CARBON CAPTURE, UTILISATION AND STORAGE IN CHINA'S IRON/STEEL SECTOR

ASSESSING THE ECONOMICS OF CO_2 CAPTURE IN CHINA'S IRON/STEEL SECTOR: A CASE STUDY

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UNIVERSITY OF EDINBURGH
Business School

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Assessing the Economics of CO_2 Capture in China's Iron/Steel Sector: A Case Study

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LIANG Xi[1,2], LIN Qianguo[1,3], LEI Ming[4], LIU Qiang[5], LI Jia[2], WU Alisa[3], LIU Muxin[2], ASCUI Francisco[1], MUSLEMANI Hasan[1], JIANG Mengfei[1]

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[1] University of Edinburgh Business School, Edinburgh, UK
[2] UK-China (Guangdong) CCUS Centre, Guangzhou, China
[3] North China Electric Power Design Institute, Beijing, China
[4] Peking University Guanghua School of Management, Beijing, China
[5] National Center for Climate Change Strategy and International Cooperation, Beijing, China

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Acronyms

ASPEN	Advanced System for Process Engineering
ASU	Air Separation Unit
BF	Blast Furnace
BFC	Blast Furnace Capture
BOF	Basic Oxygen Furnace
BSZ	Baowu Steel Zhanjiang
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CFP	Lifecycle Incremental Cost for Steel Product
CNE	China Emissions Exchange
COA	Cost of CO_2 Avoidance
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
FOAK	First–of–a–kind
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
MCC	Metallurgical Group Corporation
MOST	Ministry of Science and Technology
NDRC	National Development and Reform Commission
OHF	Open Hearth Furnace
PSA	Pressure Swing Adsorption
TSA	Temperature Swing Adsorption
UNFCCC	United Nations Framework Convention on Climate Change

1. Executive Summary

This study provides a techno–economic analysis of a hypothetical first–of–a–kind (FOAK) CO_2 capture, transport and storage project at commercial scale in a modern Chinese steel production plant. It assumes the use of amine technology to capture the relatively–high concentration CO_2 emissions from the iron–making process. The technical configuration of the project was modelled using the Advanced System for Process Engineering (ASPEN), combined with a financial model. The analysis shows that:

- The cost of CO_2 avoidance for the modelled 0.5 million tonne/year capacity CO_2 capture project with offshore pipeline transport and storage in saline formation is estimated at **CNY 442.54/tCO_2 (USD 63.22/tCO_2).**
- Assuming that the project runs at 90% capacity (0.45 MtCO_2/year), over 25 years, the project would capture 11.25 MtCO_2. However, this is offset by emissions from increased energy consumption for running the CCS process, thus the project would only reduce aggregate emissions by 0.40 MtCO_2/year, or a total of 9.93 MtCO_2 over its lifetime.
- When the cost of the project is apportioned only to the amount of steel associated with 9.93 MtCO_2 (2.6% of total steel production), the additional cost is **CNY 730.19 (USD 104.31) per tonne of steel produced.** However, given only a minority of CO_2 is assumed to be captured, if the cost is spread over the entire production of the plant, the cost per tonne of total steel production is only **CNY 18.74 (USD 2.68)/tonne.**
- The cost of CO_2 avoidance is sensitive to a number of assumptions, including the discount rate and the cost of CO_2 transportation and storage. The discount rate of the capture project is assumed to be 12%, taking into account the cost of capital of Baowu Steel and the specific risk of the CO_2 capture project. If the project is

considered as a moderate risk investment and applies an 8% discount rate, the cost of CO_2 avoidance (i.e. the abatement cost) will be reduced from **CNY 442.54/tCO_2 (USD 63.22/t)** to **CNY 407.56/tCO_2 (USD 58.22/t)**. The assumed transport and storage cost could be much lower if the project could share the infrastructure with other large stationary emission sources but the study has not yet explored.

- Although the cost is moderate and there is significant potential to minimise it through learning and upscaling in the future, the fluctuating business environment in the steel sector is unlikely to support the additional cost for such a project, without some form of external support or internal benefit. We suggest that the next step of applied research should investigate a combination of government and business innovation options that could provide the necessary financial support for FOAK demonstration projects.

2. Introduction

The Paris Agreement reached in December 2015 set out a global action plan to avoid dangerous climate change by limiting global warming in the long-term to well below 2°C compared to pre-industrial levels, and to pursue best efforts to limit increased warming to 1.5°C (UNFCCC, 2015: p. 2). The 2°C target is equivalent to a deep and rapid reduction of global emissions per capita from 7tCO_2 per annum to 4tCO_2 in 2030, and 2tCO_2 in 2050 (ADB, 2015). IEA (2017) suggests that CCS (Carbon Capture and Storage) technologies could contribute 14% of greenhouse gas emission reductions between 2010 and 2050 for the 2 degrees scenario (2DS) and 32% for the beyond 2 degrees scenario (B2DS).

China´s Intended Nationally Determined Contribution (INDC) to the Paris Agreement includes targets for carbon dioxide emissions to peak by around 2030 (with best efforts to peak earlier), to lower carbon dioxide emissions per unit of GDP by 60-65% from 2005 levels by 2030, and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 (NDRC, 2015a: p. 5). The INDC outlines a portfolio of low-carbon technologies and mechanisms to reduce greenhouse gas emissions, including setting up a national carbon market. Carbon Capture, Utilisation and Storage (CCUS) is highlighted as a key low-carbon technology (NDRC, 2015b: p. 8). China´s government has ten years of experience in supporting CCUS research, development and demonstration through various policy mechanisms (as illustrated in **Table 1**).

The steel sector provides a fundamental material to society, but the sector is also one of the most energy– and carbon–intensive industrial sectors and therefore a major contributor to global anthropogenic carbon dioxide emissions (Leeson et al., 2014). According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the production of steel generated more than 2.6 billion tonnes of carbon dioxide ($GtCO_2$) per year in 2006, equivalent to approximately 5% of global anthropogenic carbon dioxide emissions (IPCC, 2014; Fischedick et al., 2014).

Table 1. CCUS related policy documents in China

Year	Institutions	CCUS Relevant Policy Document
2006	State Council	Outline of the National Medium and Long-Term Science and Technology Development Program (2006 - 2020)
2007	Ministry of Science and Technology	China's National Climate Change Program
2007	Ministry of Science and Technology, NDRC, Ministry of Foreign Affairs etc.	China's Response to Climate Change Science and Technology Special Action
2011	Department of Social Science and Technology, Ministry of Science and Technology	China's Carbon Capture, Utilisation and Storage Technology Roadmap
2011	Ministry of Science and Technology	National "Twelfth Five-Year" Science and Technology Development Plan
2011	State Council	"Twelfth Five-Year" Greenhouse Gas Emissions Control Work Plan
2012	State Council News Office	China Energy Policy (2012) White Paper
2012	National Energy Administration	Coal Industry "Twelfth Five-Year" Development Plan
2013	Ministry of Science and Technology	"Twelfth Five-Year" National Carbon Capture, Utilization and Storage Technology Special Development Plan
2013	NDRC	Notice on Promoting the Demonstration of Carbon Capture, Utilization and Storage
2013	State Council	Opinions of the State Council on Accelerating the Development of Energy Saving and Environmental Protecting Industries
2013	Ministry of Environmental Protection	Notice on Strengthening the Environmental Protection Work of Carbon Capture, Utilization and Storage Test Demonstration Projects
2014	General Office of the State Council	Energy Saving and Emission Reduction Action Plan for Low Carbon Development 2014 - 2015
2015	State Council News Office	Strengthening the Response to Climate Change Action – China's Intended National Determined Contributions (INDCs)

Sources: State Council, 2006; MOST, 2011; NDRC, 2012; MOST, 2013; GDCCUSC, 2016: p. 24

Global crude steel production reached 1.6 billion tonnes in 2015, an increase of 41% over the 1.1 billion tonnes in 2005 (**Figure 1 and Table 2**). China alone produced 804 million tonnes of crude steel in 2015, an increase of 130% over the 350 million tonnes in 2005 (The Editorial Board of China Steel Yearbook, 2015). Although the production of crude steel in China fell by 2% in 2015, there is likely along-term growth of crude steel production in the world. Applying environmentally-friendly and low-carbon technologies is the major future trend for the global steel sector (Sodsai and Rachdawong, 2012;

Moya et al., 2013; Wen et al., 2014; Morfeldt et al., 2015; Riccardi et al., 2015; Tsai et al., 2015). The EU Commission´s Low Carbon Roadmap anticipates a global emission intensity of less than 0.2 tCO_2 per tonne of crude steel by the end of 2050, compared to the EU´s current level of above 1.3 tCO_2 per tonne, and China´s average of 2.18 tCO_2 per tonne in 2014 (Zou, et.al, 2013). The Roadmap suggests CCS is a key technology to achieve larger emission reductions in the iron/steel sector.

Figure 1. World and China steel production
Source: World Steel Association, 2016.

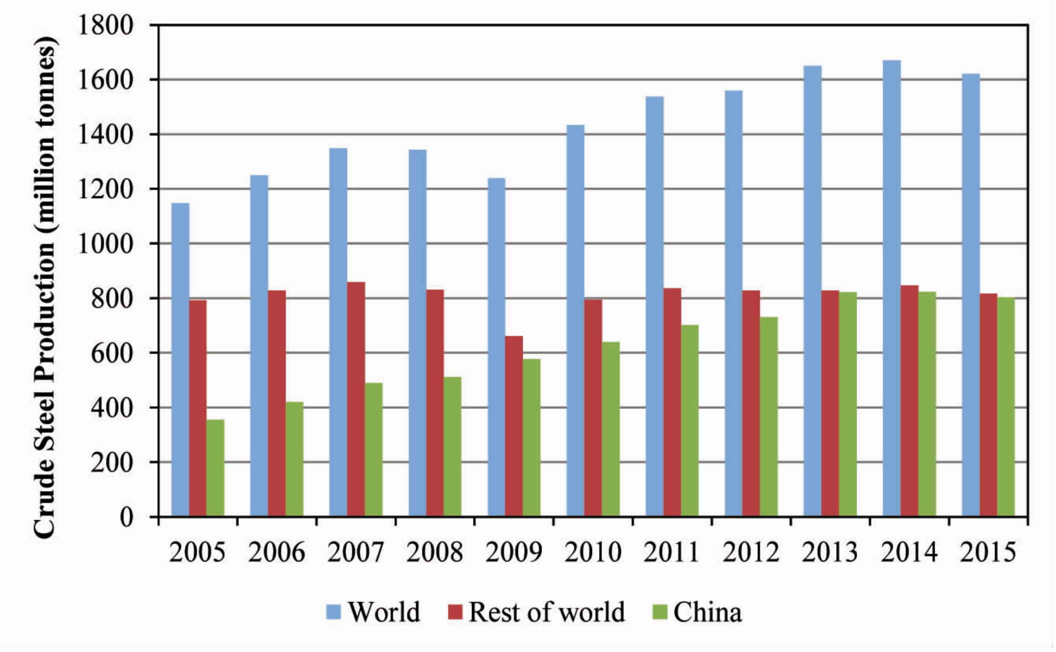
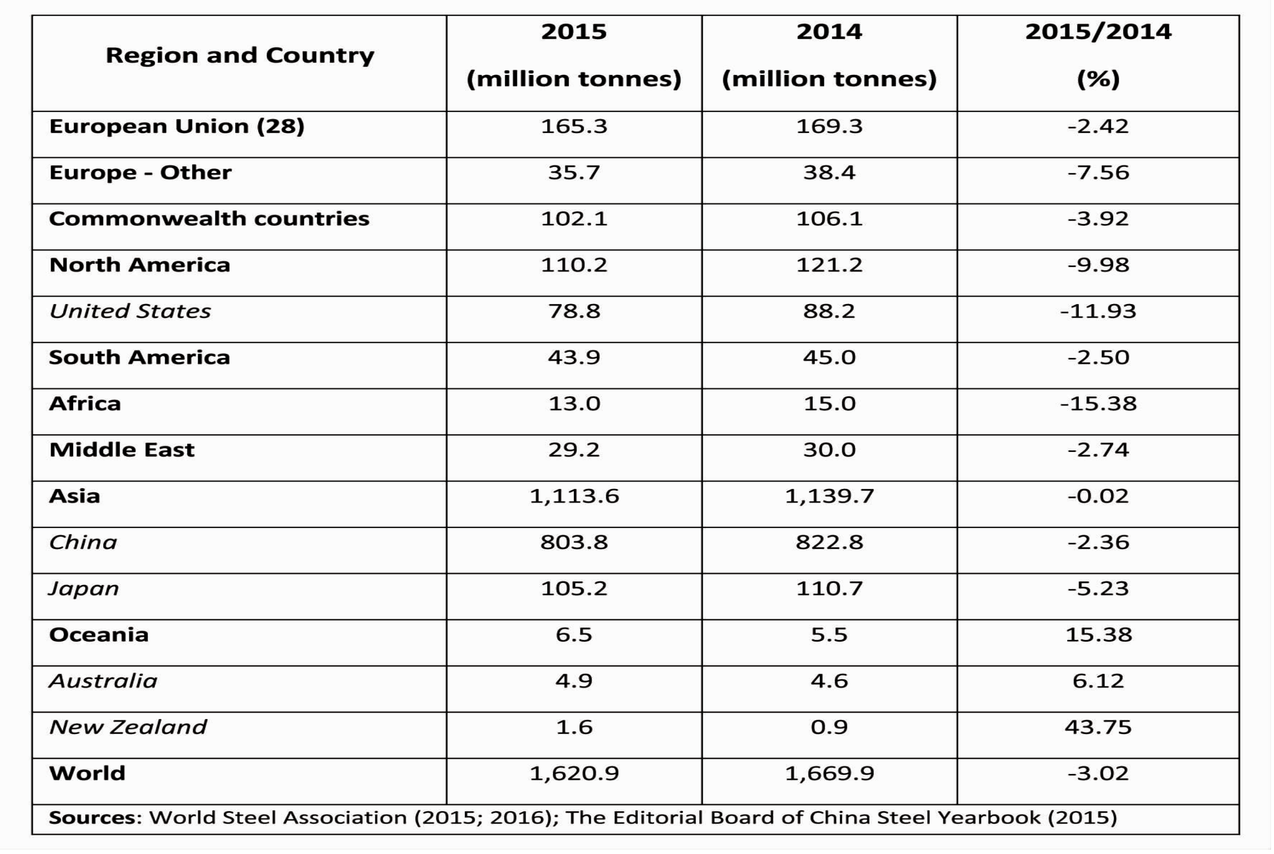


Table 2. Total production of crude steel



Region and Country	2015 (million tonnes)	2014 (million tonnes)	2015/2014 (%)
European Union (28)	165.3	169.3	-2.42
Europe - Other	35.7	38.4	-7.56
Commonwealth countries	102.1	106.1	-3.92
North America	110.2	121.2	-9.98
United States	78.8	88.2	-11.93
South America	43.9	45.0	-2.50
Africa	13.0	15.0	-15.38
Middle East	29.2	30.0	-2.74
Asia	1,113.6	1,139.7	-0.02
China	803.8	822.8	-2.36
Japan	105.2	110.7	-5.23
Oceania	6.5	5.5	15.38
Australia	4.9	4.6	6.12
New Zealand	1.6	0.9	43.75
World	1,620.9	1,669.9	-3.02

Sources: World Steel Association (2015; 2016); The Editorial Board of China Steel Yearbook (2015)

There are currently only two large-scale integrated iron/steel sector CCS projects under development in the world: the Ultra-Low CO_2 Steel Consortium (UCLOS) Blast Furnace Project and the Emirates Steel Industry CCS Project (GCCSI, 2016). The UCLOS Blast Furnace project aims to capture up to 700,000 tCO_2/year from a blast furnace gas-fired boiler located in France. The Emirates Steel Industry CCS Project capture 800,000 tCO_2/year from a Direct Reduced Iron (DRI) facility. The Emirates Steel project has started operation. Although China is the largest global producer of crude steel, it does not yet have any steel sector CCS demonstration projects. In absence of the pilot and demonstration projects in China, ADB (2015: 31) suggested that new-build steel mills in China should consider a CCS readiness design[1].

As such, this report analyses the techno-economic performance of CO_2 capture technologies at a hypothetical Chinese steel plant. It is structured as follows: Section 3 provides an overview of typical iron/steel manufacturing processes and reviews potential emission reduction mechanisms within the sector, Section 4 outlines the technical and financial modelling assumptions for a generic steel plant in China, and Section 5 presents the techno-economic analysis results, followed by our conclusions in Section 6.

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[1] A separate report on capture readiness in the steel sector has been produced by the project team and you can request a copy by email to ccus@business-school.ed.ac.uk.

3. Process of Steel Manufacturing and Mechanisms for Emissions Reduction

3.1. The Different Steel–making Processes

Steel is produced from iron ore in two major stages: (a) the iron–making process where raw iron is extracted from the iron ore; (b) the steel–making process where the raw iron is purified to make crude steel. The two stages can be further broken down into four steps (IEA, 2007; Carpenter, 2012), as illustrated in **Figure 2**:

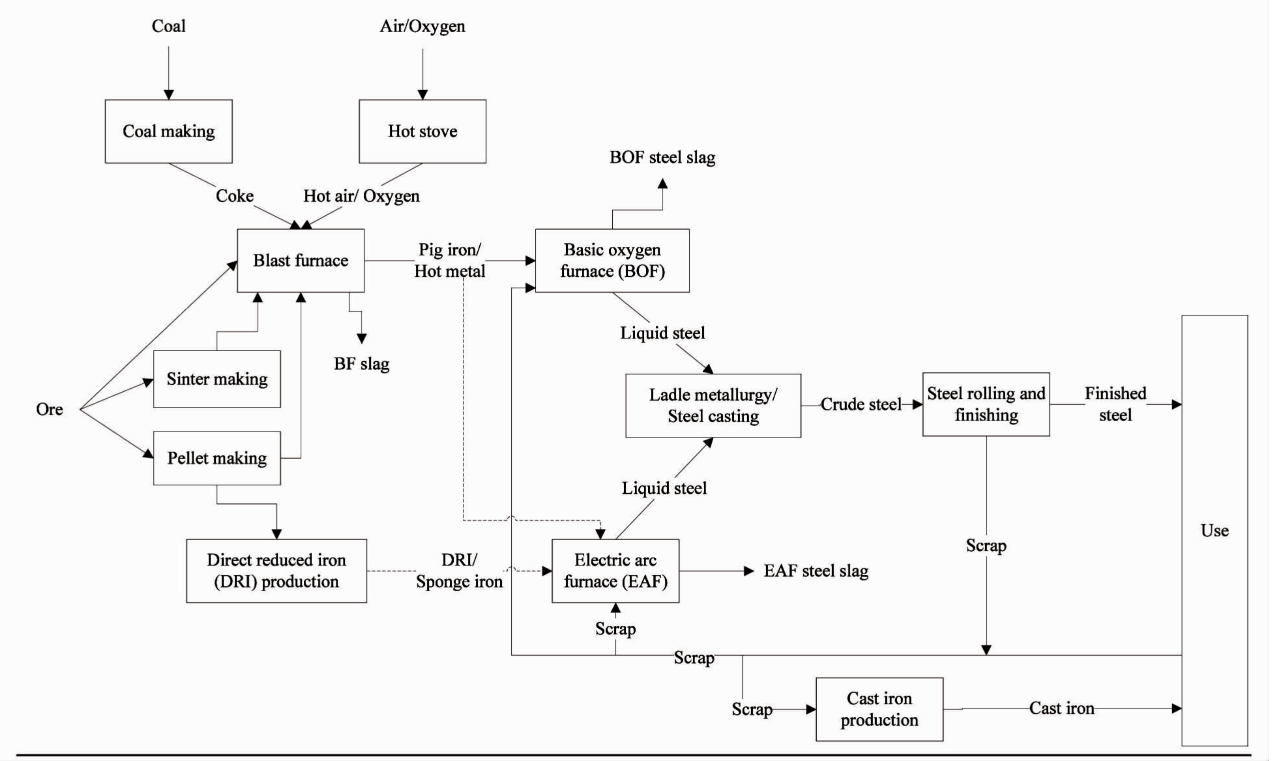
(i) Raw material preparation, that is, coke–making and iron ore preparation;

(ii) Iron–making, where the iron ore is reduced by a carbon–based agent to produce hot metal (also known as ‘pig iron´, when cast into ingots) or DRI, a solid product;

(iii) Steel–making, where the hot metal/pig iron or DRI are converted into liquid steel;

(iv) Manufacturing steel products, where the steel is cast, reheated, rolled and finished.

Figure 2. Typical steel production process flow diagram



There are two types of iron ore preparation plants: sinter and pellet plants (**Figure 3** and **Figure 4** respectively). Pellets are nearly always made of one well–defined iron ore or concentrated at the mine to be transformed into this form. Sinter is generally produced at the ironworks from pre–designed mixtures of fine ores, residues and additives (Hidalgo et al., 2003). For the past twenty years, almost 60% of steel has been derived from hot metal/pig iron, although the share of steel produced from DRI has steadily increased. Pig iron is produced in blast furnaces. Apart from blast furnace, about 5% of global steel is produced from DRI process, and 35% of crude steel is derived from scrap. These process options are important because they significantly affect energy use and CO_2 emissions (IEA, 2007).

Figure 5 presents a simplified schematic diagram of the iron–making and steel–making production routes. Globally, there are two most popular routes for the production of steel: the blast furnace–basic oxygen furnace (BOF) route and electric arc furnace (EAF) route. The key difference between the routes is the type of raw materials they consume. For the BOF route these are predominantly iron ore, coal, and recycled steel, while the EAF route produces steel mainly using recycled steel (scrap). Depending on the plant configuration and availability of recycled steel, other sources of metallic iron such as DRI or hot metal can also be used in the EAF route. The BOF route always uses some scrap (up to 30%), while an EAF can be charged with 100% steel scrap. Another steel–making technology, the open–hearth furnace (OHF), accounts for about 1% of global steel production. The OHF process is highly energy intensive and is in decline owing to its environmental and economic disadvantages. As shown in **Table 3**, a majority of steel plants in China apply the BOF route.

Figure 3. The sinter production process flow diagram

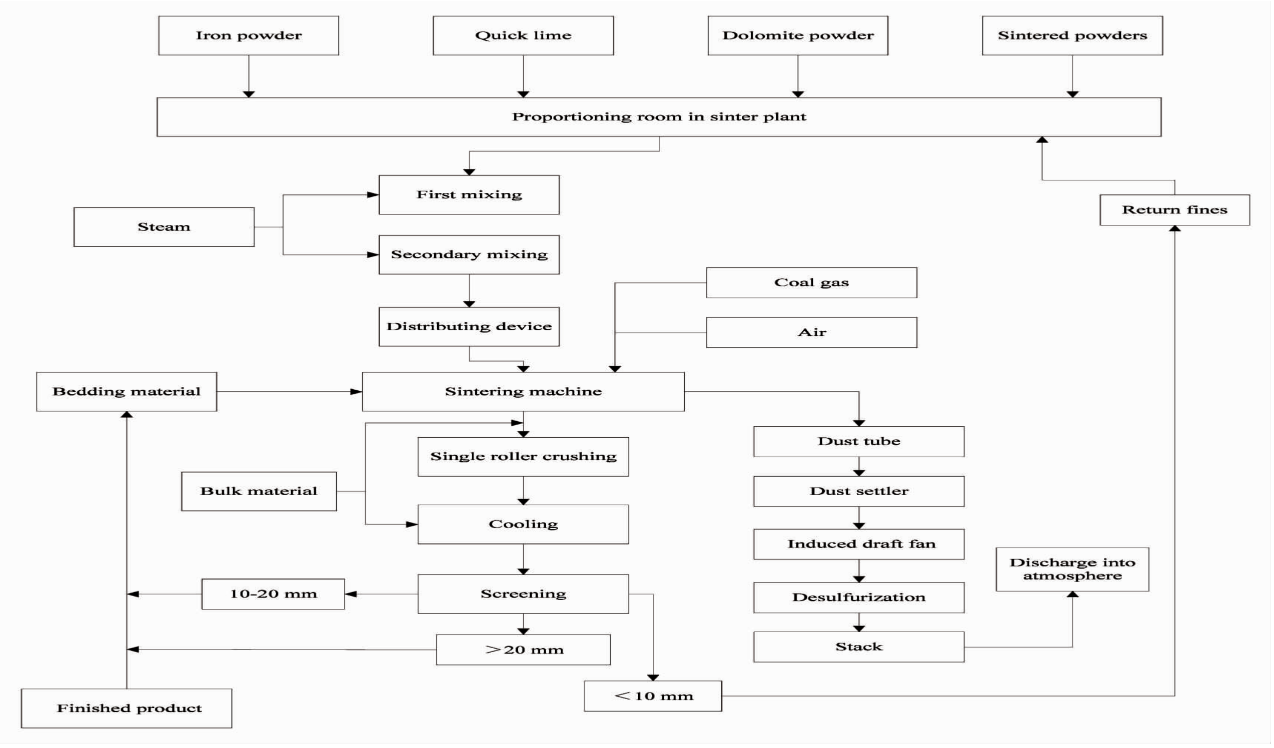


Figure 4. The pellet production process flow diagram

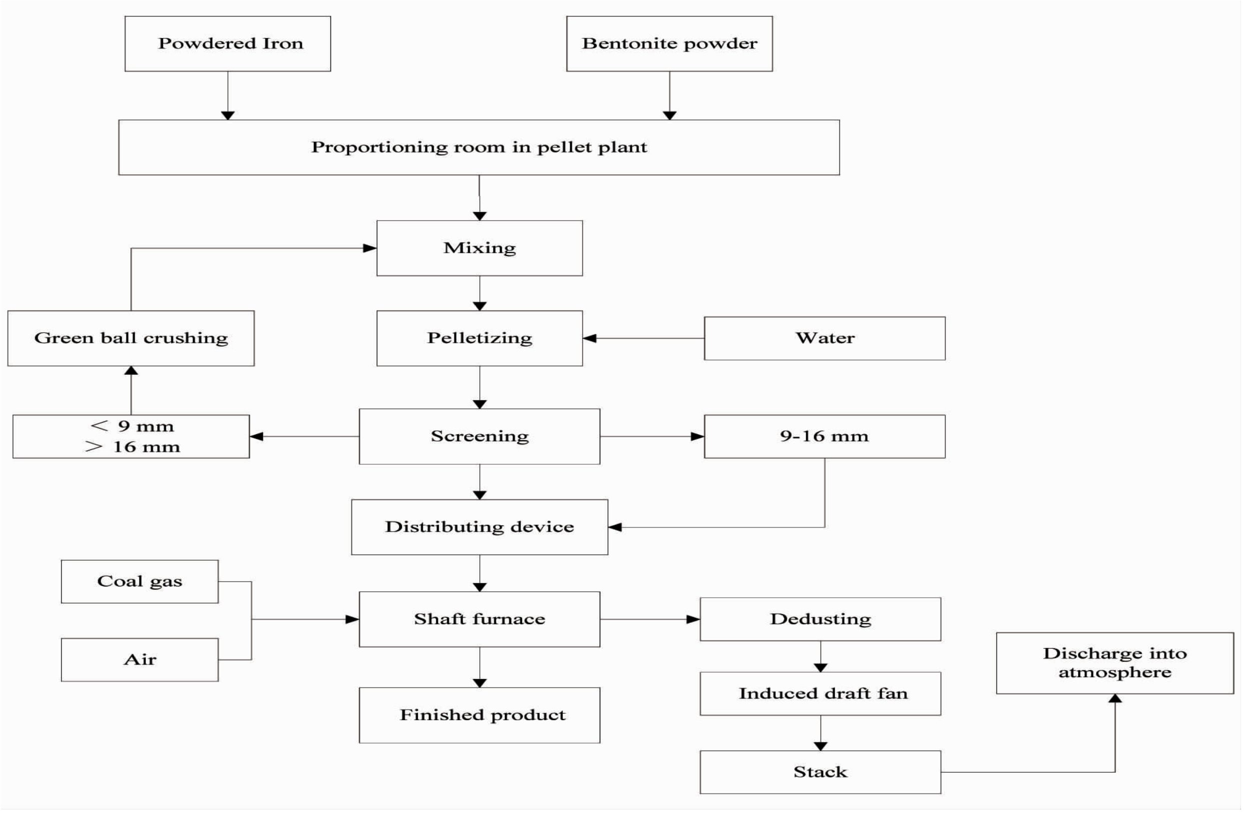
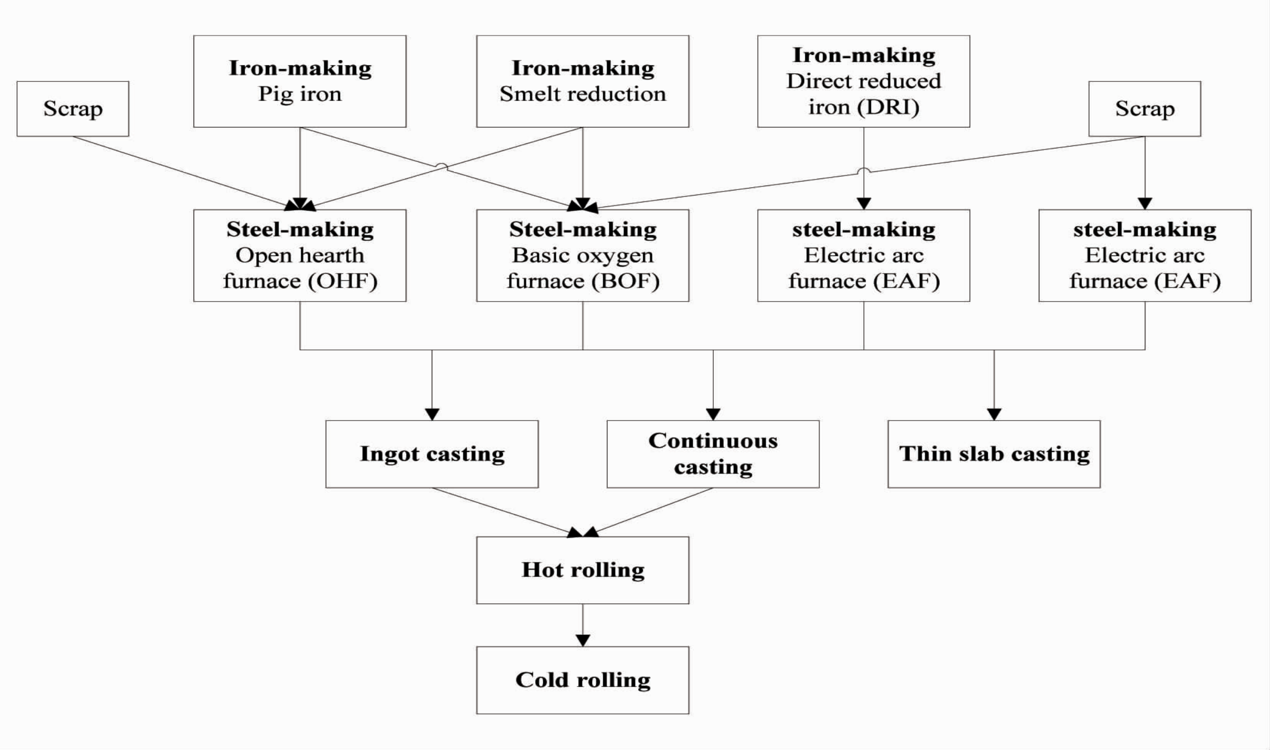


Table 3. Crude steel production and steel–making process in China by enterprise in 2015

Enterprise		Location	2015 Crude Steel Production (Million tonnes)	Steel-making Process
Hesteel Group	TangSteel	Hebei	47.75	BOF
	HanSteel			BOF
	XuanSteel			BOF
	ChengSteel			BOF
	WuSteel			BOF
	ShiSteel			EAF, BOF
Baosteel Group		Shanghai	34.94	EAF, BOF
Shagang Group		Jiangsu	34.21	EAF, BOF
Ansteel Group		Liaoning	32.50	BOF
Shougang Group		Hebei	28.55	BOF
Wuhan Steel Group		Hubei	25.78	EAF, BOF
Shandong Steel Group	JiSteel	Shandong	21.69	BOF
	LaiWuSteel			BOF
Maanshan Steel		Anhui	18.82	EAF, BOF
Tianjin Bohai Steel		Tianjin	16.27	EAF, BOF
Jianlong Group	TangshanJianlong	Hebei	15.14	BOF
	ChengdeJianlong	Hebei		BOF
	Heilongjiang Jianlong	Heilongjiang		BOF
	Jilin Jianlong	Jilin		BOF
	Fushun New Steel	Liaoning		BOF
	Tangshan XinBaotai	Hebei		BOF
Benxi Steel		Liaoning	14.99	EAF, BOF
Rizhao Steel		Shandong	14.00	BOF
Fangda Steel		Jiangxi	13.21	BOF
Baotou Steel		Inner Mongolia Municipality	11.86	BOF
Jingye Steel		Hebei	11.32	BOF
Liuzhou Steel		Guangxi	10.83	BOF
Anyang Steel		Henan	10.74	EAF, BOF
Zongheng Steel		Hebei	10.38	EAF, BOF
Taiyuan Steel		Shanxi	10.26	BOF, EAF
Jinxi Steel		Hebei	9.77	BOF
Sanming Steel		Fujian	9.58	BOF
Xinyu Steel		Jiangxi	8.64	BOF
Nanjing Steel		Jiangsu	8.59	EAF, BOF
Guofeng Steel		Hebei	8.29	BOF
Jiuquan Steel		Gansu	7.69	EAF, BOF

Figure 5. Iron and steel–making production routes

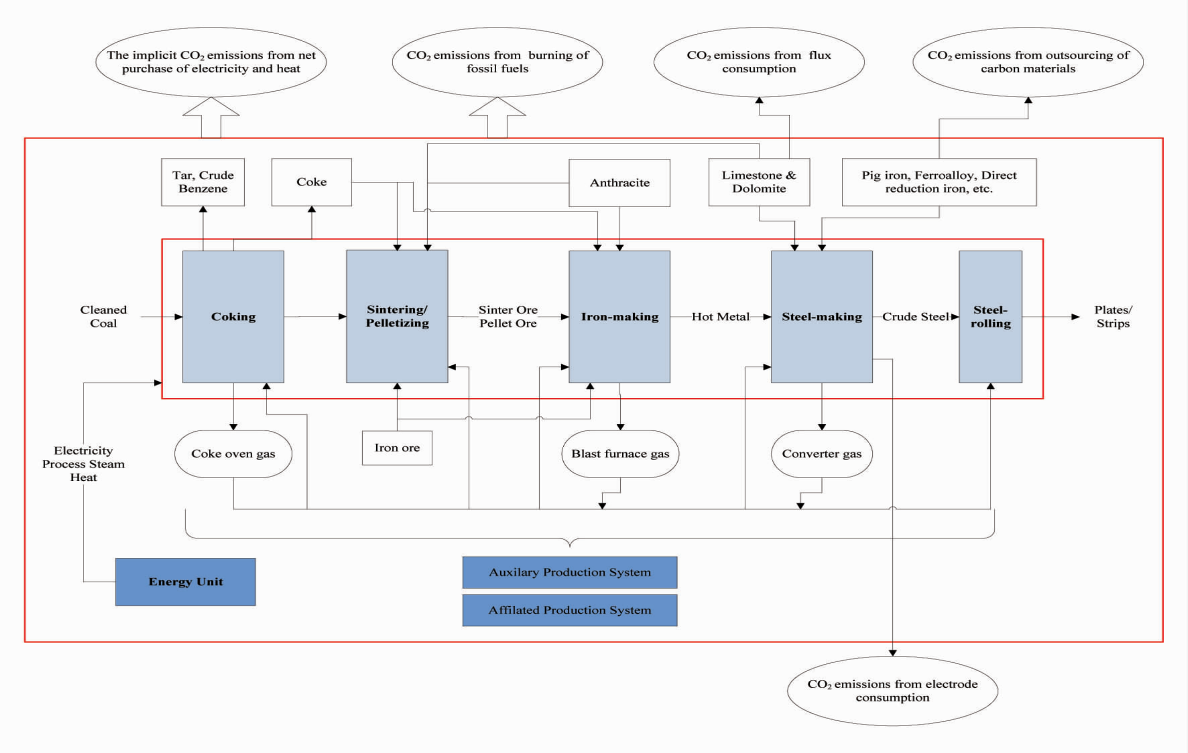


3.2.CO_2 Emission Sources in Iron/Steel Sector

Steel manufacturing contributes the largest share of CO_2 emission of all global manufacturing sectors. The high CO_2 emissions are due to the energy intensity of steel production, its reliance on coal as the main energy source and the large volume of steel produced (Carpenter, 2012). The average CO_2 intensity for the steel industry is 1.9 tCO_2 per tonne of steel produced (IEA, 2007; Kundak et al., 2009; Quader et al., 2014). The carbon intensity of iron and steel production varies considerably between the production routes, ranging from around 0.4 tCO_2/t crude steel for scrap/electric arc furnaces (EAF), 1.7–1.8 tCO_2/t crude steel for the integrated blast furnace–basic oxygen furnace (BOF) to 2.5 tCO_2/t crude steel for coal–based direct reduced iron (DRI) processes (Carpenter, 2012; Ruijven et al., 2016).

The iron–making process is the most emissions–intensive part of steel production, contributing 70–80% of carbon dioxide emitted. Making iron involves reacting iron ore with a reducing agent, such as coking coal, which produces a large volume of CO_2. There are several main streams featuring high concentrations of CO_2 in a steel plant. Figure 6 presents the system boundaries and CO_2 emission sources of a typical steel mill. The system boundary of the mill consists of the following processes: coking plant, sinter plant, iron–making, steel–making and rolling mills. In addition, the system boundary of the mill site includes the energy unit producing electricity, process steam and heat at the mill site as well as the purchase and sale of energy. Process gases, such as coke oven gas and blast furnace gas, are used for energy production at the mill site (Siitonen et al., 2010; Jin et al., 2015; Lisienko et al., 2015). This study doesn´t take into account other emissions that occur off–site, but a further consequential analysis[2] for CO_2 emissions from the steel sector would be beneficial (Huang et al., 2010).

Figure 6. System boundaries and CO_2 emission sources of a typical steel mill



CO_2 is emitted at a variety of points in the iron and steel production processes including: (1) direct emissions from on–site combustion of fossil fuels; (2) process–related (that is, non–energy) emissions; and (3) indirect emissions from electricity consumed during the production process (**Table 4**). The main equipment resulting in direct CO_2 emissions includes the sintering machine, coke oven, dry quenching furnace, blast furnace, converter, continuous casting machine, rolling mill, shaft kiln and rotary kiln, and power generation boiler (Carpenter, 2012; Zhang et al., 2013a; Zuo et al, 2013; GB/T 32151.5–2015).

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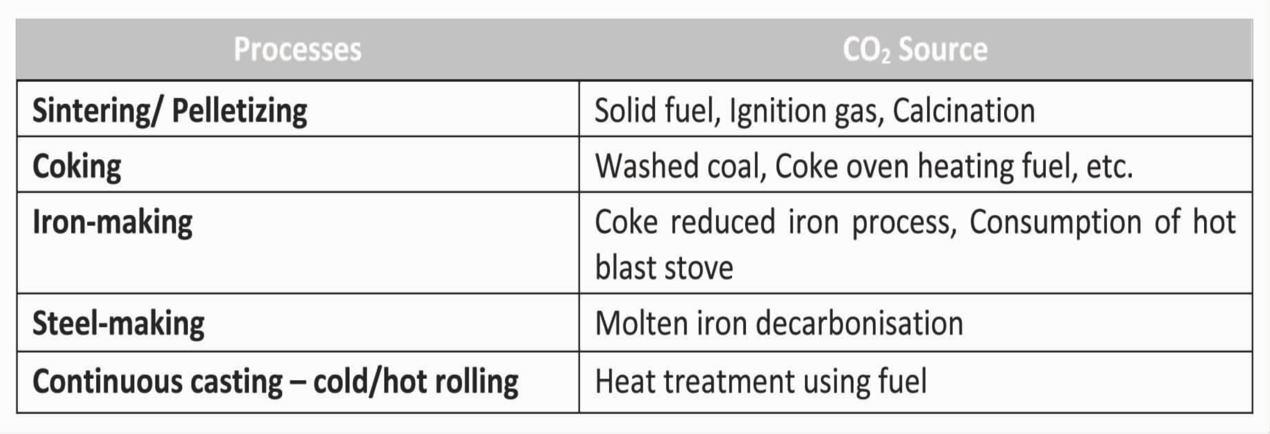
[2] A consequential analysis is conducted by the project. The report could be obtained by contact CCUS@business–school.ed.ac.uk

Table 4. Primary CO_2 sources in the steel production processes



Processes	CO_2 Source
Sintering/ Pelletizing	Solid fuel, Ignition gas, Calcination
Coking	Washed coal, Coke oven heating fuel, etc.
Iron-making	Coke reduced iron process, Consumption of hot blast stove
Steel-making	Molten iron decarbonisation
Continuous casting – cold/hot rolling	Heat treatment using fuel

3.3. Potential Emission Reduction Technologies

Based on the sequences of CO_2 emissions from different iron– and steel–making processes, the pathways available to reduce CO_2 emissions in the steel sector[3] can be classified into three categories based on:

(1) Fuel Switching (shifting to a lower CO_2 emission factor fuel),

(2) Energy Efficiency Measures (i.e. minimising energy consumption and improving the energy efficiency of the underlying processes), and

(3) Carbon Capture and Storage (capturing CO_2 and storing it underground) (Xu and Cang, 2010; Hasanbeigi and Price, 2012; Xu et al., 2013; Quader et al., 2014; Carpenter, 2012).

The notion of fuel switching emission mitigation is to switch to a fuel and/or reducing agent with lower carbon content. Carbon dioxide can be prevented from being emitted by using ‘zero–carbon´ – or ‘lower carbon´ – energy carriers (such as wind energy, nuclear energy, water power, biomass, fuel cells, etc.) instead of fossil fuels. By switching away from fossil fuels, the demands of energy consumption can be met with less CO_2 emissions (Quader et al., 2014; Mousa et al., 2016). The extent to which coal can be replaced is dependent on the iron–making process. In general, direct reduction processes can utilise up to 100% wood charcoal either within the reactor (rotary kilns, rotary hearths) or by gasifying biomass instead of coal and injecting the resultant syngas into the shaft furnace (Carpenter, 2012). Smelting reduction processes that directly reduce using non–coking coal (lump, fines or pellets) have been developed, thus eliminating the need for coke ovens and sinter plants with their associated CO_2

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[3] The project team will draft a report on abatement options for steel plants. You can request a copy of the report by email ccus@business–school.ed.ac.uk

emissions.

Another route to decarbonisation is to minimise the CO_2 emitted from steel plants by employing energy saving measures. This entails improvements in the efficiencies of energy conversion, transportation and utilisation (Quader et al., 2014). The principal measures for improving energy efficiency include enhancing continuous processes to reduce heat loss, increasing the recovery of energy and process gases, and efficient design (Carpenter, 2012). Over the years, the iron and steel industry has made significant efforts to reduce energy consumption and lower CO_2 emissions by improving energy efficiency, reducing coke and coal consumption, utilising by–product fuels, increasing the use of biomass and renewable energy, and implementing other techniques.

The third category is focused on carbon capture and storage. The notion is to recycle or capture the emitted CO_2, then storing it in permanent carbon sinks (i.e. storage sites) instead of being released to the atmosphere (Quader et al., 2014). Beyond the aforementioned reductions brought about by enhancing energy efficiency, there is substantial potential for further reductions that could only be achieved by equipping plants with carbon capture and storage (Ghanbari et al., 2015). Applying CCS to all the stacks in a steel works is possible, provided there is space (Carpenter, 2012; Burchsrt–Korol et al., 2016; Kuramochi, 2016). It would not interrupt the upstream and downstream processes, but the cost for transporting and storing CO_2 is relatively high. The study will analyse an amine–based technology for CO_2 capture in a steel blast furnace. The amine–based technology is one of the most popular global carbon capture technologies and is also recognised as a cost–efficient method. It has been established for over 60 years in the oil and chemicals industries for removal of hydrogen sulphide and CO_2 from gas streams. Commercially, it is the most well–established of the techniques available for CO_2 capture, although practical experience exists mainly in low partial pressure flue gas streams such as in power plants and in petrochemical plants. By using this technology, CO_2 recovery rates of 98% and product purity in excess of 99% can be achieved (Liang et al., 2010).

Solid adsorbents, such as zeolites and activated carbon, can be used to separate CO_2 from gas mixtures. In pressure swing adsorption (PSA), the gas mixture flows through a packed bed of adsorbent at elevated pressure until the concentration of the desired gas approaches equilibrium. The bed is regenerated by reducing the pressure. In temperature swing adsorption (TSA), the adsorbent is regenerated by raising its temperature. PSA and TSA are commercially applied methods of gas separation and are used to some extent in hydrogen production and in removal of CO_2 from natural gas. However, adsorption is not yet considered attractive for large–scale separation of CO_2 from flue gas because the capacity and CO_2 selectivity of available adsorbents is low. It may, however, be successful in combination with another capture technology (Wang et al., 2010). Gas separation membranes allow one component in a gas stream to pass through faster than the others. There are many different types of gas separation membranes, including porous inorganic membranes, palladium membranes, polymeric membranes and zeolites. Membranes cannot normally achieve high degrees of separation, so multiple stages and/or recycling of one of the streams is necessary. This leads to increased complexity, energy consumption and costs (Sanders et al., 2013). There are other potentially–disruptive technologies investigated by researchers, such as ammonia capture (Han et al., 2014), water gas shift technology (Van Dijk et al., 2015), modified blast furnace with pre–combustion capture (Onarheim and Arasto, 2016) and calcium looping (Mattila et al., 2014; Ravelli, 2015; Cormos, 2016). Another novel approach studied by a team member of this project is to combine membrane with physical adsorption technology to enhance the efficiency of the capture process. However, the amine–based technology remains the most mature option for carbon capture in the steel sector, while bench and pilot scale demonstration of novel technologies may contribute to cost reduction in the long–term.

4. Case Study Assumptions

4.1.Technical Assumptions

The study assesses the economics of carbon capture and storage from a generic crude steel production plant via the blast furnace (BF) route, applying the process and financial assumptions of Baowu Steel Zhanjiang plant (BSZ) in Guangdong, China as a case study example (Baowu Steel, 2016a)[4]. We assume a hypothetical retrofit project to capture 0.5 $MtCO_2$/year from a slip stream from the BF. The study assumes the application of a mature amine CO_2 post-combustion capture technology.

The BSZ is one of the most design-advanced steel plants in China, with a compact layout, an integrated waste metal recycling unit and a pollution control unit. It is located at Donghai Island in Zhanjiang City, in the west of Guangdong province, and covering an area of 12.98 km2. The plant is co-located with the site of the SINOPEC-Kuwait project, a major petrochemical complex at its development stage. The BSZ plant completed construction in July 2016. The total capital investment was CNY 50 billion (USD 7.1 billion). The plant has a production capacity of 9.38 million tonnes of steel per year (4.48 million tonnes hot casted and 4.9 million tonnes cold casted). The plant was designed by China Metallurgical Group Corporation (MCC). The major equipment of the BSZ project is listed in **Table 5** below.

In this study, the blast furnace integrated steel-making process includes six modules and ASPEN was used to evaluate the financial assumptions of BSZ plant. ASPEN is a state-of-the-art process simulator and economic evaluation package designed for use in engineering fossil energy conversion processes. The system can perform steady-state material and energy balances, determine equipment size and costs, and carry out preliminary economic evaluations. The methodology employed in this assessment is derived from the IEAGHG (2013a and 2013b) and Tsupari et al. (2013, 2015) studies where modules were coded for simulation and cost analysis purposes as per **Table 6**. The study did not make an assumption about the engineering design for CO_2 storage, but for costing purposes, storage is coded as BF800.

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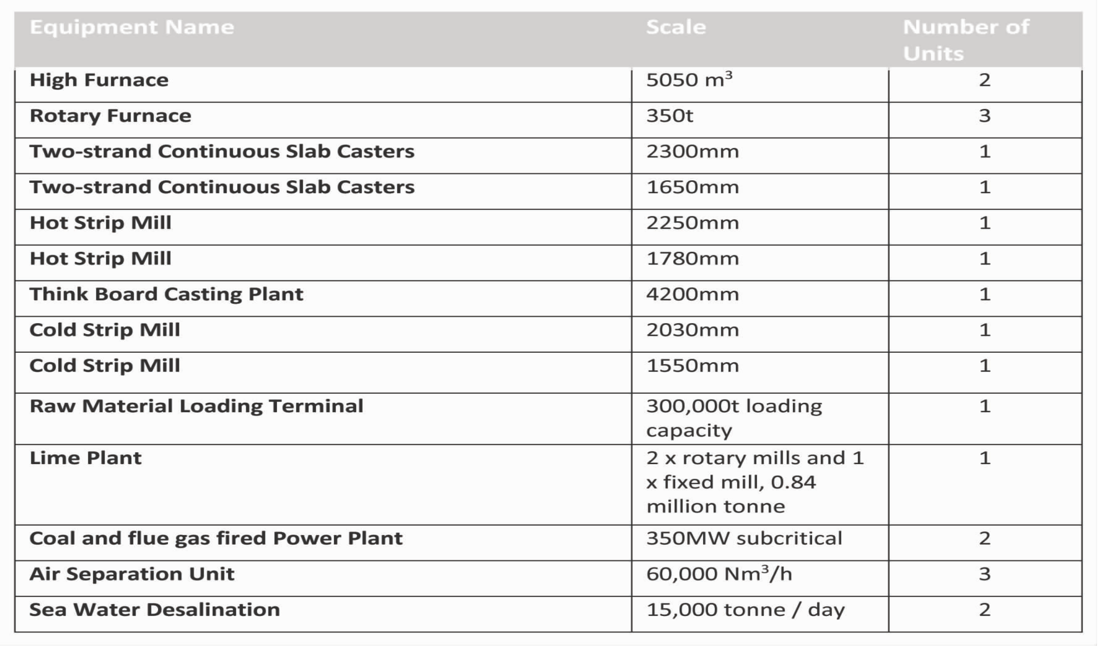
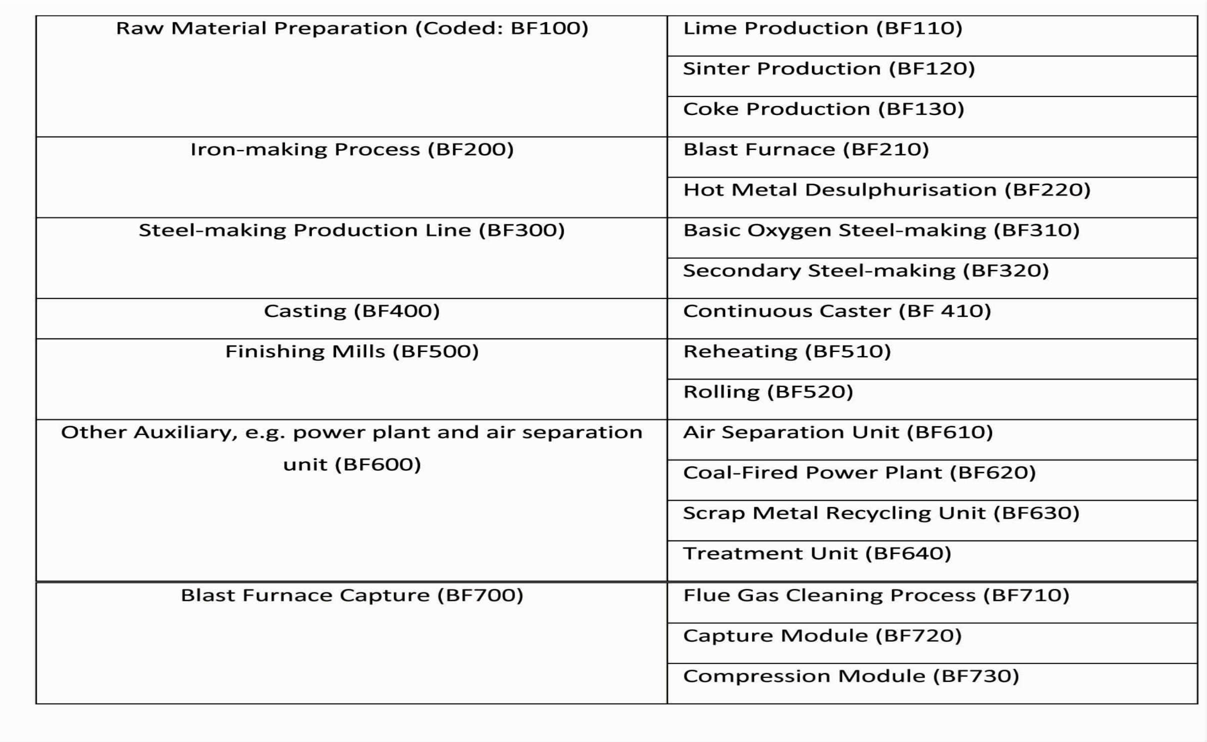
[4] Bao Steel. 2016b. Technical Personal Communication with Bao Steel Zhanjiang Project. Meeting on 16/Jul/2017, Zhanjiang, Guangdong, China.

Table 5. Major equipment and facilities in Baowu Steel Zhanjiang Project



Equipment Name	Scale	Number of Units
High Furnace	5050 m^3	2
Rotary Furnace	350t	3
Two-strand Continuous Slab Casters	2300mm	1
Two-strand Continuous Slab Casters	1650mm	1
Hot Strip Mill	2250mm	1
Hot Strip Mill	1780mm	1
Think Board Casting Plant	4200mm	1
Cold Strip Mill	2030mm	1
Cold Strip Mill	1550mm	1
Raw Material Loading Terminal	300,000t loading capacity	1
Lime Plant	2 x rotary mills and 1 x fixed mill, 0.84 million tonne	1
Coal and flue gas fired Power Plant	350MW subcritical	2
Air Separation Unit	60,000 Nm^3/h	3
Sea Water Desalination	15,000 tonne / day	2

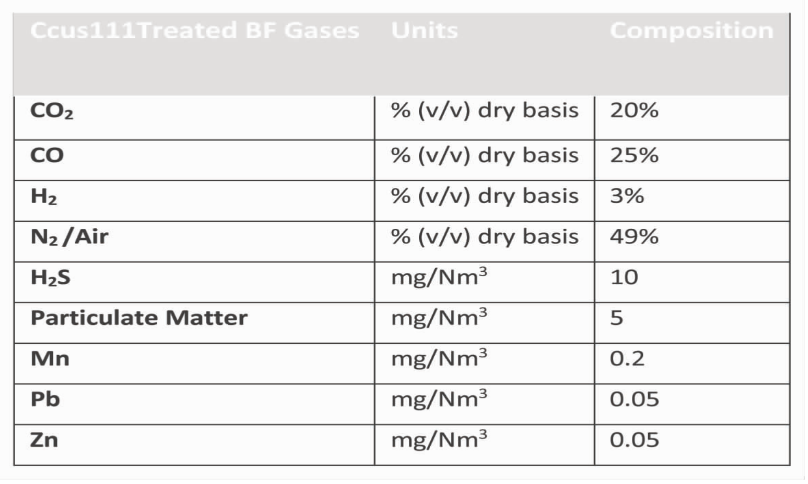
Table 6. Coded processes and sub–processes



Raw Material Preparation (Coded: BF100)	Lime Production (BF110)
	Sinter Production (BF120)
	Coke Production (BF130)
Iron-making Process (BF200)	Blast Furnace (BF210)
	Hot Metal Desulphurisation (BF220)
Steel-making Production Line (BF300)	Basic Oxygen Steel-making (BF310)
	Secondary Steel-making (BF320)
Casting (BF400)	Continuous Caster (BF 410)
Finishing Mills (BF500)	Reheating (BF510)
	Rolling (BF520)
Other Auxiliary, e.g. power plant and air separation unit (BF600)	Air Separation Unit (BF610)
	Coal-Fired Power Plant (BF620)
	Scrap Metal Recycling Unit (BF630)
	Treatment Unit (BF640)
Blast Furnace Capture (BF700)	Flue Gas Cleaning Process (BF710)
	Capture Module (BF720)
	Compression Module (BF730)

We estimate the CO_2 from the blast furnace flue gas at 20% concentration (Zhang et al., 2013b). The CO_2 flue gas from the top of the blast furnace enters a gas cleaning process (BF710). Cleaned–up flue gas enters the amine base chemical absorption module (BF720), and the captured high–purity CO_2 would be compressed before it is transported for storage. The remaining flue gas rich with H2 and CO is recycled to the bottom of blast furnace via a gas heater. The composition of gas from the BF is listed in Table 7.

Table 7. Estimated composition of blast furnace flue gas steam



Ccus111Treated BF Gases	Units	Composition
CO_2	% (v/v) dry basis	20%
CO	% (v/v) dry basis	25%
H_2	% (v/v) dry basis	3%
N_2/Air	% (v/v) dry basis	49%
H_2S	mg/Nm^3	10
Particulate Matter	mg/Nm^3	5
Mn	mg/Nm^3	0.2
Pb	mg/Nm^3	0.05
Zn	mg/Nm^3	0.05

4.2.Economic Assumptions

The economic analysis focuses on the computation of two main outputs:

a) Cost of CO_2 Avoidance (CNY/tCO_2), denoted COA, is given by equation [1]:

$$COA = \frac{\sum_{n=0}^{T} \frac{(I_n+O_n+F_n+S_n)}{(1+r)^n}}{\sum_{n=0}^{T} \frac{(Q_n-A_n)}{(1+r)^n}} \qquad (1)$$

Where

I_n is the investment cost at year n,

O_n is the fixed operating and maintenance cost at year n,

F_n is variable costs (incl. fuel and solvent) at year n,

S_n is the transport and storage cost at year n,

Q_n is the total amount of CO_2 captured from the project at year n,

A_n is the total amount of CO_2 generated from an auxiliary power plant for supplying steam and electricity for capturing and compressing CO_2 at year n,

r is the discount rate (i.e. the required rate of return), and

T is the lifetime of the project.

b) Incremental Cost for Steel Product (CNY/t), denoted CFP, given by equation [2]:

$$CFP = \frac{\sum_{n=0}^{T} \frac{(I_n+O_n+F_n+S_n)}{(1+r)^n}}{\sum_{n=0}^{T} \frac{\theta \cdot Y_n}{(1+r)^n}} \qquad (2)$$

Where

I_n is the investment cost at year n,

O_n is the operating and maintenance cost at year n,

F_n is the variable costs (incl. fuel and solvent) at year n,

S_n is the transport and storage cost at year n,

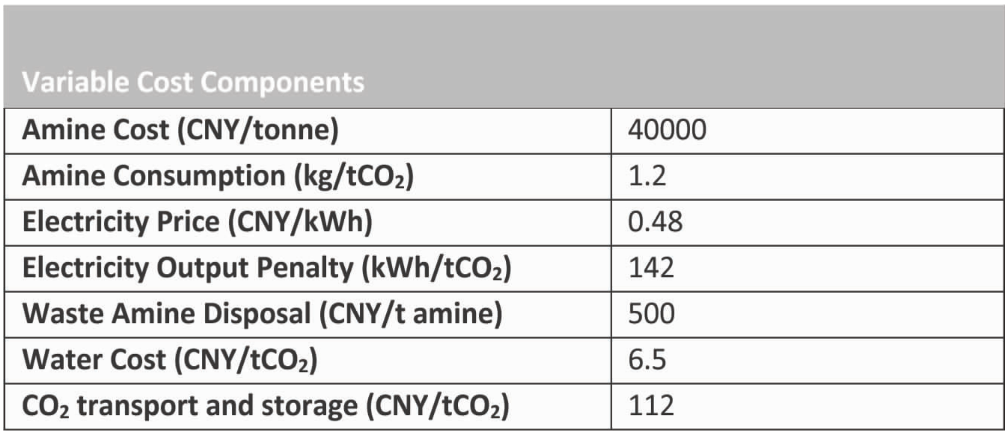
Y_n is the total amount of crude steel produced at year n,

r is the discount rate (i.e. the required rate of return),

and θ is the percentage representing the fraction of CO_2 avoided divided by the steel total CO_2 emissions from the steel plant without capture

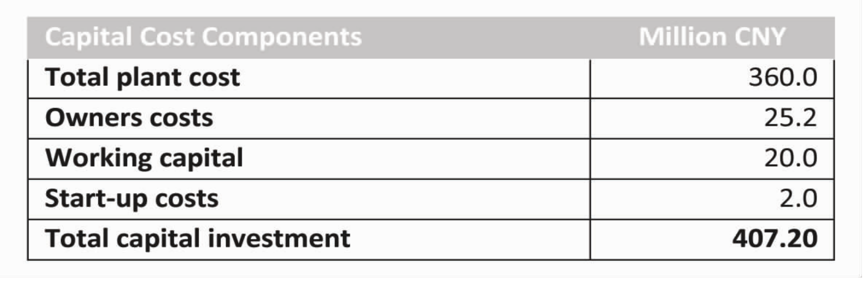
The capital cost of the capture plant is estimated at CNY 360 million (USD 51 million) with an additional 7% margin for owner´s cost (Table 8). An additional CNY 20 million (USD 2.9 million) is assumed for working capital for a company to oversee the development of the project and a CNY 2 million (USD 0.29 million) one-off start-up cost. The modelling results indicate an electricity output penalty for the auxiliary power plant (to generate steam and electricity for capture, compression and storage) of 142kWh/tCO_2 captured (Table 9). The coal price is assumed to be CNY27/GJ (approximately US$4/GJ), and the electricity price for calculating the cost of using auxiliary power is CNY0.48/kWh (USD 7 cents/kWh) – approximately 10% above the benchmark wholesale electricity price in Guangdong. The cost of purchasing solvent is CNY 40,000 per tonne of amine. The fixed O&M cost is assumed to be CNY 12 million (USD 1.7 million) per year (Table 10).

Table 8. Capture plant capital cost assumptions



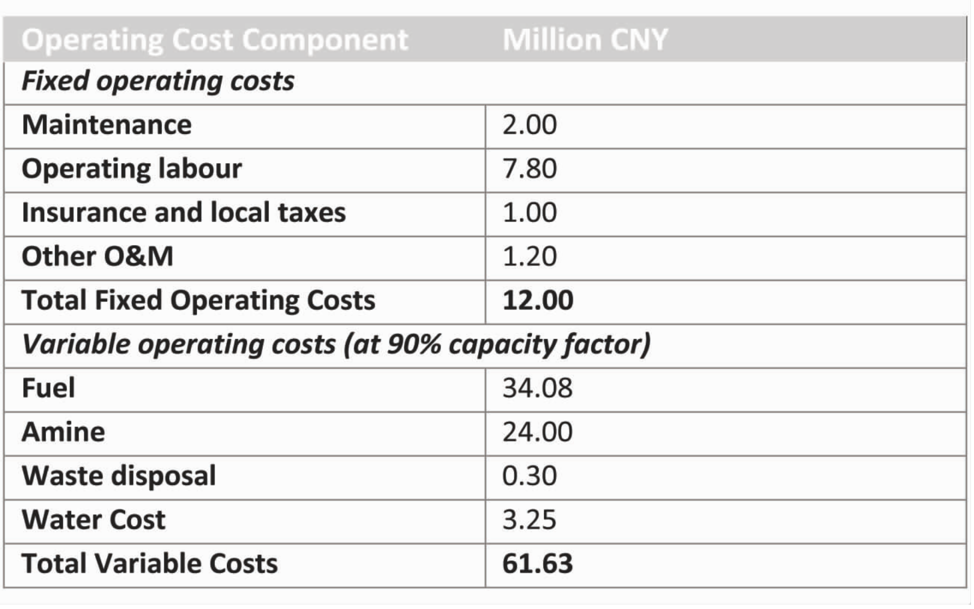
Variable Cost Components	
Amine Cost (CNY/tonne)	40000
Amine Consumption (kg/tCO_2)	1.2
Electricity Price (CNY/kWh)	0.48
Electricity Output Penalty (kWh/tCO_2)	142
Waste Amine Disposal (CNY/t amine)	500
Water Cost (CNY/tCO_2)	6.5
CO_2 transport and storage (CNY/tCO_2)	112

Table 9. Capture plant variable cost assumptions



Capital Cost Components	Million CNY
Total plant cost	360.0
Owners costs	25.2
Working capital	20.0
Start-up costs	2.0
Total capital investment	**407.20**

Table 10. Assumptions of capture plant operating costs



Operating Cost Component	Million CNY
Fixed operating costs	
Maintenance	2.00
Operating labour	7.80
Insurance and local taxes	1.00
Other O&M	1.20
Total Fixed Operating Costs	**12.00**
Variable operating costs (at 90% capacity factor)	
Fuel	34.08
Amine	24.00
Waste disposal	0.30
Water Cost	3.25
Total Variable Costs	**61.63**

The discount rate of the capture project is assumed to be 12%, taking into account the cost of capital of Baowu Steel and the risk of the CO_2 capture project. A sensitivity analysis was also conducted for 11% and 13% discount rate scenarios. The plant is currently assumed to emit 1.65 tCO_2/tonne steel produced (as an average of reported emissions from major steel plants) with total CO_2 emissions of 15.5 $MtCO_2$ per year. The auxiliary power plant has an emission factor of 743 gCO_2/kWh. The total amount of CO_2 avoidance capacity is 397,247 tonnes per annum with a CO_2 capture capacity of 500,000 tonne CO_2 per annum.

The capture project is assumed to have a 25-year lifetime and to be 100% equity-financed. For simplification, we assume that both the capture plant and the blast furnace will run stably at 90% capacity factor each year. The transportation and storage cost is assumed to be CNY112/tCO_2 (USD 16/tCO_2) based on market research surveys.

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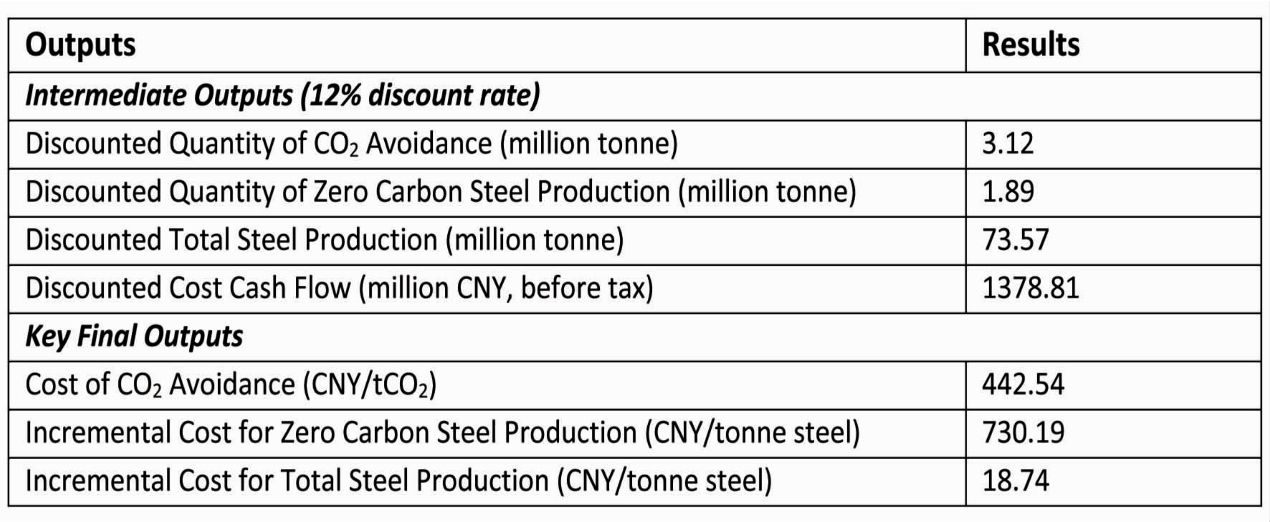
[5] [Electricity Output Penalty (kWh/tCO_2) * 500,000 tCO_2 * Emission Factor (gCO_2/kWh) * 10]

5. Economic Analysis Results

The assessment estimates the cost of CO_2 avoidance for a 0.5 million tonne capacity CO_2 capture project with transport and storage at **CNY 442.54/tCO_2 (USD 63.22/tCO_2) (Table 11)**. The project would capture 0.45 MtCO_2/year over 25 years, totalling 11.25 MtCO_2. However, this is offset by emissions from increased energy consumption so the project would only reduce aggregate emissions by 0.40 MtCO_2/year, or a total of 9.93 MtCO_2 over its lifetime. When the cost of the project is apportioned only to the amount of steel associated (2.6% of total steel production), the cost is **CNY 730.19 (USD 104.31)** per tonne of steel produced. However, if the cost is spread over the entire production of the plant, the cost per tonne of total steel production is only **CNY 18.74/tonne (USD 2.68/tonne)**.

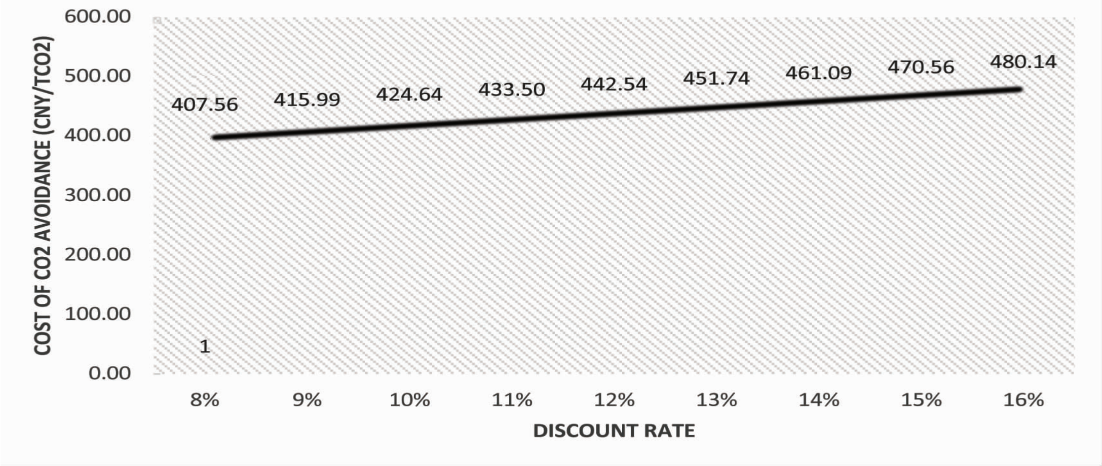
The cost of CO_2 avoidance is sensitive to a number of assumptions, including the discount rate and the cost of CO_2 transportation and storage. If a project is considered as a moderate risk investment and an 8% discount rate is applied, the cost of CO_2 avoidance (i.e. the abatement cost) will be reduced from CNY 442.54/tCO_2 at 12% discount rate to CNY 407.56/tCO_2 at 8% discount rate (USD 63.22/tCO_2 to USD 58.22/tCO_2) (**Figure 7**). In contrast, the abatement cost would increase to CNY 480.14/tCO_2 (USD 68.59/tCO_2) at a 16% discount rate. If the CO_2 storage and transport cost increased from 112 CNY/tCO_2 to 123 CNY/tCO_2 (USD 16 to 18/tCO_2), the abatement cost would be CNY 443.96/tCO_2 (USD 63.42/tCO_2) at a 12% discount rate.

Table 11. Economic analysis results for a hypothetical 0.5 MtCO2 CCUS project in China



Outputs	**Results**
Intermediate Outputs (12% discount rate)	
Discounted Quantity of CO_2 Avoidance (million tonne)	3.12
Discounted Quantity of Zero Carbon Steel Production (million tonne)	1.89
Discounted Total Steel Production (million tonne)	73.57
Discounted Cost Cash Flow (million CNY, before tax)	1378.81
Key Final Outputs	
Cost of CO_2 Avoidance (CNY/tCO_2)	442.54
Incremental Cost for Zero Carbon Steel Production (CNY/tonne steel)	730.19
Incremental Cost for Total Steel Production (CNY/tonne steel)	18.74

Figure 7. Cost of CO_2 avoidance under different discount rate scenarios



A study of CCS in the steel sector in Australia suggests that the cost of avoidance with conventional amine CO_2 capture technology could range from AU$70 to AU$250 (USD 50 to 178) excluding transportation and storage costs (Wiley et al., 2011; Ho et al., 2013). Our results suggest the estimated cost in China is relatively low. The main driver for a lower cost per tonne CO_2 abated is driven by a lower capital cost in China in contrast with that in Australia. Guangdong is China´s largest province with demand for more than 1 million tonnes of CO_2 in industry and food processing (GCCSI, 2013). Selling CO_2 for local utilisation could reduce the total avoidance cost for FOAK project. However, the utilisation of CO_2 for local consumption does not reduce anthropogenic CO_2 emissions unless it can be demonstrated that the captured CO_2 replaces naturally–mined CO_2.

6.Conclusions and Recommendations for Further Research

The study makes a preliminary investigation of a hypothetical CCUS project on a steel plant in China and takes a modern steel plant in Zhanjiang, Guangdong as a model for technical and financial analyses. The preliminary findings of the model produce an abatement cost of **CNY 442.54/tCO_2 (USD 63.22/t CO_2)** at 12% discount rate. This translates to a cost of CNY730.19t (or USD 104.31/t CO_2) steel to fully decarbonise 2.56% of total steel manufactured in the plant, or CNY 18.74/t steel (USD 2.68/t), when the cost is spread over the whole production. Although the cost is moderate and there is great potential to minimise it through future learning and upscaling, the fluctuation business environment in the steel sector is unlikely to support the additional cost for such a project, without some form of external funding or significant internal benefits.

The net profit margin for Baowu Steel was less than 1% in 2015 and less than 3% in 2014 (Baowu Steel, 2016b). The profit margin improved in 2017 but the business environment for the steel sector is fluctuating.

The hypothetical model suggests three possible mechanisms to make an economically viable steel sector CCUS demonstration project at a 0.5 $MtCO_2$ scale:

- Provide the project with a carbon allowance price support at CNY 442.54/tCO_2 (USD 63.22/t CO_2) and above;
- Market 0.36 million tonne CO_2 production as ‘zero-carbon steel´ and add a minimum premium of CNY 730.19/t (USD 104.31/t) steel to high value-added market users; or
- Provide a minimum CNY 18.74/tonne (USD 2.68/tCO_2) steel tax refund for plants partial capturing at least 0.5 $MtCO_2$/year which produce more than 8.44 million tonnes of steel per year (at an assumption of 90% capacity factor shown in Table 5).

In the absence of any funding support, the report finds that a present value of CNY1.38 billion is required to finance the project. There is currently insufficient carbon pricing support from the ETS in Guangdong to support a price of CNY 442.54/tCO_2 (USD 63.22/t CO_2) for the demonstration project. The Guangdong ETS is still at an early stage and the short-term estimated price of CO_2 is about CNY 15/tCO_2 (USD 2/tCO_2) (CNE, 2017). As the National ETS was established in December 2017, the price of CO_2 is anticipated to increase and stabilise in the future, but it is still unlikely to reach CNY 442.54/tCO_2 (USD 63.22/t CO_2) in the foreseeable future. It is also unlikely for steel-makers to pass the additional cost for demonstrating CCUS through to consumers, unless a new business model or new policy regime is successfully developed.

The study considers a typical modern large steel plant, and as such one limitation to its findings is that they may not be applicable to other steel plants using different routes to steel making, in which case actual cost estimates could vary by up to +/– 40%. The study has not incorporated the benefits of increasing calorific value of blast furnace flue gas by enhancing the concentration of CO when CO_2 was reduced. The assumed transport and storage cost could be lower if the project shares infrastructure with other large stationary emission sources. There are other possible innovative processes and novel designs for CCUS in steel plants that are not investigated in the study, e.g.

utilising CO_2 to replace furnace blowing.

We suggest that this work should be followed by applied research that explores a combination of government and business innovation ideas which could provide the necessary financial support for demonstration projects. These might include marketing ‘zero–carbon´ or ‘low–carbon´ steel products to certain consumers, allocating government revenues from ETS auctions to supporting demonstration projects, and/or border carbon tax adjustments. Other innovative and potentially–disruptive capture technologies should also be investigated.

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