Flue Gas	CO_2 20% 120℃	High CO_2 conc. Low dust	Post-combustion	Chemical absorption	Yes	Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	
				Membrane separation		Yes	*	****		**	Raw water Instru. air		
				Physical adsorption		Yes	***	***		*	Instru. air		
Hot strip mill	CO_2 10%	Low CO_2 conc., Ferric oxide dust, High water content		Chemical absorption		Yes	***	*	***	***	Raw water Demin water Instru. air	Yes	

Notes: 1. The number of '*' indicates the relative size of demand.

2. The coke oven gas will be sent to the sintering and power plant as gaseous fuel, or used for producing carbinol and making H_2 by PSA, chemical absorption, cryogenic methods, etc.

3. "Calcium-Looping CO_2 Capture Technology" was developed by Taiwan Cement Corporation and Taiwan Industrial Technology Research Institute.

4. Blast furnace gas with low heat value will be sent to hot stoves, coke oven or power plant boiler and used as gaseous fuel. The application of CO_2 removal will help to promote the heat value of the gas.

5. Demin water refers to Demineralised water; Instru. air refers to instrument air.

6. As gaseous fuel, Linz-Donawitz gas (LDG) with high heat value, to be sent to power plant or other equipment.

7. WWT: Waste Water Treatment.

- For carbon capture:
    - Flue gas pre-treatment unit;
    - CO_2 capture unit;
    - CO_2 compression and liquefaction unit;
    - Raw material storage facilities; and
    - Building complex, including Distributed Control System (DCS) control rooms, and the electrical switching rooms, research laboratories and offices.
- For utilities & auxiliary facilities (possibly shared with steelmaking plant):
    - Electrical distribution system (auxiliary transformer, cable, switch gear);
    - Cooling water system;
    - Raw water and desalted water treatment; and
    - Waste treatment and disposal system.
- Other common facilities (located in the main production area of the steelmaking plant):
    - Flue gas ducts;
    - Pipe racks or buried piping for the utilities distribution head; and
    - Other auxiliary systems, such as a compressed air system, maintenance, and a fire station.

4.3.2. Possible pre-investment options for CCS readiness

As well as satisfying the essential requirements of space, access and a route to storage, further pre-investments can be made to reduce the cost and downtime for the retrofit of CO_2 capture. Some potential capture-readiness pre-investments apply to all technologies, including oversizing pipe-racks and making provisions for the expansion of the plant control system and on-site electrical distribution. These pre-investments are generally low in cost and could result in significant reductions in the costs and downtime for CCS retrofit. Potential pre-investments could be applied to the following:

- Flue gas desulphurisation (FGD) equipment;
- DeNO$_X$ equipment;
- Particulate removal unit (bag filter likely to be better for post-combustion capture than an electrostatic precipitator, due to improved aerosol removal);
- Steam sources and waste heat recovery options;
- Water-steam condensate cycle;

- Compressed air system;
- Cooling water system;
- Raw water pre-treatment plant;
- Desalination plant;
- Waste water treatment plant;
- Electrical equipment;
- Chemical dosing systems and steam water analysis system;
- Plant pipe racks;
- Control and instrumentation;
- Safety equipment;
- Fire-fighting and fire protection system;
- Plant infrastructure; and
- Steam turbine options for CO_2 compression.

While some pre-investments for capture readiness are expected to have low costs and high potential benefits, there are two major reasons for not making major capture readiness pre-investments: economic discounting and uncertainty. Discounting is a well-established economic principle which means that economic resources in the future are worth less than they are at present. Also, due to uncertainty regarding future regulations and the value of carbon credits, it is uncertain if – or when – capture would be required. It is also uncertain how capture technologies will develop in the future. The costs of capture technologies are expected to decrease in the future due to 'learning by doing' and incremental technological improvements. If a plant is made capture-ready for a single existing technology, it risks becoming locked-in to a technology which may become obsolete, thus making the pre-investment worthless. Capture-ready plants should therefore be designed to accommodate anticipated future technological improvements, as far as reasonably possible. Nevertheless, it is difficult to predict future technology developments and the risk of obsolescence remains a major reason for not making substantial *technology-specific* pre-investments.

5. Case study of a hypothetical 0.5 million tonnes scale iron/steel capture readiness project

The objective of this case study is to develop a conceptual design for a hypothetical 0.5 million tonnes scale iron/steel sector capture readiness project. In the absence of any existing specification for capture-readiness of steel plants, guidance issued for power plant capture readiness in the UK has been used as a reference for this study. The 'Carbon Capture Readiness Guidance' was published by the UK Department of Energy & Climate Change in 2009 (DECC, 2009: 8), in which the CCR requirements were outlined as below:

"As part of their application for Section 36 consent applicants will be required to demonstrate:

- *That sufficient space is available on or near the site to accommodate carbon capture equipment in the future;*
- *The technical feasibility of retrofitting their chosen carbon capture technology;*
- *That a suitable area of deep geological storage offshore exists for the storage of captured CO_2 from the proposed power station;*
- *The technical feasibility of transporting the captured CO_2 to the proposed storage area; and*
- *The likelihood that it will be economically feasible within the power station's lifetime, to link it to a full CCS chain, covering retrofitting of capture equipment, transport and storage.*

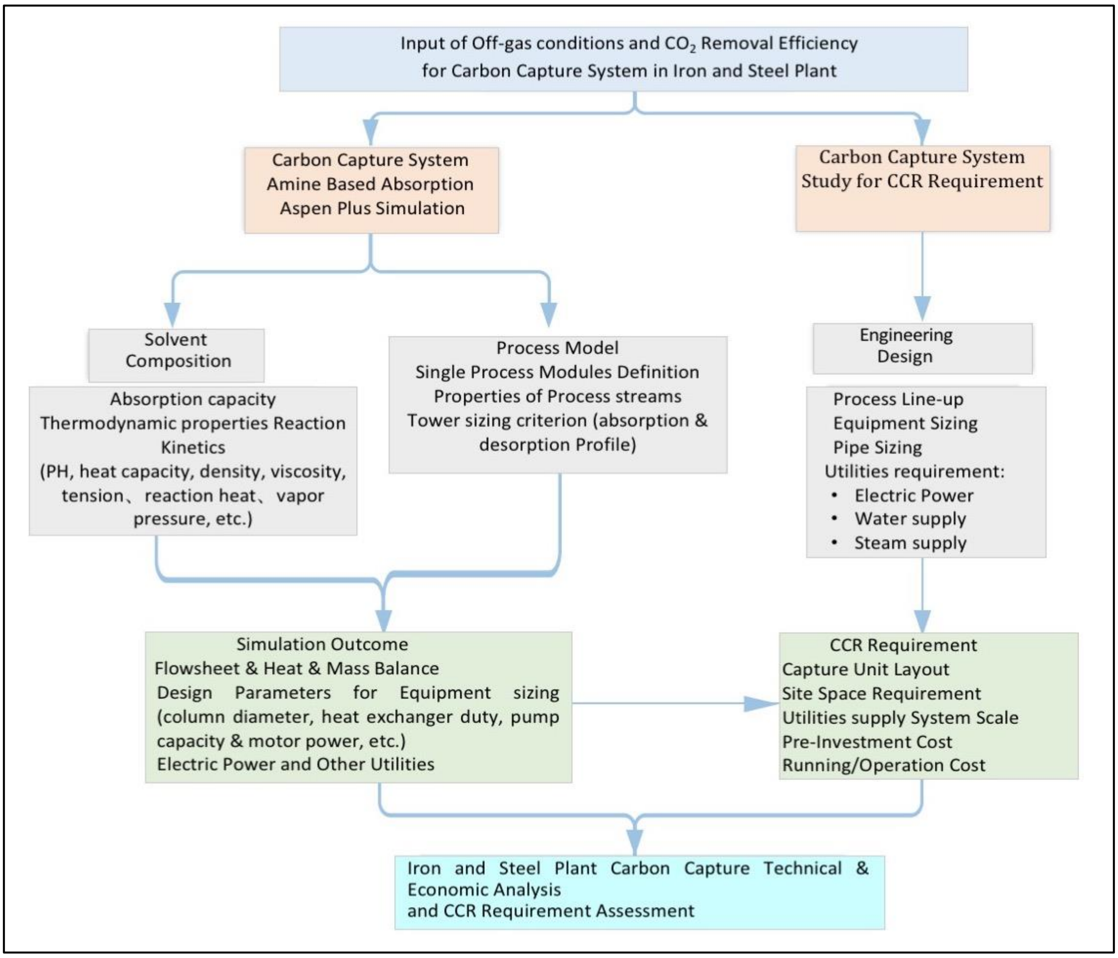
Applicants must make clear in their CCR assessments which CCS retrofit, transport and storage technology options are considered the most suitable for their proposed development."

Note, however, that the reference to offshore storage reflects particular UK conditions and is not a general requirement relevant to iron/steel CCS plants in China.

5.1. Technology hypothesis and methodology

The most widely considered technology for post-combustion capture involves the use of chemical solvents, typically a form of amine. Amine-based scrubbing technologies have been applied in CO_2 capture in many industries, such as coal-fired power plants, natural gas plants, coal-chemical plants, etc. New types of amines are still being developed and commercially-available amines include some proprietary amines developed by technology providers, as well as conventional amines with open access, such as MEA and MDEA, which are the earliest and most common amine family members used in CO_2 separation processes. Compared with MEA, proprietary solvents generally have lower regeneration heat duties and higher CO_2 absorption capacities. In general, the CCR requirements of future new types of amine should not be greater than those of current conventional amines. **This study will therefore focus on assessing the carbon capture readiness requirements associated with using a generic amine solvent (30 wt% MEA) as a base-case scenario** (Arasto et al., 2013).

Figure 4. Methodology for the hypothetical capture readiness study



The study uses **ASPEN** Plus (Advanced System for Process Engineering) software to perform process simulation, which is then used to develop a conceptual design for CCR requirements. ASPEN Plus is a proven chemical process simulation software that has been widely applied for R&D, design of large chemical systems, and production operation optimisation of the whole chemical plant. As a powerful engineering design tool, ASPEN Plus can provide engineering design parameters, chemicals consumption and utility requirements. The estimation of the operation cost can be performed based on the outcome of the ASPEN Plus simulation, as a starting point for further technical and economic analyses. The overall approach is illustrated in Figure 4.

5.2. Assumptions for the capture readiness study

5.2.1. CO_2 emissions sources

Typically, the CO_2 concentration will vary in the range of 10-35%, depending on the source, raw materials and iron/steel production process. Table 3 presents examples of the main CO_2 emission sources of a conventional rolled-coil steel plant.

A representative concentration value of 25% CO_2 is proposed for this study. Different CO_2 concentrations may need to consider other technical options.

Table 3. Typical off-gas inlet conditions

No.	Emission Source	CO_2 Emission Per tonne steel	CO_2 Concentration
1	Sinter Strand Pellet Plant	288 kg/t	~5-10%
2	Coke plant	285 kg/t	~25%
3	Lime kiln	57 kg/t	~30%
4	Power plant	709 kg/t	~20%
5	Blast furnace gas*		~20%
6	Hot blast stove	329 kg/t	25-28%;
7	Hot strip mill	84 kg/t	~10%
8	Flares	63 kg/t	
	Total**	**1815 kg/t**	

* Not-directly emitted to atmosphere, typically sent to the hot stoves to burn as a low heat value fuel.
** The production of 1 tonne of rolled coil steel will emit 1815 kg CO_2 in total to the surrounding environment.
Source: IEAGHG (2007)

Table 4. Typical hot blast stove off-gas inlet conditions and CO_2 capture assumptions

Item		Unit	Value
Composition	H_2O	Vol %	3.83
	CO_2	Vol %	25.00
	N_2	Vol %	68.66
	O_2	Vol %	2.51
Total Flow		Nm^3/h	158,700
Yearly Operating Hours		Hours	7,200
Total CO_2 Inlet to Capture Unit		kg/h	77,903
Expected CO_2 Capture Efficiency		%	90
Total CO_2 Captured Target		kg/h	70,127
		t/year	504,914

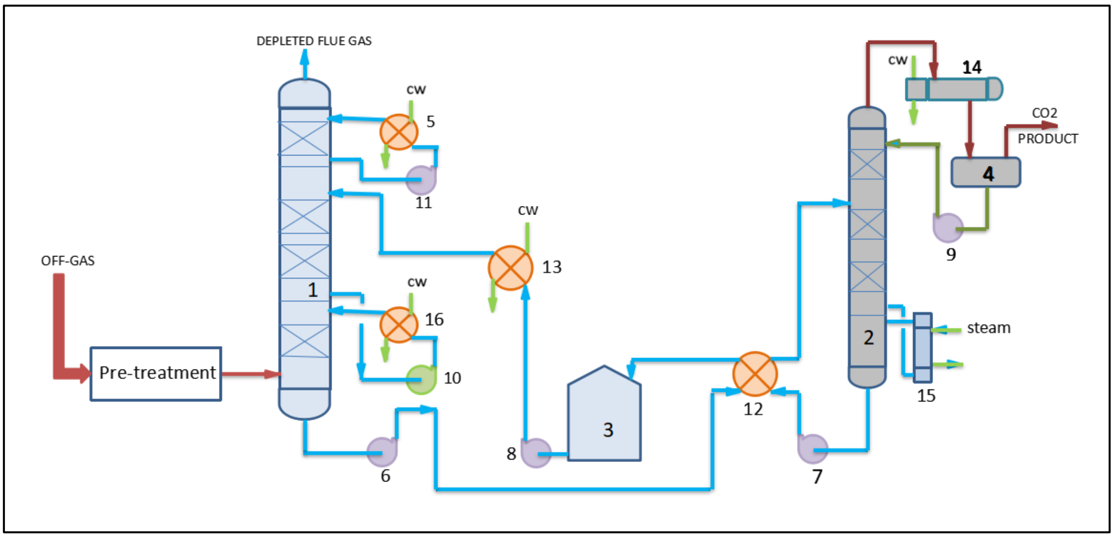
5.2.2.Input of off-gas conditions and CO_2 capture capacity

This case study assumes the capture of 500,000 tonnes of CO_2 per year from the off-gas of the hot blast stove at a capture efficiency of 90%. See Table 4 for typical off-gas inlet conditions.

5.2.3. CO_2 capture process description

Figure 5 presents a flow diagram of a typical CO_2 capture process based on amine scrubbing technology.

Figure 5. Typical amine-based absorption process flow diagram



1- Absorber, 2- Stripper, 3- Lean amine tank, 4- Reflux accumulator, 5- Wash water cooler, 6- Rich amine pump, 7- Lean amine pump, 8- Absorber feed pump, 9- Reflux pump, 10- Intercooler pump, 11- Wash water pump, 12- Lean/Rich Heat exchanger, 13- Lean amine cooler, 14- Condenser, 15- Reboiler, 16- Inter cooler
Source: Authors' Own Diagram

The process is described as follows:

Pre-treatment unit

The pre-treatment unit is designed to lower the temperature of the off-gas to 40°C, and also reduce the contaminant (SO_x, NO_x, acid mist, dust, etc.) concentrations to extremely low levels to prevent them from reacting irreversibly with the solvents and to avoid other negative impacts to the CO_2 absorption units.

The off-gas is routed to a booster fan (not shown) to provide enough pressure to overcome the pressure drop over the downstream equipment, and then flows to a scrubber to quench and sub-cool the flue gas. Wash water is fed to the scrubber where it comes into direct contact with the flue gas to lower the temperature of the gas stream and reduce contaminant and SO_x levels. Heated water from the outlet at the bottom of the scrubber is sent to the water cooler for cooling, and then sent back to the scrubber for reuse. A caustic supply system may be needed to feed caustic solution to the scrubber for decreasing residual sulphur dioxide.

Amine-based CO_2 absorption unit

The cooled gas is subsequently ducted to the CO_2 absorber. CO_2 absorption from the off-gas occurs by counter-current contact with the amine solvent in a multi-level, packed-bed column where amine is fed in at the top and off-gas enters at the bottom of the column. CO_2 is absorbed from the gas by the amine, and CO_2-rich amine exits from the bottom of the absorber, while low-in-CO_2 flue gas exits from the top of the absorber. CO_2 absorption is an exothermic reaction, therefore to prevent heat accumulation in the tower, and to improve the amine absorption capacity, hot amine is collected by a chimney tray above the bottom packing section, pumped to the intercooler, cooled by a water cooler and ultimately recycled back to the absorber to resume CO_2 absorption in the bottom packing section.

The treated flue gas exiting the top of the CO_2 absorption section passes through a water wash section. This section, included at the top of the CO_2 absorber, is designed to capture any volatile and entrained amine mist from the flue gas. The treated gas leaving the wash water section flows upwards and is released to the stack.

The CO_2-rich amine from the bottom of the absorber is heated in a lean-rich exchanger and sent to the CO_2 regenerator, where amine is regenerated by heat provided by a reboiler. Low-pressure (LP) steam condensates from the reboiler are routed to a plant condensate collection section. Overhead vapour from the regenerator is cooled by a condenser and the two-phase mixture is separated in a reflux accumulator. The reflux is returned to the regenerator while the CO_2 vapour produced is sent to the CO_2 compression system. The design basis assumptions for battery limits conditions, including off-gas composition, flowrate and pressure & temperature profiles, at the inlet to the pre-treatment unit and the inlet to the amine-based CO_2 absorption unit, are shown in Figure 6.

Figure 6. Assumed design conditions of a typical amine-based absorption process

Typical off-gas condition at Capture plant Inlet [1]

Composition (Vol %)	
H_2O	3.83
CO_2	25.00
N_2	68.66
O_2	2.51
Total Flow kg/h	230855
Total Flow Nm^3/h	158700
Temperature ℃	155.7
Pressure atm	1

Off-gas to be sent to pre-treatment unit prior to entering CO_2 absorption unit

for cooling down, removal of dust, SO_2, NOx

Off-gas condition inlet to Absorber [2]

Composition (Vol %)	
H_2O	6.83
CO_2	24.22
N_2	66.52
O_2	2.43
Total Flow kg/h	228773
Total Flow Nm^3/h	163814
Temperature ℃	40
Pressure kPag	>4

Modified from IEA (2011). Notes:

1. Typical off-gas condition, also listed in Table 4. A representative concentration value of 25% CO_2 is applied to this case study. Source: Iwasa et al., 2015.
2. The off-gas with high temperature is quenched and subcooled, then fed to the absorber under water-saturated conditions.

5.2.4. Aspen Plus simulation model description

Aspen Plus includes a wide range of unit process modules which simulate processes including mixing and separation, flash evaporation, heating/cooling and distillation, as well as components such as reactors, pressure changers, pumps, compressors, pipes drop, etc. The models were developed using an equilibrium-based mass transfer approach.

The main reactions occur between MEA and CO_2 in the simulation computation:

$$2H_2O \leftrightarrow H_3O^+ + OH^- \quad [1]$$

$$CO_2 + 2H_2O \leftrightarrow HCO_3^- + H_3O^+ \quad [2]$$

$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+ \quad [3]$$

$$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+ \quad [4]$$

$$MEACOO^- + H_2O \leftrightarrow MEA + HCO_3^- \quad [5]$$

The main purpose of the absorption simulation is to discharge a 0.024-mole-fraction of CO_2 in the purified gas at the top of the absorber. By adjusting the parameters of the solution, including the composition of the solution, the absorption temperature, and solvent circulation rate, the expected carbon capture performance can be achieved. The regeneration simulation aims at reaching the desired regenerative degree of the rich solvent by adjusting the regeneration pressure, temperature and the heat load of the reboiler. The temperature of the tower top condenser is adjusted to achieve a CO_2 mole fraction >0.9 in the regenerated gas

CO_2 emitted from the top of the tower in order to meet the requirements of further compression.

5.3. Simulation outcomes

5.3.1. Flow diagram

The process model flow diagram maps out the entire system, according to Figure 5 above. The diagram shows one or more inlet streams entering into the system's first unit operation (i.e. heat exchanger, compressor, reactor, distillation column, etc.) and continues through the process, illustrating all intermediate unit operations and the interconnecting streams.

5.3.2. Heat & Mass Balance (HMB)

The process model specifies all chemical components of the system from the necessary reactants and products, to steam and cooling water. All product streams in the flow diagram are summarised in a heat and mass balance (HMB); each stream and unit operation condition is labelled and identified.

All unit operations in the process model are kept under particular operating conditions (i.e. temperature, pressure, and size). Table 5 below provides the composition, flow rate, temperature, pressure, and physical properties of the main process streams. The modelling results show that:

- The total CO_2 (77,902.6kg/h in the off-gas inlet stream S1 and 7,776.1kg/h in the treated gas stream S2) indicates a CO_2 capture amount of 70,126.5kg/h (around 1700 tonnes per day), thus achieving the carbon capture efficiency and annual capture capacity expected targets of 90% and 0.5 million tonnes respectively;
- The CO_2 captured by the amine solvent in the absorber is stripped out from CO_2-rich amine in the stripper at a rate of 70,126.5kg/h, shown in stream S7;
- The CO_2 product gas recovered in the desorption section (stripper), stream S7, is cooled down to a low temperature that is suitable for downstream CO_2 compression with 97% purity (wt, wet).
- The solvent circulation rate, including the flow rate of lean amine and rich amine, shown in streams S3, S4, S5 and S6.

Table 5. Simulation results of the main streams

Main Process Stream / Composition	S1 Flue gas inlet	S2 Treated gas	S3 Lean amine to absorber	S4 Lean amine out from stripper	S5 Rich amine to stripper	S6 Rich amine out from absorber	S7 CO_2 product gas	S8 Reflux to stripper
Mass flow kg/h								
MEA	0.0	76.3	213,613.5	215,433.6	27,243.1	27,243.1	0.0	0.00
H_2O	8,996.2	39,365.9	790,735.0	758,223.7	757,489.7	757,489.7	2,164.8	39,934.04
CO_2	77,902.6	7776.1	0.0	18.4	13.4	13.4	70,126.5	49.69
H_3O^+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.09
OH^-	0.0	0.0	10.3	4.3	1.2	1.2	0.0	0.00
HCO_3^-	0.0	0.0	472.9	2,294.9	8,765.3	8,765.3	0.0	0.28
CO_3^{2-}	0.0	0.0	1,973.4	124.2	3,427.8	3,427.8	0.0	0.00
$MEAH^+$	0.0	0.0	83,177.7	81,216.6	183,568.3	183,568.3	0.0	0.00
$MEACOO^-$	0.0	0.0	131,719.1	131,774.9	280,873.3	280,873.3	0.0	0.00
N_2	136,187.4	136,182.6	0.0	0.0	4.8	4.8	4.8	0.00
O_2	5,686.9	5,686.5	0.0	0.0	0.4	0.4	0.4	0.00
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
H_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
H_2S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
S^{2-}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Total flow kg/h	228,773.0	189,087.4	1,221,701.8	1,189,090.8	1,261,387.1	1,261,387.4	72,296.5	39,984.1
Total flow liq m^3/h			1,158.2	1,193.2	1,189.3	1,138.0		40.5
Total flow gas Nm^3/h	163,814.0	165,908.0					38411.9	
Total flow gas actual volume m^3/h	173,780.2	205,906.1					30353.1	
Pressure kPag	8	2	300	76	205	2	48	200
Temperature ℃	40	73	40	119	112	56	46	46
Vapour fraction	1.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00
Density kg/cum	1.316	0.918	1,054.9	996.6	1,046.3	1,108.4	2.382	988.4

5.3.3. Design parameters

1) Tower sizing for the absorber and stripper

Aspen Plus's estimation of the required tower sizing was run using the packing sizing method (the tower size is based on the chemical packing height and diameter). The columns were sized using the generalised pressure drop correlation (Table 6).

Table 6. Tower sizing criteria

Criterion	Description
Fractional approach to maximum capacity	In interactive sizing mode, the column diameter is computed such that the closest approach to maximum capacity at any point in the section equals this value.
Design capacity factor	In interactive sizing mode, the column diameter is computed such that the maximum capacity factor equals this value. In sizing (diameter) calculations, this factor is applied using conditions from the stage with the highest flow.

The packing parameters for the absorber and stripper towers are given in Tables 7 & 8. The absorber and stripper diameters were estimated at 7.3m and 5.8m respectively.

Table 7. Absorber tower parameters

Design Parameters	Values	Unit
Column diameter	7.3	Meterm
Maximum fractional capacity	0.58	
Maximum capacity factor	0.06	m/s
Section pressure drop	2318	N/m^2
Average pressure drop/Height	77.25	N/m^3
Maximum stage liquid holdup	9.23	m^3
Maximum liquid superficial velocity	0.01	m/s
Surface area	249	m^2/m^3

Table 8. Stripper tower parameters

Design Parameters	Values	Unit
Column diameter	5.8	Meterm
Maximum fractional capacity	0.59	
Maximum capacity factor	0.04	m/s
Section pressure drop	852	N/m^2
Average pressure drop/Height	42.58	N/m^3
Maximum stage liquid holdup	1.90	m^3
Maximum liquid superficial velocity	0.01	m/s
Surface area	249	m^2/m^3

2) Heat exchanger sizing

According to the specified operating conditions, Aspen Plus generates the heat duties of the heating or cooling equipment, and also computes the amount of steam and cooling water required at specified pressure and temperature (Table 9).

Table 9. Simulated parameters of the heat exchangers

	Heat duty (GJ/h)	Required heating &cooling medium	
Lean amine cooler	101	3026 m^3/h	Cooling water
Lean/rich heat exchanger	223		N/A
Condenser	103	3100 m^3/h	Cooling water
Reboiler	290	137 T/h	Low Pressure steam

3) Pumps, Booster fans and compressors sizing

The capacity of the pumps, booster fans and compressors and pressure changes will be decided by the process line-up configuration. ASPEN Plus also provides the required electric power for motors to drive the rotating equipment based on input information, shown in Tables 10 to 12.

5.4. Concept design for CO_2 capture and compression

This section outlines a CO_2 capture and compression concept design, developed from the ASPEN Plus simulation.

5.4.1. Equipment specification

The required equipment can be classified into four kinds:

- Tower, vessel & tanks;
- Heat exchangers;
- Rotating equipment; and
- Other specialty equipment (including filters and others).

A preliminary equipment list, presented in Tables 10 & 11, summarises the key specification information based on engineering design parameters extracted from the ASPEN Plus model.

Table 10. CO_2 capture preliminary equipment list

No.	Service	Outer dimensions (mm)			No.	Remarks
Tower, vessel & tanks						
No.	Service	Outer dimensions (mm)			No.	Remarks
1	Pre-scrubber	D 7,300			1	
2	Absorber	D 7,300			1	
3	Stripper	D 5,800			1	
4	Lean amine tank	D 7,000			1	
5	Fresh amine tank	D 7,000			1	
6	Reflux accumulator	D 2,000 x H 5,000			1	Horizontal
7	Steam condensate pot	D 2500			1	
8	Amine tank	D 2,500 x H 4,000			1	Horizontal
Heat exchangers						
No.	Service	Heat Duty (GJ/h)			No.	Remarks
1	Wash water cooler	16			1	
2	Lean amine cooler	51			2	
3	Lean/rich heat exchanger	112			2	
4	Condenser	52			2	
5	Reboiler	150			2	
6	Other coolers	100			2	
Rotating equipment						
No.	Service	Flow rate & DP*		Motor kW	No.	Remarks
		m^3/h	kPa			
	ID fan					
1	Booster fan	83,500	7	300	3	one spare
	Pumps					
1	Water washing pump	800	200	75	2	one spare
2	Virgin amine pump	12	200	1.5	1	
3	Absorber feed pump	580	400	110	3	one spare
4	Rich amine pump	570	470	132	3	one spare
5	Intercooler pump	570	180	55	3	one spare
6	Wash water pump	700	200	45	2	one spare
7	Reflux pump	41	350	7.5	2	one spare
8	Lean amine pump	600	170	55	3	one spare
9	Steam reclaimer pump	140	200	18.5	2	one spare
10	Amine reclaimer pump	57	500	15	2	one spare
11	Amine drain pump	12	200	1.5	1	

** DP: Differential Pressure between Suction and Discharge of the Pump or Booster Fan/Compressor.*

Table 11. CO_2 compression preliminary equipment list

No.	Service	Outer dimensions (mm)			No.	Remarks
Tower, vessel & tanks						
No.	Service	Outer dimensions (mm)			No.	Remarks
1	Tanks	D 7,300			1	
Heat exchangers						
No.	Service	Heat duty (GJ/h)			No.	Remarks
1	Gas coolers	17			4	
Rotating equipment						
No.	Service	Flow rate & DP		Motor kW	No.	Remarks
		m^3/h	MPa			
	Compressor					
1	CO_2 compressor	15,000	7.8	3,800	2	
	Pumps					

5.4.2. Utilities consumption

This section provides detailed information on the utilities consumption of the CO_2 capture and compression concept design, developed from the ASPEN Plus simulation (Table 12).

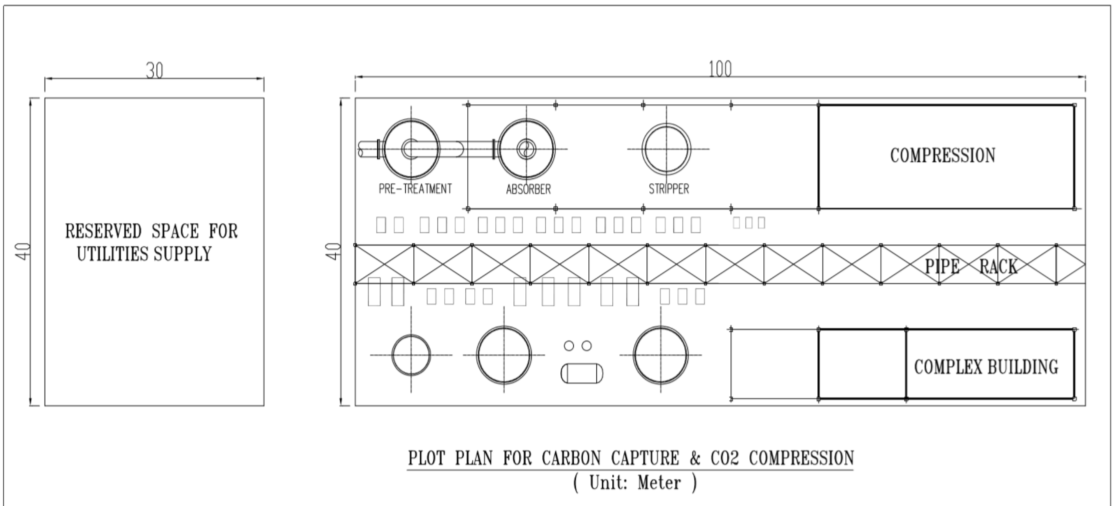
Table 12. Utilities consumption

Item	Users	Amount		Remarks
Steam (350kPag, Saturated)	Amine unit	137 t/h		
	Other users	10 t/h		
Cooling water (The assumed supply and return temperatures are 32 ℃ and 40℃ resp. 32 / 40 °C)	Pre-treatment	500 t/h		
	Amine unit	10,000 t/h		
	CO_2compression	2,000 t/h		
	Total	12,500 t/h		
Process water	Pre-treatment	4 t/h		
Demineralised water	Amine unit	4 t/h		
Electric power		Running	Installed	
	Pre-treatment	700 kW	1,050 kW	
	Amine unit	800 kW	1,250 kW	
	CO_2compression	7,700 kW	7,700 kW	
	Total	**9,200 kW**	**12,030 kW**	
Instrumentation air		40 Nm^3/h		~600 kPag

5.4.3. Equipment layout

A preliminary equipment layout is shown in Figure 7, which is developed from the major equipment listed in Tables 10 and 11.

Figure 7. Preliminary layout of CO_2 carbon capture & compression unit and utilities supply



From this we can conclude that a rectangular area, approximately **4,000 m²** (100m x 40m), needs to be reserved to accommodate the equipment of the pre-treatment unit, amine unit, the CO_2 compression unit for CO_2 transportation and storage, as well as a building complex including the control centre, analytical laboratory and the electrical switching rooms, etc. Additional space may be required for utilities supply facilities, estimated at around 1,200 m^2 (30m x 40m).

5.4.4. Integrated appraisal of energy recovery options

5.4.4.1. Potential of waste heat recovery in steel-making plants

By-product gases are important secondary energy sources for the iron/steel industry (Table 13), and can amount up to 30-40% of the total energy consumption of the industry (He & Wang, 2017). By-product gases mainly include BFG, LDG, and COG, all of which are recovered and used in Japan and Germany. However, in China, by-product gases are not 100% reused and are still partly flared.

Table 13. By-product gases in the iron and steel industry

	Chemical Composition	Heat Value	Production/tonne product
BFG	H_2 4% CO 25% CO_2 20% Remainder is N_2	3,000-3,800 kJ/m^3	1,400-1,800 m^3/tonne of iron
LDG	CO_2 15-20% O_2 ≦2% CO 60-70% N_2 10-20% H_2 ≦1.5%	7,500-8,000 kJ/m^3	80-100 m^3/tonne of iron
COG	H_2 45-64% CH_4 20-30% CO 5-10% CO_2 2-5% O_2 0.1-4% CnHm 0.1-3%	16,000-19,300 kJ/m^3	400-450 m^3/tonne of iron
Source: IEA, 2007			

Waste heat is another important secondary energy resource for the iron/steel industry. Recovering waste heat can be accomplished through various technologies to provide valuable energy sources and reduce the overall energy consumption. In China, 8.44 GJ of residual heat is generated per tonne of steel produced, of which only 28% is recovered. As such, waste heat recovery and utilisation in the iron/steel industry has significant potential.

Table 14. Recovery and utilisation of different qualities of waste heat in the iron/steel industry in China

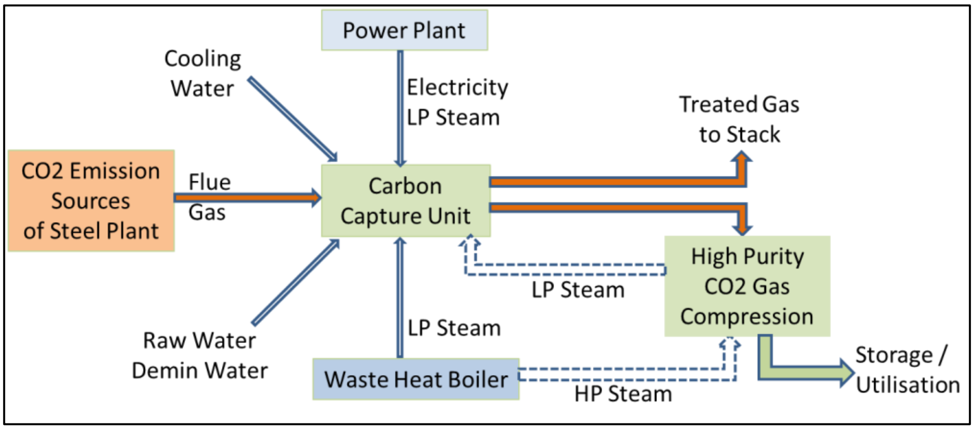
Quality of waste heat	Quantity and rate of recovery		Description
Low grade below 150 ℃	Quantity of total (GJ/t-s)	2.89	Waste steam and hot water, all kinds of low-temperature flue gas and low-temperature materials etc.
	Quantity of recovery (GJ/t-s)	0.22	
	Rate of recovery (%)	7.61	
Medium grade 150–500 ℃	Quantity of total (GJ/t-s)	2.19	Blast furnace gas and sintering flue gas, exhaust gas recovery of waste heat from the primary after flue gas, etc.
	Quantity of recovery (GJ/t-s)	0.66	
	Rate of recovery (%)	30.2	
High grade higher than 500 ℃	Quantity of total (GJ/t-s)	3.36	High-temperature flue gas: coke oven gas, converter gas, electric furnace gas and heating furnace flue gas etc.; High-temperature liquid: iron slag, steel slag and high-temperature water etc.; High-temperature solid: sintering materials, high-temperature coke, high-temperature steel etc.
	Quantity of recovery (GJ/t-s)	1.49	
	Rate of recovery (%)	44.4	
Source: He & Wang, 2017			

5.4.4.2. The comprehensive utilisation of waste heat in CCS

In CCS energy is consumed by two main stages, the low-pressure steam of 137 t/h at 0.35 MPa fed to the reboiler for amine regeneration and the electricity consumption of approximately 7,100 kW for the hypothetical CO_2 compressors, based on the study's results. Steam turbines are well-suited as prime movers for driving boiler feed-water pumps, forced or induced-draft (ID) fans, blowers, compressors, and other rotating equipment. This service generally calls for a backpressure noncondensing steam turbine. The low-pressure steam turbine exhaust is available for feed-water heating, preheating of deaerator makeup water, and/or process requirements.

In this study, we proposed using the steam turbines to drive a multi-stage CO_2 compressor. As indicated in Fig. 8, the steam at high pressure (HP) is fed to the steam turbine for driving the CO_2 compressor, exhaust steam at low pressure (LP) from the back-pressure turbine then flows back to the reboilers of the carbon capture unit as the heat source.

Figure 8. The comprehensive utilisation of waste heat in CCS



Source: Authors' Own Diagram

Based on general engineering design principles, the steam turbine is the preferred energy-saving option for large-scale compressors and pumps – typically of 1,000kW or above in driving power. Compared with the electric motor, the use of the turbine eliminates the impact of a huge starting current on the power grid. An approximate calculation of the compressor's characteristics is presented in Table 15; four-stage compression is employed in the CO_2 liquefying process. Correspondingly, the estimation shows that the turbines, with the consumption of medium grade steam of 102t/h at 2.35MPa in total, can generate the shaft power of 7.1MW in total required by the multi-stage CO_2 compressor.

Table 15. Calculations of the compressor and turbine characteristics

Item	Unit	Stage 1	Stage2	Stage3	Stage4
Multi-stage compressor					
CO_2 gas	Gas flow kmol/h	1,714	1,616	1,606	1,600
Inlet / outlet	Pressure MPa	0.149 / 0.401	0.401 / 1.079	1.079 /2.901	2.901 / 7.800
	Temperature ºC	40 / 140	40 / 132	40 / 134	40 / 136
Power required	MW	2.0	1.8	1.7	1.6
Cooling duty	GJ /h	12	7.5	7.4	12
Turbine steam consumption					
Power capacity	MW	7.1			
Steam inlet /	Steam t/h	102			
Steam Exhaust	Pressure MPa	2.35 / 0.49			
	Superheated.	390 / 252			
	Entropy kJ/kg	3219.4 / 2965.8			
	Enthalpy kJ/kg.K	7.013 / 7.29			
Steam Consump.	kg / kWh	14.2			

For comparison, specifications of a commercial steam turbine are also provided in Table 16.

Table 16. Steam turbine specification

Item	Specification 1	Specification 2	Unit
Turbine Model	B1.6~B3	B3~B8	
Power capacity	1.6~3	3 ~ 8	MW
Steam inlet	2.3~4.9	2.3~4.9	MPa
	300~470	300~470	°C
Steam Exhaust	0.2~2.5	0.2~2.5	MPa
Steam Consumption	8 ~ 14		kg/kWh

The low-pressure steam at 0.49MPa of 102t/h exhausted from the turbines could be available and fed to the reboilers of the amine-based capture unit. This is less than the total steam requirements; the remainder of the steam demand can be met by other low-grade steam sources. As illustrated in Table 13, 70% of the medium grade (150-500 °C) waste heat is still not recovered in most steelmaking plants in China. Thus, there is a large potential in waste heat recovery to cover the energy needs of CO_2 capture and compression. This would be advantageous for CCS applications in China's steel production.

The post-combustion capture technology is considered to be technically realisable in the near future. As one of the technical options, it is possible to render amine-based technologies affordable in most steel plants by utilising waste heat from the steel-making process itself. Consequently, the additional CO_2 generated by steam and electricity production in iron/steel sector CCS could be avoided.

5.5. Requirements for capture readiness in steel plant design

The capture readiness requirements discussed in this section are the 'essential' requirements which aim to ease the retrofit of steel plants with amine-based CO_2 capture. The capture readiness features discussed require a small additional investment and also have a low impact on plant performance whilst operating without capture.

5.5.1.Space requirements

The prime requirement for the construction of capture-ready steel plants that will utilise amine capture technology for CO_2 capture is the allocation of sufficient additional space at appropriate locations on the site to accommodate the additional CO_2 capture equipment and the required connections to it. A further requirement is to allow extension of BoP equipment to cater for additional requirements (cooling water, auxiliary power distribution etc.) of the capture equipment.

The space requirements are also discussed under individual system and equipment requirements. The space in this case study will be required for the following:

- CO_2 capture equipment: according to the description in Section 5.4.3, the lot space reserved for the capture unit is estimated at approximately 4,000m^2 (100m x 40m), which includes the pre-treatment unit, amine unit, operation control building, as well as CO_2 compression unit for CO_2 transportation and storage;
- The utilities supply facilities are estimated at approximately 1,200m^2 (30m x 40m);
- Hot blast stove additions and modifications: space for routing a flue gas duct between the induced draft (ID) fan and the amine scrubber should be reserved, with a duct diameter of approx. 1.5m;
- Space reserved for a fan to overcome the pressure drop in a post-combustion capture absorber unit;
- Waste Heat Boiler (WHB) additions and modifications: there is a need to consider the space in the WHB for routing a large low-pressure steam pipe (approx. 1m x 1m) to the amine scrubber unit;
- Extension and addition of BoP systems to cater for the additional requirements of the capture equipment;
- Additional vehicle movements (amine transport etc.); and
- Space allocation based on hazard and operability (HAZOP) management studies, considering storage and handling of amines and handling of CO_2

In addition to the required space for the installation's capture plant, space is required for construction activities. When space is available to store materials, tools and installation parts on site, construction is generally cheaper in comparison to an off-site construction area.

5.5.2. Flue gas desulphurisation (FGD) unit

In recent years, steel plant emission standards in China for particulate matter, sulphur dioxide and nitrogen oxides have been tightened from 40, 180 and 300mg/m^3 to stricter 20, 50 and 100mg/m^3 limits respectively. Moreover, to minimise solvent degradation due to reaction with sulphur dioxide, a flue gas desulphurisation (FGD) unit has to be designed to reduce SO_X

in the flue gas to very low levels, i.e. 10 to 30 mg/Nm^3 – even lower than the limits imposed by current environmental regulations.

For steel plants with $DeSO_X$ plant (FGD) designed to cater for future requirements, no additional requirements are foreseen. For steel plants with FGD designed to meet current SO_X emission limits, additional capture-ready requirements may arise, depending on the design of the FGD plant. These are discussed below:

a) If the original FGD design and construction allows for mechanical or chemical enhancements in the future to meet amine scrubber SO_X level limits, no additional capture-ready requirement is foreseen in the flue gas system.

b) If the original FGD design and construction does not allow for mechanical or chemical enhancements, then an FGD polisher to meet the amine scrubber SO_X level limits will be required. The ID fan may not be able to accommodate the additional pressure drop introduced by the FGD polisher, and a booster fan may also be required. Hence space to install the booster fan and associated ductwork and provisions for tie-ins would have to be considered.

For steel plants without any $DeSO_X$ measures, space will be required at an appropriate location to install a $DeSO_X$ plant, along with connecting ductwork and provisions in the ID fan discharge duct for interconnection, with consideration of new ID fans/booster fan(s), as appropriate. The space required depends on different off-gas sources and SO_x concentrations.

5.5.3. Water-steam condensate cycle

This section discusses capture-ready requirements in the water-steam condensate system. During the plant's operation with CO_2 capture, the steam from the WHB is required for the amine scrubbing plant reboiler (based on current amine based solvents). The condensate system arrangement in a steel plant often consists of either 2 x 100% condensate pumps or 3 x 50% condensate pumps. This arrangement will lead to pump operation at non-optimum conditions after the capture retrofit. To enable condensate pumps to operate at optimum conditions before and after capture retrofit, pre-investment in 3 x 60% condensate pumps could be considered.

5.5.4. Cooling water system

As noted earlier, 12,500t/h of cooling water (assumed a supply and return temperature of 32/40^{o}C respectively) will be required for the cooling equipment. The amount of cooling water may vary with local weather conditions, as well as with the water cooling system type. The additional cooling tower and additional cooling water piping requirements depend on the type of cooling water system envisaged (closed-loop cooling or once-through cooling with seawater/freshwater). The following pre-investments can be made to ease the CO_2 capture retrofit:

- For steel plants with once-through freshwater *and* seawater cooling systems: if local regulations or permits that have already been obtained do not allow for an increase in discharge water temperature beyond the limit agreed upon before the capture retrofit, pre- investments can be made to accommodate the additional estimated flow in the cooling water supply and discharge network (e.g. larger cooling water pumps and larger cooling water pipes).
- For steel plants with closed-loop cooling system: No capture-ready pre-investment is foreseen to be of value, as the addition of a separate auxiliary cooling water network during capture retrofit to cater for the capture equipment auxiliary cooling water requirement is considered as a more viable option.

5.5.5.Compressed air system

As the addition of capture equipment calls for additional compressed air requirements, pre-investment could be considered for the sizing and selection of the capture-ready plant's compressed air system, including the estimated future compressed air requirements. This may call for a marginal increase in the capacity of individual compressors, and a corresponding increase in capacity of the driers and receivers.

5.5.6. Raw water pre-treatment plant

To cater for the future additional cooling water requirements of the capture equipment, pre-investment can be made in the capture-ready plant's raw water pre-treatment plant area by:

- Including estimated future additional raw water treatment plant capacity in sizing and selection of the raw water pre-treatment plant;
- Increasing the storage capacity of the raw water tank to accommodate future increases in storage requirements; and

- The make-up of the cooling water system may need to be taken into account for future increase in demand.

A raw water flowrate of 4m^3/h is estimated to meet the needs of water make-up in the off-gas pre-treatment system, but it does not include the raw water make-up of the cooling water system, because water evaporating from the open circulating water cooling system requires a large amount of make-up - depending on the local meteorological conditions which are difficult to predict. If a closed loop cooling water system is applied, there is no need for any make-up water.

5.5.7. Demineralisation/desalination plant

Capture-ready design is foreseen to be required in this system, as the demineralised water requirement is expected to increase by 4m^3/h after the CO_2 capture retrofit.

5.5.8. Waste water treatment plant

Modifications and additions to the wastewater treatment plant are expected for capture retrofit in order to enable the plant to treat and safely dispose of the additional effluent from the capture equipment. As the effluent may need a different treatment regime, a separate wastewater treatment system may have to be installed and interconnected with the plant's wastewater discharge network. Hence pre-investment will only be considered for increasing the shared discharge network pipe size to ensure it has sufficient capacity, as the separate treatment system can be installed in the future along with the capture retrofit.

5.5.9. Electrical

The introduction of amine scrubbing along with flue gas cooler, FGD polisher (if appropriate) and CO_2 compression plant will lead to a number of additional electrical loads (pumps, fans, compressors) and will call for major additions in the plant auxiliary power distribution system. Pre-investments in the following areas are expected to ease the CO_2 capture retrofit:

- Design and construction of cable vaults and cable trenches including pull pits and overhead cable trays to handle future cabling work; and
- Switch gear and Motor Control Centre energising cable selection considering estimated additional auxiliary power consumption after capture retrofit (excluding power consumption by the amine scrubber unit and CO_2 compression plant, as auxiliary loads for these items are considered to be met with a dedicated and separate power supply system).

As discussed in Section 5.4.2, additional electrical loads of 9,200kW in total are estimated to be required to operate the carbon capture and compression plant. If the motor power exceeds 250kW, pumps equipped with high voltage motors would be selected. The power distribution system should consider two kinds: low and high voltage motors.

The application of waste heat recovery, as discussed in Section 5.4.4, could reduce the electric power consumption by approximately 7,100kW by employing CO_2 compressors driven by back-pressure steam turbines. Pre-investments in this option which could be considered include reserving flexibility in the siting of the connection port to the waste heat boiler to ease the CO_2 capture retrofit.

5.5.10. Chemical dosing systems and steam water analysis system

As no difference in the requirements of the condensate and feed water chemistry exists for the CO_2 capture retrofit, no capture-ready pre-investments are foreseen in the chemical dosing plant. With process integration after the addition of capture equipment, monitoring of condensate water quality at the outlet of heat exchangers is expected, as part of the heating of the condensate will be undertaken in the amine scrubber plant. Pre-investment can be considered for provision in the steam and water analysis system of a sampling network and panels for easy addition of these sampling points.

5.5.11. Plant pipe racks

Consideration of pre-investment in the areas listed below will ease the addition of new pipe work required for the retrofit (refer to Figure 7 for an illustration of the pipe work required for capture retrofitting):

- Design of pipe rack structures (near the respective systems) to handle additional pipe loads;
- Provisions in pipe racks near the respective systems to accommodate additional piping; and
- Provisions in the steam turbine building to route a larger LP steam pipe.

5.5.12. Control and instrumentation

The incorporation of the amine scrubber and CO_2 compression plant and process integration of the water-steam-condensate cycle with the capture equipment calls for the introduction of additional control components and control loops to ensure reliable and safe operation of the steel plant. Additional I/Os (Input/Output) resulting from this need to be handled by the plant control system. This will call for additional control modules and panels, monitoring systems and additional cabling. Based on the estimated additional I/Os, pre-investment can be made in:

- Designing the plant control system including the estimated additional I/Os required in the future; and
- Sizing the plant network (data highway) to handle (estimated) future additional signals.

It should be noted that the DCS and historical data systems are often licensed for a specified number of I/O channels and may not allow easy expansion. The above pre-investments could eliminate this risk and ease the integration of the capture equipment control system with the main plant control systems.

5.5.13. Safety

No capture-ready pre-investment requirement is foreseen.

5.5.14. Fire-fighting and fire protection system

No capture-ready pre-investment requirement is foreseen.

5.5.15. Plant Infrastructure

No capture-ready pre-investment requirement is foreseen.

5.5.16. Steam supply sources options

The required steam can be supplied by two options, the waste heat recovery boiler or the back-pressure steam turbines for driving the multi-stage CO_2 compressor. Waste heat recovery would be a good option to supply low-pressure steam to the amine regeneration system. As such, installation space for waste heat boilers should be reserved and pre-investment needs to be made in tie-ins in existing facilities for future retrofitting.

5.5.17. Laboratory analysis

To support the CCS plant's activities, real-time laboratory solvent analysis is essential. The analytical apparatus for the amine process may be very different from that required for steelmaking. However, it is still possible to share lab-equipment and laboratory rooms with the steel plant. Therefore, pre-investment is only expected for extra lab room reservation in the building design.

6. Conclusions

This study has reviewed the historical development of the concept of 'capture readiness', noting that it has evolved over time, from a narrow appreciation of the basic physical requirements for future retrofit of capture technologies, to a broader understanding of the need to anticipate and support a variety of future CCS-related needs across the full chain of capture, transportation and storage.

The study focuses on key elements required to make steel plants CCS-ready in China. These are:

- The **geographic location** of the plants, which plays a major role in determining its suitability for CO_2 capture as this, after the addition of the capture plant, enables captured CO_2 to be transported for geological storage and/or EOR;
- The **technical feasibility** of retrofitting the chosen carbon capture technology;
- The availability of **sufficient space** on or near the site to accommodate carbon capture equipment in the future; and
- **Pre-investment** considerations to ease the capture retrofit and reduce plant down-time in the future retrofit.

A preliminary GIS analysis indicated that **51 out of 142 steel plants with production capacity higher than 1 million tonnes per year in China are within a 200km radius of a potential EOR CO_2 storage site**, which opens up scope for further research on CO_2 storage opportunities for steel plants. A review of the essential requirements of various carbon capture technology options for nine types of flue gas streams was undertaken to provide the basis for further selection. An update to this review would be beneficial to track the progress of emerging capture technologies. Equally important is ensuring that plants can accommodate any new technologies that may not be as competitive currently, so that they may be rapidly deployed when they become available.

A case study for a hypothetical CCSR project for capturing 0.5 million tonnes of CO_2 has been performed to develop a conceptual design for meeting the requirements of a carbon capture-ready steel plant. The study assumed the use of a generic amine solvent (30 wt% MEA) – the most mature CO_2 capture technology to date. The study assumes the capture of 70 tonnes of CO_2 per hour from off-gas with a representative concentration value of 25% CO_2 at expected capture efficiency of 90%. ASPEN Plus process simulation software was used to develop a CCSR concept design. The study results are summarised below:

- A high-level capture plant design was developed in this case study, including an indicative amine-based absorption process flow diagram showing major streams and the main equipment, Heat and Mass Balance, preliminary equipment size, utilities consumption and other key engineering performance parameters;
- The space required for the capture unit at a 0.5 million tonnes level is estimated at around 4,000m^2, which includes the pre-treatment unit, amine unit, operation control building, as well as a CO_2 compression unit for CO_2 transportation and storage. The additional space required for utilities supply facilities is estimated at around 1,200m^2;
- The comprehensive utilisation of waste heat would be advantageous for CCS applications in China's steel production. It is recommended that back-pressure steam turbines are used to drive multi-stage CO_2 compression instead of electric-motor-driven compressors with huge power loads of 7,100kW. The steam recovered from waste heat boilers is fed to the steam turbine, exhaust steam at low pressure from the back-pressure turbine then flows back to the reboilers of the carbon capture unit to provide approximately 75% of the amine regeneration heat requirements (without the MVR process heat recovery option); and
- Potential pre-investment options are identified to ease future capture retrofit.

Generally, this study provides an analytical approach and engineering principles to support CCR plant design. As specific design implications depend on the type of process for carbon capture that will be applied at the plant, more rigorous conceptual CCS-readiness design of steel plants at the FEED (Front-End Engineering Design) stage may be adopted to develop a specific steel plant CCR project.

References

Arasto, A., Tsupari, E., Kärki, J., Pisilä, E., & Sorsamäki, L. (2013). Post-combustion capture of CO_2 at an integrated steel mill–Part I: Technical concept analysis. *International Journal of Greenhouse Gas Control*, *16*, pp. 271-277.

Asian Development Bank (ADB) (2014). *Carbon Capture and Storage (CCS) – Ready Policy to Facilitate Future CCS Deployment in the People's Republic of China*. Available at: https://www.adb.org/sites/default/files/publication/180082/ccs-ready-policy-prc.pdf [Accessed March 20, 2018]

Bohm, M.C., Herzog, H.J., Parsons, J.E., Sekar, R.C., (2007). Capture-ready coal plants – Options, technologies and economics, *International Journal of Greenhouse Gas Technologies*, *1*, pp. 113-120.

China Steel Yearbook (2017). *The Editorial Board of China Steel Yearbook.*

Chinese National Development and Reform Commission (2013). *The Guidelines to Ironmaking and Steelmaking Enterprises for Accounting Methods and Reporting of Greenhouse Gas Emissions in China* (trial).

Dahowski, RT., Li, X., CL, Davision., Wei, N., Dooley, JJ. (2009) *Regional Opportunities for Carbon Dioxide Capture and Storage in China. U.S. Department of Energy.* Available at: https://energyenvironment.pnnl.gov/pdf/roccs_china_pnnl_19091.pdf [Accessed November 9, 2018]

DECC (UK Department of Energy and Climate Change) (2009). *Carbon Capture Readiness*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/43609/Carbon_capture_readiness_-_guidance.pdf [Accessed May 10, 2018]

GCCSI (Global CCS Institute) (2010). *Defining CCS: an approach to an international definition*. https://www.globalccsinstitute.com/publications/defining-ccs-ready-approach-international-definition [Accessed April 10, 2018]

GDCCUSC (UK-China Guangdong CCUS Centre) (2014). *China Resources Power (Haifeng) Units 3 and 4: 2 x 1000 MW Ultra-Supercritical Coal-fired Plants Carbon Capture Readiness (CCR) Report. No. 2014/D03*. Available at: http://www.gdccus.org/col.jsp?id=116 [Accessed March 10, 2018]

Gibbins. J. (2004). *Making pulverized coal plant "capture ready": methods and benefits*. 7th International CO_2 Capture Network Meeting, Vancouver, Canada. March 2004.

Gibbins, J., Lucquiaud, M., Li, J., Lord, M., Liang, X., Reiner, D. and Sun, S. (2006). *Capture ready fossil fuel plants: definitions, technology options and economics*. Proc. 7th European Gasification, 25-27 Apr 2006, Barcelona, Spain.

He, K. & Wang, L. (2017). A review of energy use and energy-efficient technologies for the iron and steel industry. *Renewable and Sustainable Energy Reviews, 70,* pp. 1022-1039.

IEA (2007). *Tracking industrial energy efficiency and CO_2 emissions.* Paris, France. Available at: https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf [Accessed September 28, 2018]

IEA (2011). *Technology Roadmap – Carbon Capture and Storage in Industrial Applications*. Available at: http://hub.globalccsinstitute.com/sites/default/files/publications/22002/ccs-industry-roadmap-web.pdf [Accessed July 20, 2018]

IEA (2013). *CCS in Industrial Applications. A workshop of the CCUS Action Group in Preparation for the 4th Clean Energy Ministerial.* London, UK. Available at: http://www.iea.org/media/workshops/2013/ccs/industry/cem_workshopreport.pdf [Accessed July 19, 2018]

IEAGHG (International Energy Agency Greenhouse Gas Programme) (2007). *CO_2 Capture Ready Plants.* https://www.iea.org/publications/freepublications/publication/CO2_Capture_Ready_Plants.pdf [Accessed April 22 2018]

IEAGHG (2018). *Cost of CO_2 Capture in the Industrial Sector: Cement and Iron and Steel Industries.* 2018-TR03, September. http://documents.ieaghg.org/index.php/s/YKm6B7zikUpPgGA?path=%2F2018%2F Technical%20Reviews [Accessed October 25, 2018]

IPCC (2007). *Fourth Assessment Report: Climate Change 2007 (AR4): Work Group III: Mitigation of Climate Change.* Available at: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch7s7-4-1.html [Accessed September 30, 2018]

Iwasa, K., Hodotsuka, M., Zhao, X., & Suzuki, K. (2016). Application of Carbon Capture to CO_2 Emissions of Steel Plants. *Clean Coal Technology and Sustainable Development*, pp. 353-358. Springer, Singapore.

Li, J., Liang, X., Gibbins, J., Reiner, D., (2012). *Chinese Advanced Power Plant Carbon Capture Options (CAPPCCO)*. Published by UK Department of Energy and Climate Change. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/66052/7476-cappcco-final-summary-report-march-2012-.pdf [Accessed November 2, 2018]

Liang, X., Reiner, D., Gibbins, J., Li, J. (2009). Assessing the Value of CO_2 Capture Ready in New-build Pulverised Coal-fired Power Plants in China. *International Journal of Greenhouse Gas Control*, *3*, pp. 787-792.

Lu, D., Wang, L., Ren, L., Jia, Z., LIN, Q., LIANG, X., Muslemani, H., Jiang, M., Ascui, F., (2018). *Lower Carbon Technology Approaches for Steel Manufacturing in China (Draft Report).* Working Paper 4.7 for the BHP Industrial CCS Project 'Unlocking the Potential of CCUS for Steel Production in China'. North China Electric Power University, UK-China (Guangdong) CCUS Centre and the University of Edinburgh, Edinburgh.

NDRC (National Development and Reform Commission) (2013). *Greenhouse Gas Auditing Methodology and Reporting Guideline for Iron and Steel Production Companies in China* (Trial). http://www.ndrc.gov.cn/zcfb/zcfbtz/201311/t20131101_565313.html [Accessed September 22, 2018]

NRDC (Natural Resources Defense Council) (2004). *Clean Power, in NRDC's China Clean Energy Project*. Available at: http://www.nrdc.org/air/energy/china/cleanpower.asp [Accessed July 12, 2018]

Progressive Energy Limited (2015). *TVU CCS Pre-FEED: WP1 – SSI Process Study: Optioneering & Screening Report*. Document Nu: 16202312/9001-X01-0001.

ULCOS (2013). *CCS for Iron and Steel Production*. Available at: https://www.globalccsinstitute.com/insights/authors/dennisvanpuyvelde/2013/08/23/ccs-iron-and-steel-production [Accessed September 30, 2018]

Wilson, M. and Gibbins, J. (2005). *Getting Ready for Carbon Capture and Storage: Canada's Progress*. Energy INET Report.

World Steel Association (2018). *Steel Statistical Yearbook*. Available at: https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook-.html [Accessed November 4, 2018]