BHP Iron and Steel Sector CCS Project

Unlocking the Potential of CCS in China's Steel Sector

University of Edinburgh Business School
North China Electric Power University
UK-China (Guangdong) CCUS Centre

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About the Report

Over the past decade, carbon capture (utilisation) and storage (CC(U)S) has attracted increasing attention globally as an important technological option for climate change mitigation. As the largest greenhouse gas emitter in the world, China aims to drastically reduce its greenhouse gas emissions. This can be achieved either by replacing its usage of coal with energy supplies from renewable energy and nuclear power, or by installing demonstration-size followed by large-scale CC(U)S technologies. At present, and given the magnitude of coal dependence of the Chinese economy and the country's lack of alternative energy resources, it is likely that the Chinese will make substantial efforts to develop CC(U)S and continue relying on fossil-fuel-based generation before taking the more drastic step of phasing out coal altogether from its energy mix over the next few decades.

Emissions from the iron/steel industry is estimated at around 6.5% of overall global CO_2 emissions. As the steel production process features multiple substantial emission source points, any effective CC(U)S strategy in the sector needs to address the complex technological and economic issues posed by the sector. Furthermore, the application of CC(U)S to large-scale industrial facilities is reflected in the construction of large-scale demonstration plants as a bridge to full commercial deployment. The pace, orientation and scale of CC(U)S deployment will mainly depend on engineering advances and the evolution of comparative costs.

Research on CC(U)S is developing on two fronts: analysis of how societies are engaging with CC(U)S as a mitigation option, and exploration of basic technology developments for mitigation and how these align with the needs of the climate and environmental policy community. Cutting across both of these themes is a three-way focus on CC(U)S and the emergence of long-term climate and energy strategies; regulation, policy instruments and public acceptance; and the international politics of CC(U)S in developing countries.

This collaborative research project, funded by BHP, seeks to build on these developments by focusing in particular on the development and evaluation of innovative and sustainable technology and business solutions for CC(U)S in China's iron/steel sector, as China represents an important case study for the development and deployment of CC(U)S technologies. In June 2016, BHP and Peking University (PKU) announced a three-year US$7.4m research collaboration to unlock the potential of CC(U)S for steel production in China. The University of Edinburgh Business School (UEBS) jointed the project in November 2017 to support PKU Guanghua School of Management in the delivery of the business case/economics strand of the work programme. North China Electric Power University (NCEPU) and the UK-China Guangdong CCUS Centre (GDCCUSC) further joined the collaboration as an additional source of technical and academic expertise in CC(U)S. The two-year research project, ended November 2019, comprised of 13 working packages, delivering a feasibility study for a first-of-a-kind CO2 capture project in the steel sector. The summaries of the working packages are outlined in this report.

To request access to or a full copy of the working package(s), please email the project team at ccus@business-school.ed.ac.uk or visit us at http://financing-ccs.business-school.ed.ac.uk/

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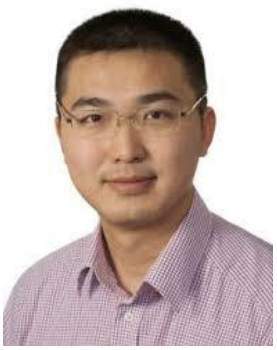

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		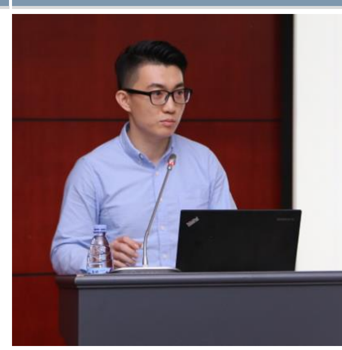
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Background

Carbon Capture and Storage (CCS) is a technology that capture carbon dioxide emissions from emitting sources such as power plants, steel plants and chemical plants, and permanently stores it underground preventing it from re-entering into the atmosphere. As of yet, there are no large-scale applications of the technology in China, with large-scale projects mainly existing in Norway, the United States and a few other countries. In 2010, a synthesis report by the United Nations Industrial Development Organisation (UNIDO) acknowledged that the application of CCS to energy-intensive industrial sectors was an area which had 'so far not been the focus and discussions and therefore much attention needs to be paid to the application of CCS to industrial sources if the full potential of CCS is to be unlocked'.[1]

The business case for and hence the value brought about by (early) deployment of CC(U)S has been highlighted in terms of the significant cost reductions that it brings about in overall decarbonisation and towards society over time. The International Energy Agency (IEA) estimates that the exclusion of CCS as a carbon mitigation tool for the power sector would increase costs of emissions mitigation by around US$2 trillion by 2050 – a 70% increase in mitigation costs if alternatives, including renewables, were instead employed over the time period.[2] The International Panel on Climate Change (IPCC) further reports that it would be 138% more expensive to decarbonise energy-intensive sectors without CC(U)S in the mix.[3]

From an industrial subsector's perspective, Element Energy pointed out that the likelihood of successful CC(U)S implementation is a factor of 1) whether the subsector produces pure CO_2, and 2) whether the subsector is subject to strong global competition – the relevance of the latter manifesting in whether costs could be ultimately passed on to consumers.[4] Moreover, unless complementary international environmental policies are in place, sectors producing global commodities are at risk of 'carbon leakage', i.e. where production from non-CCS retrofitted plants in a state may shift overseas, leading to failure in mitigating overall emissions from the sector globally. For these industries, some of which might not be able to absorb CC(U)S costs due to low profit margins, alternative financing mechanisms and incentives must be in place if no additional revenue is generated from capturing carbon (e.g. through product sales). In this project, the case for prioritising the implementation of CC(U)S technologies within the steel sector in particular over other industrial subsectors (e.g. cement, crackers, chemicals, ammonia and hydrogen, etc.) is here presented.

Second only to the cement sector, the steel sector is one of the largest industrial subsectors by emissions.[5] Although the cement sector features a much higher overall potential for carbon abatement – 3x higher – than its steel counterpart6, there is a varying impact that the implementation of carbon capture technology would have on production costs in both sectors. In the UK, for instance, while the levelised cost of abatement (LCoA) within both sectors falls in the range 50-60 £/tCO_2[6], the relative impact of implementing carbon capture technology on the production cost of cement is estimated to be significantly higher (+73%) than on that of steel (+19%).4 It will generally be more expensive to capture CO_2 from sectors where products exhibit low market prices and feature higher carbon intensity (e.g. cement), and vice versa. The combination of a high abatement potential with low impact on

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[1] De Coninck, H., Mikunda, T., Gielen, D., Nussbaumer, P., & Shchreck B. (2010). *Carbon Capture and Storage in Industrial Applications, Technology Synthesis Report*.

[2] International Energy Agency (IEA) (2016). *20 years of carbon capture and storage – Accelerating future development*.

[3] International Panel on Climate Change (IPCC) (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

[4] Element Energy (2018). *Industrial carbon capture business models: Report for the Department for Business, Energy and Industrial Strategy*

[5] World Steel Association (WSA) (2019). *Climate change mitigation – factsheet*.

[6] Element Energy (2014). *Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study*. DECC and BIS.

production cost makes a clear case, at least at present, for focusing on CC(U)S applications in the steel sector.

The European Ultra-Low CO_2 Steel-Making (ULCOS) consortium has been recently actively pushing for a deep cut in emissions from the steel industry, with an ultimate aim of reducing emissions by over 50% from today's best available steelmaking routes.[7] ULCOS has selected a range of effective technologies for further development, all of which when combined with CCS, can meet its reduction target in line with recent institutional developments.[8] The only other large-scale experience of the steel industry with CCS is the Emirates Steel Industry CCS Project. However, results from the latter are not indicative of the global status, and hence future prospects, of CCS development within the industry, as carbon is captured from a facility that utilises a Direct Reduced Iron (DRI) route to steelmaking – the least adopted route to steelmaking worldwide.[9]

Many of the processes involved in steelmaking are energy intensive, such as the extraction of iron in the blast furnace which requires high temperatures and coke for reduction. Expected emissions from each of the largest integrated iron/steel blast furnace plants are in the range of 5-8MtCO_2/yr.[10] There are likely to be multiple sources of CO_2 for each site, which increases the complexity of carbon capture implementation. Aside from the technical complexity involved, a myriad of other challenges facing industrial CCS have been widely acknowledged. This project's reports – summarised in the following sections – explore political, technical and economic challenges of implementing CC(U)S in the steel sector and how current CC(U)S business models in the power and industrial sectors have attempted to address these challenges.

[7] Steelmaking (2015). *Ultra-low carbon dioxide steelmaking: Consortium overview*.

[8] Todorut, A. V., Cirtina, D., & Cirtina, L. M. (2017). CO_2 abatement in the iron and steel industry-the case for carbon capture and storage (CCS). *Metalurgija*, *56*(1-2), pp. 259-261.

[9] Global CCS Institute (2016). *The Global Status of CCS. Special Report: Introducing Industrial Carbon Capture and Storage*. Melbourne, Australia.

[10] 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*, 1022-1039.

Our Findings at a Glance

Technologies for low-carbon steel production in China

We reviewed existing low-carbon technology options for the steel sector, excluding fuel switching and carbon capture and storage. This included compiling a comprehensive list of energy-efficient and carbon abatement technologies for different steelmaking processes, including data on their capital costs, operation and maintenance costs, energy-saving capacity, carbon abatement capacity and the current share of their applications in the steel industry. The carbon abatement costs and potentials for the selected technical options (total of 41) are based on a bottom-up 'Marginal Abatement Cost Curve (MACC)' model, shown in Figure 1. The Marginal Abatement Cost Curve assesses the cost-effectiveness of these technologies as well as their carbon abatement potentials in the Chinese steel industry. The MAC curve assumes a discount rate of 15% over the period 2010-2030.

Of the technological options assessed, 37 technologies were either technically- or economically-applicable to the Chinese steel industry, where the share of technologies applied exceeding 10% and where 5 technologies have already been fully-adopted by the steel industry in China:

- 29 technologies are fuel-saving options,
- 17 technologies are electricity-saving options, where
- 5 technologies can save **both fuel and electricity**; these include Continuous Casting, Thin Slab Casting, Annealing Line Heat Recovery, Preventative Maintenance, Energy Monitoring and Management Systems and Cogeneration.

The cumulative carbon dioxide emissions reduction from all selected abatement options was 668 $KgCO_2$/tce, or put differently, if all the aforementioned abatement options were adopted, they would result in a 43.2% reduction in emissions per tonne of steel produced from the current average levels in China. The results of the implementation rate in comparison with the marginal abatement costs are shown in Figure 2. For the purposes of our research, where the implementation rate of a technology exceeds 50%, the technology is assumed to be maturely promoted.

Seven technologies, including Eccentric Bottom Tapping, LT-PR of Converter Gas, Heat Recovery from the Sinter Cooler, Coal Moisture Control (CMC), Recovery of BOF Gas and Sensible Heat, Combined-cycle Power Plant (CCPP) and Continuous Annealing, have both a poor economic efficiency and a lower than 50% implementation rate which poses major obstacles to their universal promotion. Another 9 non-cost-effective technologies, including Preheating of Sinter Plant, Waste Heat Recovery in Hot Rolling and Casting, Furnaces Insulation, CDQ, Steam Use Reduction, Annealing Line Heat Recovery, and Flue Gas Monitoring and Control, on the other hand, have high implementation rates (i.e. over 50%), amongst which Preheating of Sintering Plant has been fully-adopted in the steel industry.

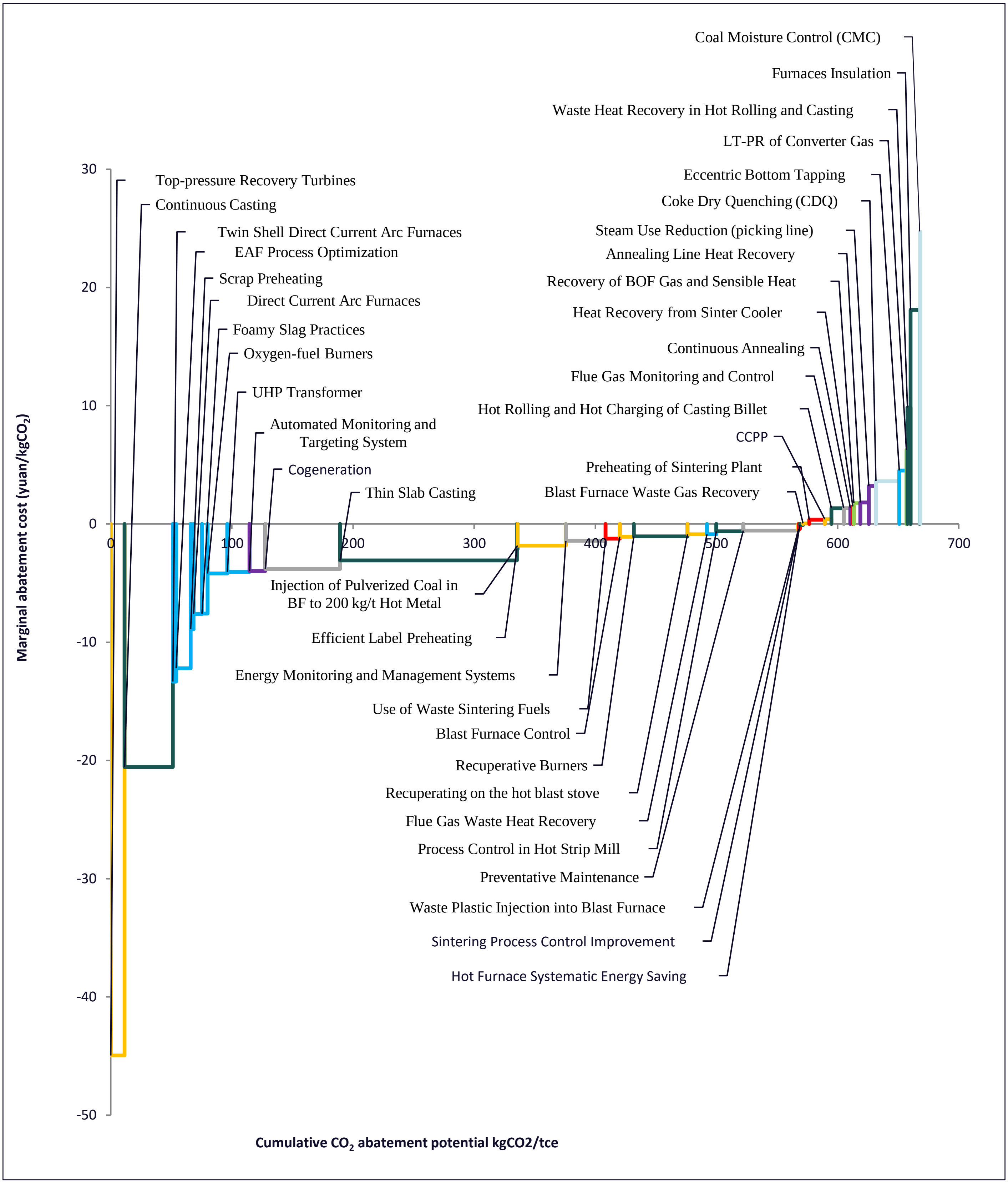

Figure 1. A Marginal Abatement cost curve (MACC) for the Chinese steel industry in China.

Nine technologies boast good economic efficiency albeit with a low implementation rate and are thus worthy of further promotion. In addition, 16 cost-effective technologies are being successfully promoted at scale, of which 4 technologies (Thin Slab Casting, Continuous Casting, Efficient Label Preheating and Use of Waste Sintering Fuels) have been thoroughly implemented. Most of these 16 technologies focus on saving energy in the production process, while only two technology options focus on waste energy savings. While this indicates that energy-saving measures for the steel production process in China are better promoted than waste energy saving technologies, some of the latter may feature high economic efficiency. One reason for this could be that past and existing national policies or measures on industries issued by Chinese Government had focused on process structure improvement and process optimisation. However, since the publication of the 11th Five Year Plan, the Government has realised its shortfalls in supporting waste energy recycling and reuse because of technical and economic limitations.

The cumulative carbon abatement potential of the 25 most cost-effective technologies is around 570 kgCO_2/tce, representing a 36.9% reduction in average CO_2 emissions per tonne of steel produced. While over half of the selected technologies promoted by the 12th Five Year Plan remain cost-ineffective, they could become cost-effective technologies given future increases in energy and carbon prices combined with targeted policy interventions in the Chinese steel industry.

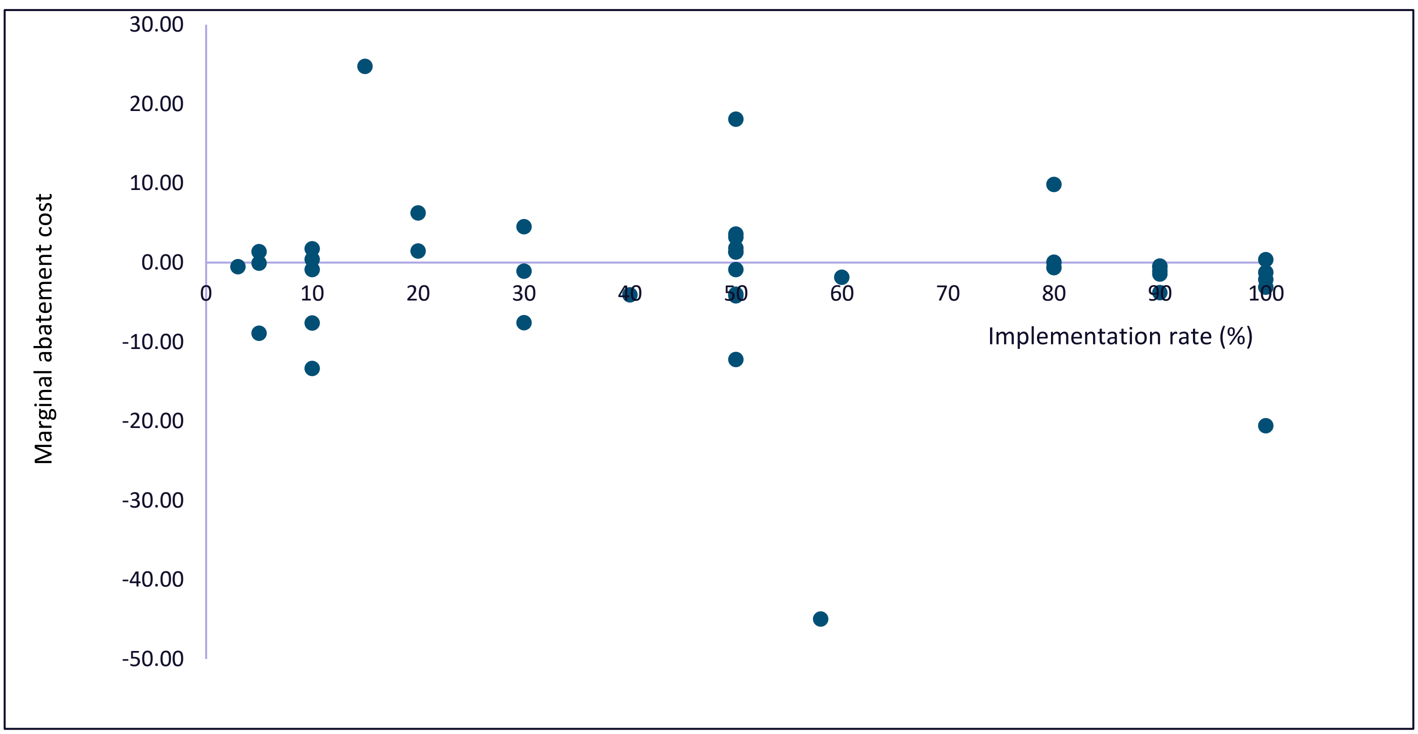

Figure 2. Technologies distribution by implementation rate and marginal abatement cost.

How to finance a large-scale CCUS demonstration project in the steel sector?

The steel sector emits approximately 6.5% of global anthropogenic greenhouse gas emissions and since 2012, China's steel plants have contributed approximately half of global steel production. Carbon Capture, Utilisation and Storage (CCUS) technology is a technically-viable way to decarbonise steel plants with minor modifications to existing processes. However, the technology is costly and there is a lack of sufficient incentives to finance CCUS in the steel sector at a large scale. Our work explores options for financing large-scale Carbon Capture, Utilisation and Storage demonstration projects in the Chinese steel sector.

Cost of CO_2 avoidance

Our research reviewed 17 large Chinese steel plants owned by three large steel groups, HBIS, Baowu Steel and Shougang Group, which produced a combined total of 128 million tonnes of crude steel in 2017, accounting for 15% and 7% of the Chinese and global steel production, respectively. Of the reviewed plants, 13 can be retrofitted with mature amine separation technologies to capture emissions from their blast furnaces (BF). The costs of capturing CO_2 at up to a 60% scale at major BF-Basic Oxygen Furnace (BF-BOF) steel plants were estimated using an experience curve model. We found that:

- 13 steel plants contribute 218 megatonne per annum (Mtpa) of carbon dioxide emissions while the other 4 plants (considered unlikely to be retrofittable) are estimated to emit 39 Mtpa;
- 89 Mtpa of CO_2 could be captured from these 13 steel plants, leading to permanent storage of an estimated 74 Mtpa of CO_2;
- The cost of CO_2 avoidance ranges from CNY 175 to CNY 435 per tonne of CO_2 (USD 25-62) for 7 plants which feature an opportunity for EOR within an accessible distance. The cost ranges from CNY 313 to CNY 585 per tonne of CO_2 (USD 45-84) for 13 plants with proximity to saline formation storage sites, equivalent to a weighted average cost of CNY356 per tonne of CO_2 (USD 51); and
- 74 million tonnes of carbon dioxide per annum (i.e. 34% of these plants' total emissions) could be avoided at a total cost of around CNY 26 billion (USD 3.7 billion). If EOR opportunities at 7 plants within a reasonable distance of onshore oil fields are exploited, the cost could be reduced by approximately 18% to CNY 21.7 billion (USD 3.1 billion).

Financial incentives for steel CCUS

We conducted a comprehensive review of existing economic incentives for CCUS projects internationally – with a focus on the *United States, Canada and Norway* – where a majority of the currently-operating and in-construction projects are located. We also reviewed current CCUS supporting policies and financial incentives for piloting large-scale CCUS applications in China. By building an experience curve model based on 13 Chinese representative retrofittable steel plants, we found that 74 million tonnes of carbon dioxide per annum (i.e. 34% of these plants' total emissions) could be avoided at a total cost of around CNY 26 billion (USD 3.7 billion) with a weighted average cost of CNY 356 (USD 51) per tonne of CO_2. Building on this, we identified potential economic incentives, including various financial sources such as R&D grants, support from international and multilateral donors, and steel firms' own capital, all of which are required to enable large-scale CCUS demonstration projects in the Chinese steel sector.

Reviewing the economic incentives which have driven investments in large-scale integrated CCUS projects (LSIPs) internationally and – in the absence of any LSIPs in China – investments in CCUS pilot projects in the country, we found that:

- Climate policies and carbon pricing are currently not the main drivers for LSIPs: 13 out of 17 operational projects in the world are predominantly driven by the benefits generated from the use of the captured carbon dioxide for enhanced oil recovery (EOR);
- Pilot projects in China are driven by a broader range of drivers, from EOR to technological learning and social responsibility;
- Although China has been piloting emissions trading schemes (ETS) with a national ETS having also been launched in 2017, the iron/steel sector is thus far not covered within the national ETS. It is also worth noting that current carbon prices (approximately CNY 3-60 per tonne CO_2) remain insufficient to incentivise deployment of LSIPs in China;
- The Chinese Government recognised the urgent need to develop and implement CCUS technology. Since 2011, four targeted policies for developing and implementing CCUS have been released by the Ministry of Science and Technology, along with more than 10 other relevant energy and climate change policies since 2006; and
- The Chinese Government has provided over CNY 3 billion (USD 430 million) to a number of CCUS research, development and demonstration projects through national science-technology plans including the National Basic Research Program (973 Program), the National High-Technology Program (863 Program) and the National Science and Technology Support Plan during the 11th Five-Year Plan (2006-2011). Only one project however targeted CCUS in the Chinese iron/steel sector.

Financial streams for steel CCUS

We also identified potential sources of finance for CCUS in China's steel sector and analysed their feasibility based on preliminary feedback from government and industry stakeholders. These sources are categorised into: private financing mechanisms, public financing mechanisms and market-based mechanisms. We concluded that:

- Implementing a cooperative technology strategy could potentially be a primary driver for developing large-scale CCUS projects. Most existing large Chinese steel companies have vertically-integrated structures which normally include an R&D and engineering design institute, thus the interests of these institutes may influence the corporate strategy of the steel giants in China;

- Utilising the CO2 captured from steel plants to increase domestic oil production not only provides additional economic benefits but also addresses Chinese concerns over oil dependency. Still, EOR cannot reliably be the only mechanism for incentivising a large-scale steel CCS plant considering uncertainties in demand and the relatively-higher capture costs for steel plants compared to capture from other processes such as gas processing or hydrogen production;
- Grants and loans by vendors are often targeted at large-scale projects and vendor-financing could be an important mechanism to support large-scale steel CO_2 capture demonstration projects;
- Financial support from the Chinese local governments (provincial or municipal) to CCUS is uncertain while international CCUS initiatives can provide a limited but significant source of funding for a large-scale CCUS demonstration in China, albeit with a possible long lead time;
- Carbon pricing through emissions trading is not likely to be a main driver for CCUS in China in the near future; and
- Combining different financial sources such as R&D grants, support from international and multilateral donors, and steel firms' own capital is required to enable large-scale CCUS demonstration projects in the steel sector in China.

Assessment of overall GHG emissions from a CCUS-fitted steel plant

The primary motivation for implementing carbon capture (utilisation) and storage technology is its role as a CO_2 abatement technology, and it is therefore highly important to assess the GHG emissions caused by the introduction of CC(U)S. One method of assessing lifecycle emissions, dubbed an ‘attributional’ lifecycle assessment, is a commonly used method for assessing the environmental impacts of technologies, however it does not necessarily capture the total system-wide change in emissions caused by a decision or intervention. A *consequential* GHG assessment method, on the other hand, aims to quantify the total system-wide change in emissions caused by an action or intervention. With a lack of existing consequential studies for CC(U)S technologies, this research provided an initial scoping study for the system-wide change in emissions caused by the implementation of carbon capture, utilisation and storage for a steel plant in China.

Step 1. Defining the action/intervention studied;

Step 2. Mapping the causal chain to identify the main GHG sources/sinks that change as a result of the action/intervention studied;

Step 3. Modelling the GHG emissions/removals in the baseline scenario (i.e. the scenario most likely to occur in the absence of the action/intervention);

Step 4. Modelling the GHG emissions/removals in the intervention scenario;

Step 5. Subtracting the intervention scenario emissions/removals from the baseline emissions/removals to calculate the change in emissions/removals caused by the action/intervention. This method is often referred to as the ‘baseline-and-credit’ method, and the overall structure of the method is illustrated in Figure 3.

The GHG Protocol’s *Policy and Action Standard*[1] was adopted as the main consequential GHG accounting methodology here, complemented by further guidance from the consequential LCA literature[1,1]. The *Policy and Action Standard* incorporates a transparent ‘baseline’ and ‘intervention’ scenario structure, and allows for the explicit modelling of GHG emissions/removals over time. It is also broadly consistent with the international project-level carbon accounting framework established under the United Nations Framework Convention on Climate Change, known as the Clean Development Mechanism (CDM). In brief, the *Policy and Action Standard* framework methodology involves the following steps:

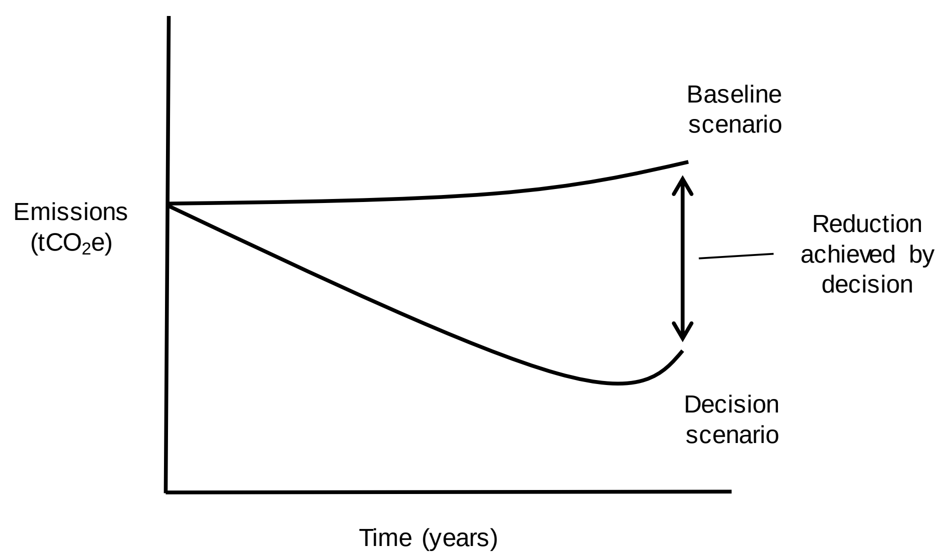

Figure 3. Illustration of the structure of the baseline-and-credit method.

The economics of CO_2 capture in a Chinese steel plant

Our work included a techno-economic analysis of a hypothetical first-of-its-kind (FOAK) CO_2 capture, transport and storage project at commercial scale in a modern Chinese steel plant. As the most common capture technology, we assumed the use of amine technology to capture the relatively-high concentration of CO_2 emissions in the production process. We used the Advanced System for Process Engineering (ASPEN) to define the technical configuration of the project, 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 a saline formation is estimated at around **CNY 442/tCO_2 (i.e. USD 63/tCO_2)**;
- Assuming that the project runs at 90% capacity (i.e. 0.45 MtCO_2/year) over 25 years, the project would capture a total of 11.25 MtCO_2. However, this is partially offset by emissions from increased energy consumption for running the CCS process, where net emissions would be reduced 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 (i.e. 2.6% of total steel production), the additional cost of production is around **CNY 730 – or USD 104 – per tonne of steel produced**. However, as this case study assumes that only a minor amount of CO_2 is captured, if the cost of CCS were spread over the plant's entire production output, the additional cost per tonne of total steel production becomes only around **CNY 19 (USD 2.7)/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 were considered a moderate risk investment and accordingly applies an 8% discount rate, the cost of CO_2 avoidance (i.e. the abatement cost) is reduced from around **CNY 442/tCO_2 (USD 63/t)** to **CNY 407/tCO_2 (USD 58/t)**. The assumed cost for T&S could be further lowered were the project to share infrastructure with other large stationary emission sources; and
- While additional costs of CCS in this case study are moderate and there is a further significant potential to reduce it through learning and upscaling, uncertainties in demand and supply of steel might deter the steel sector from bearing the additional costs for such projects, unless some form of external support or internal benefit is guaranteed.

We suggest that the next step of applied research investigates a combination of government and business innovation options that could provide the necessary financial support for FOAK demonstration projects.

The Emission Trading Scheme (ETS) as an incentive for CCS in the steel sector

An emissions trading scheme (ETS) is a market-based mechanism that can help achieve emission reduction targets in a cost-effective way. Our research explored three potential options for incentivising CCS in the Chinese steel sector via an emissions trading instrument:

- **A first option** is to **treat the CO_2 stored through CCS as 'not emitted' as far as ETS compliance is concerned,** so that covered CCS-fitted steel plants are able to achieve emission reductions at the time of performance, hence effectively generating revenue by selling spare allowances (or not having to purchase allowances) in the market;
- **A second option** takes a **project-based baseline-and-credit approach**, where entities covered by the national ETS can purchase offset credits from CCS-fitted steel plants and use those credits to meet their ETS compliance obligations; and
- **A third option** is to **use the revenue generated by the auctioning of allowances** to support CCS technology development and demonstration in the steel sector.

The first two options require a high price of allowances in the market, meaning that all cheaper abatement options would need to be fully exploited before steel sector CCS applications become the marginal price-setting option. However, as current credit price levels in China's national ETS are unlikely to support a CCS project in the iron/steel sector at present, further subsidies from other sources are necessary. The third option offers a promising approach to support early stage CCS projects, although detailed regulations and procedures would need to be established while relevant government finance departments would need to approve this method. The third option remains the most flexible option with the possibility of also being combined with the other two options. The third option, if implemented, could leverage much stronger support than options 1 or 2 in the short term. In the long run, once the carbon price becomes high enough, option 1 solely would suffice to support steel CCS projects. For options 1 and 2, suitable and robust **legal bases and comprehensive MRV systems** are required. For option 3, the funds from auctioning of allowances could be used to support early-stage CCS pilot or demonstration projects in the Chinese pilot regulatory framework.

CCUS business models

Carbon Capture, Utilisation and Storage (CCUS) has been recognised as a key technology in reducing carbon emissions, however its application has been mostly limited to the power sector, despite emissions from the non-power industrial sector accounting for around 30% of global anthropogenic CO_2 emissions. This report explores the challenges of and requirements for implementing CC(U)S in industrial sectors in general, and in the steel sector in particular, with the objective of identifying drivers of successful business models for the technology's commercialisation. This builds on a review of the current status of CC(U)S developments in the steel sector, and a comprehensive literature review of CC(U)S business models (both in the power and industrial sector), their constituting elements, and currently-established business models for large-scale CC(U)S projects operating in different policy environments. The analysis is further complemented by inputs collected through a survey questionnaire and targeted semi-structured interviews with global CCS experts and representatives from industry, academia, government and consultancies. The analysis reveals that:

- The revenue model is the most central element to building successful CC(U)S business models, around which the following elements are built: funding sources, capital & ownership structure and risk management/allocation;

- Survey responses and stakeholder consultations make it evident that the creation of a low-carbon/green steel product market is a promising mechanism to subsidise the additional costs of industrial CC(U)S, while the need to create clear risk-allocation systems along the full CC(U)S chain is especially highlighted;

- The introduction of CC(U)S as an enabling emission reducing technology within energy-intensive industries is mainly driven by consumer and shareholder pressures, pressing environmental standards, ethical resourcing, resource efficiency, and producer's drive to be first-movers in an emerging market;

- The value proposition of CC(U)S is assumed to be the eventual 'burial' of CO_2, and a CC(U)S value chain is described in six major steps: 1) carbon source characterisation, including a) data, such as its location, the CO_2 output flowrate, the CO_2 purity, and b) the type of output stream; 2) CO_2 capture process, where CO_2 is separated from the output stream using an appropriate technology based on the type of stream. This is the most extensively-explored component of the value chain, and capture technologies are widely classified within one of three categories: a) post-combustion, b) pre-combustion, or c) oxy-fuel combustion technologies. Capture technologies can also be classified based on CO_2 partial pressure, i.e. CO_2 concentration level in the flue gas stream (High: 30-70%, Medium: 35% and Low: 3-20%); 3) purification; 4) compression, which take place based on the final product or permanently stored in geological reservoirs;

- For any industrial CCS contract, the following five challenges are prioritised in the literature: 1) upfront capital investment for CO_2 capture, 2) recurring costs for capture plant operation, 3) technical performance risks, 4) benefits of reduced carbon emissions, and 5) a clear solution once carbon exits the boundary of the capture site;

- Four routes are identified to contractually organise projects:

    1) Within a single company (self-build) in a **vertically-integrated business model**, where the energy company must have a capture source and a storage/EOR site as well as means of transportation. Such a model limits entrants to the markets to specific enterprises that can invest in and operate an entire CCUS industry chain. However, a vertically-integrated model alleviates the risks associated with difficulties of cooperation among different sectors;
    2) Between different companies/**joint venture model**, where CO_2 is captured from a power plant owned by a third party, where CO_2 is then transported to a storage/EOR site, also owned by a third company. A typical ownership structure of a JV business model is 40% (power company), 30% (transport company), and 30% (oil field company);
    3) **CCS operator business model**, where the parties to this model include the CCS operator, the oil company, and power generation company, and the expenses in this model are split as follows: the CCS operator bears equipment and O&M costs of capture, transport and storage, while the oil field company bears equipment and O&M costs of EOR and expenses of CO2 purchasing; and
    4) **CCS transporter business model**, where the power company captures CO_2, covers equipment and O&M costs of capture and generates revenue through CO_2 sales and from trading carbon credits. The transport company covers equipment and O&M costs of transport and generates revenue via a fee charged for transporting CO_2, one which is pre-agreed upon among the stakeholders. Finally, the CO_2 user, i.e. the oil field company, covers equipment and O&M costs of EOR or storage and the purchase of CO_2, and generates revenue from a storage subsidy or sales of oil due to EOR.

Creating a Special Purpose Vehicle (SPV) for steel CCUS projects

Steel sector stakeholders are generally unfamiliar with opportunities and risks in CCS. This report reviews business models of current CCS projects and identifies potential challenges. By learning from the successful experiences of Japan CCS Ltd. and Norway Gassnova, and based on the current policy system and the energy industry structure in China, we explore an option of creating a special purpose vehicle (SPV) to kickoff CCS in the steel sector. The SPV has a higher degree of risk tolerance and is capable of attracting financial support from the public sector.

The business models of the case studies appraised make it evident that:

- Every current CCS project is either owned by the government or supported to a certain extent by the government, while the revenue model is key to creating value proposition and current projects remain largely reliant on revenue from Enhanced Oil Recovery (EOR).
- Unlike global large-scale CCS SPVs, such as Japan CCS and Norway's Gassnova which are both directly-funded by their respective governments, the Chinese Government will not own a SPV to kickoff steel CCS projects. Therefore, steel plant owners who intend to deploy a CCS project should establish a SPV independently.

Once a steel company makes a final investment decision on a CCS project, an SPV should be established which would own the assets of CO_2 capture facilities. All CCS-related businesses can then be transferred from the steel company to the SPV. As a legal entity and operational body of the CCS project, the SPV can:

1. Receive domestic financial support and policy support from the government;
2. Sign contracts with a construction company and supply company to ensure the successful construction of the project;
3. Achieve agreements with both international and national research institutes and universities to develop CCS technology R&D;
4. Contract with a transport company and oil company to deploy a full-chain CCS project, and
5. Attract CCS-related private companies to participate in the project.

Feasibility of a full-scale FOAK CCS-EOR project in the steel sector

The Blast Furnace - Basic Oxygen Furnace (BF-BOF) process is the most commonly used method for producing steel in China, and the blast furnace gas (BFG) remains the largest source with low concentration of CO_2 in the BF-BOF process. Carbon capture technology can be directly applied to purify the CO_2 in the BFG, providing a large-scale and direct emissions reduction option for the Chinese steel industry. Previous studies on the BFG focused almost solely on the development of technologies and on economic assessments of capture costs, while a lack of economic assessments and feasibility studies for a full-chain CCUS project and in particular within the Chinese context is evident. This hampered decision-making at the governmental and industry's levels, deterred the Chinese Government from formulating incentive policies to support CCS/CCUS project demonstrations in the steel industry, and in turn discouraged investors from promoting those projects.

In light of this, our research focused on undertaking an **economic assessment and feasibility study** of a full chain First-of-a-Kind (FOAK) 100ktpa steel sector CCS Enhanced Oil Recovery (CCS-EOR) project, taking the Chinese engineering capacity into consideration. By identifying low-cost capture, transportation and utilisation/storage options for a FOAK project and the development of a 100ktpa FOAK project in China, we found that:

- Capturing CO_2 from the BFG will result in a dual benefit of increasing the calorific value along with CO_2 internal use of nitrogen replacement and external sales for industrial utilisation and enhancing oil recovery;
- When considering environmental issues and system complexities associated with the chemical absorption technology, and that an existing Blast Furnace Top Gas Recovery Turbine Unit (TRT) could be used to recover high pressure energy from CO_2-free BFG, the membrane, PSA, and cryogenic methods and their integration technologies are technically feasible for a 100ktpa FOAK in China, where requirements of 90% capture rate and 99% CO_2 concentration and transportation to external utilisation and storage site are met;
- Considering the flexibility of internal and external uses of the captured CO_2 and the transferability of the FOAK facility to other steel plants with a shorter transportation distance to storage sites, the 100ktpa FOAK CCUS project is proposed with 50ktpa gaseous CO_2 of 95% concentration captured by a PSA-membrane unit for internal use, and 50ktpa liquid CO_2 of 99% concentration captured by a membrane-PSA and cryogenic distillation unit for external uses. The use of trucks is recommended to transport the liquefied CO_2 to either external industrial users who are at an average of 100km distance away, or to EOR users in Jiangsu province (distance of 250km); and
- The FOAK 100ktpa CCS-EOR project can be economically feasible when a subsidy of US$15/t for CO_2 storage is combined with funding support of over 80% of the capital investment, assuming a sale price of US$45/t and transportation distance of 250km.

Techno-economic analyses of CCUS in a Chinese steel plant

We carried out a systematic techno-economic analysis of the efficacy of different carbon capture technologies for major sources of carbon emissions in the steelmaking industry. CCUS remains the only technology that can deliver large-scale direct emission reductions in the industry, with less restructuring costs for established plant-specific energy systems. An investigation of CO_2 emission sources in an integrated steel plant and analysis of the features of the flue gas of lime kilns, coke oven and the associated power plant, as well as of the hot blast stove gas, blast furnace gas and converter furnace gas suggest that:

- The CO_2 content of the flue gas of lime kilns, hot blast stove gas, blast furnace gas and converter furnace gas is *higher* than that of the post-combustion flue gas generated from a typical coal-fired power plant;
- The blast furnace gas before the Top Pressure Recovery Turbine Unit has a higher pressure than atmospheric pressure;
- The flue gas from a hot blast stove normally has a higher temperature than other emission sources; and
- The discharge of Linz-Donawitz Gas (LDG) from the converter furnace is intermittent, while others are continuous or approximately continuous.

We explore the applicability of capture technologies, including absorption, adsorption, membrane, and cryogenic separation methods, in relation to the characteristics of the source gases, potential by-products and the intended use and purity requirements of the captured CO_2. We found that:

- The chemical absorption method is suitable for low-concentration gases while the pressure swing adsorption, membrane separation and cryogenic distillation methods are more suitable for high-concentration gases;
- The chemical absorption method is suitable for obtaining high purity CO_2 streams (>99.9% pure) than other methods, while the membrane and PSA separation methods and their integration technologies are suitable for producing storage-grade CO_2 streams (about 95% pure);
- The technical applicability and economic performance of capture technologies are affected by the by-product opportunities associated with the removal of CO_2; and
- The technical applicability and economic performance of capture technologies are also dependent on capture rates.

We recommend that **capturing CO_2 from the blast furnace gas, hot blast stove gas and lime kiln flue gas is prioritised in China's steel industry** due to: 1) the high concentration of CO_2 in those gas streams; 2) the fact that the calorific value of the BFG can be significantly improved by removal of CO_2; and 3) that nitrogen gas, which is in high demand by the steel industry, can be obtained as a co-product from the hot blast stove gas and lime kiln flue gas options.

Least-cost optimisation model of source-sink matching of a full-chain CCUS cluster

High costs of CCUS remain a major obstacle to its large-scale demonstration and deployment, however, optimal source-sink matching can reduce the cost of CCUS projects and enhance their economic feasibility. A full-chain CCUS cluster could subsequently be formed based on an optimal source-sink match of multiple capture sources with one or more storage sites. However, while the operation of these multiple capture and storage sources could ultimately be integrated through a pipeline network, building and commissioning of each CCUS project may take place over different time periods and at different scales. Therefore, it is encouraged to plan early for the development of a full-chain CCUS cluster in order to support the low-cost implementation of CCUS projects as a whole.

As steel production processes feature multiple potential CO_2 capture sites, our works seeks to achieve optimal matching between capture and storage sites through the use of an optimisation model. The model aims to minimise the total cost of a full-chain CCUS cluster, subject to a a variety of technical and economic constraints in the context of the steel industry. We further highlight and demonstrate the advantages and applicability of the model through a case study of a full-chain CCUS cluster for the steel sector in China's Yangtze River Delta region. Our findings are highlighted as follows:

- The optimisation model is based on the least-cost source-sink matching of a full-chain CCUS cluster system reflecting the dynamics of the scale, timing and siting of construction and operation of a full-chain CCUS project. The model can further provide robust bottom-up decision support for planning a full-chain CCUS cluster, based on the development and operation of CCUS projects in the steel industry;
- After analysing the implementation strategies of different source-sink matching schemes under different scenarios, we find that the model can address the impacts of steel-related technical and market policies on the source-sink matching of a full-chain CCUS cluster. The model can thus enable the planning of a CCUS cluster while accounting for the objectives and constraints specific to CCUS projects in the steel industry; and
- The optimisation model is based on capture from a variety of emission sources with multiple capture conditions at a steel plant, and can thus be used to support robust source-sink matching of a full-chain CCUS demonstration project and provide the basis for the planning of a full-chain CCUS cluster for the industry.

Cost estimation of a large-scale full-chain CCUS project in the steel industry

Carbon Capture, Utilisation and Storage (CCUS) is one of the few technologies that can help industry achieve large-scale CO_2 emission reductions. Currently, large investment and operating costs are recognised as the main obstacles to the implementation of large-scale CCUS projects. Cost estimates and economic assessments of CCUS projects can help decision-makers understand and identify the lowest cost pathways towards implementation. However, a CCUS system is complex, involving multiple interactions between capture, transportation, utilisation and storage activities. For the steel industry, CCUS involves not only multiple gas sources in the capture process, but also different capture technologies for different gas sources. In addition, a large number of technical and economic parameters associated with the CCUS system are subject to uncertainty. Conducting economic assessments and finding the lowest cost option requires a model that can identify the optimal choice for capture between gas sources within the system, taking account of the interactions between capture, transportation, utilisation and storage activities, and the uncertainty in parameters.

We combined a linear optimisation model with interval and mixed integer programming to develop a cost estimation model that reflects the interactions between various processes and the uncertainty in parameters of a full-chain CCUS system for the steel industry. The developed model can serve as a tool for economic assessment of the first large-scale CCUS demonstration project in the Chinese steel industry.

We then applied the model to a hypothetical case study of a large-scale integrated full-chain CCUS project involving capturing CO_2 from the blast furnace and the basic oxygen furnace (BF-BOF) process of a steel plant, and then transporting the CO_2 by pipeline to an oil field for EOR or for storage in depleted gas fields. The case study demonstrates that:

- The model can provide a least-cost estimate for the net cost of a CCUS system, taking into consideration the competitive characteristics of multiple gas sources in the steel industry and the interactions between activities within the full-chain CCUS system;
- The model can be used to estimate the CO_2 emissions reduction and storage efficiency of different CCUS projects, as well as the required investment resources and environmental benefits. This can help guide the planning of the optimal selection of internal gas sources for the steel industry, and in turn inform the economic assessment of CCUS projects based on cost minimisation;
- The model employs interval and mixed integer programming methods, which take into account the impact of uncertainty of parameters and variables on CCUS project economics, as well as the impact of the dynamic expansion over time of different parts of CCUS chains; and
- Scenario analyses indicate that the model can be used to appraise the impacts of economic, technical and policy factors on the cost of a full-chain CCUS system for the steel industry and support economic feasibility studies of specific CCUS projects.

Making steel plants CCS-ready

'CCS readiness' or 'CO_2 Capture Readiness' (CCR) is a design concept which requires 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. We conducted a hypothetical case study to develop a conceptual CCR design for a project which captures 0.5 million tonnes of CO_2 per year from the off-gas of a steel plant hot blast stove. Assuming a capture efficiency of 90%, capturing 70 tonnes of CO_2 per hour from the off-gas with a representative CO_2 concentration of 25%, and using a generic amine solvent (30 wt% MEA) – the most mature CO_2 capture technology to date – as a base-case scenario, we here outline the key technical and design requirements which ensure that a steel plant is *capture-ready*:

- The **geographic location** of the plants plays a major role in determining its suitability for CO_2 capture as this, after the addition of the capture plant, enables the captured CO_2 to be transported for geological storage and/or enhanced oil recovery (EOR);
- The chosen carbon capture technology must be **technically feasible** for retrofit;
- **Sufficient space must be available** on or near the site to accommodate carbon capture equipment in the future; and
- **Pre-investment**s which ease the capture retrofit and reduce plant down-time in the future retrofit must be considered.

Our GIS analysis showed that **51 out of 142 steel plants in China are within a 200km radius from a 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. Continuous updates to this review would be beneficial to track the progress of emerging capture technologies. Equally as important is ensuring that plants can accommodate any new technologies that may not be currently as competitive, so that they may be rapidly deployed when they become readily available. Our study results are summarised as follows:

- Our high-level capture plant design includes 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 power loads of 7,100kW. The steam recovered

from waste heat boilers would be fed to the steam turbine, while exhaust steam at low pressure from 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 MVR process heat recovery option);

- Potential pre-investment options are identified to ease future capture retrofit; and
- Our research provides an analytical approach and engineering principles to support the design of CCR steel plants. It may be adopted to develop a more rigorous conceptual CCS-readiness design of steel plants at the FEED stage.

Communication App - “Steel MAC”

Steel MAC is a knowledge sharing and open-access application for carbon emissions reduction options in the iron and steel sector, which provides steel companies with the option of customising the underlying processes within the tool based on their specific available technologies and process design.

Knowledge sharing can accelerate the deployment of low-carbon technologies in the iron and steel industry, but there are barriers brought about by differences in business models and languages that aim to reduce carbon emissions. The primary aim of this App is to enable an interactive platform for knowledge sharing of best practice approaches and technologies for emission reductions in the steel sector and their associated financing models. It provides diverse stakeholders such as business leaders, the public sector and policymakers with a systematic visualisation of the complex processes of steelmaking, including associated energy and emission intensities. Developers can acquire data and enhance the impact of BHP’s industrial carbon capture and storage project in China. In addition, the tool will support researchers in collecting data and communicating solutions for the decarbonisation of the steel sector. The Steel MAC tool brings together regional partners through organised workshops, network meetings, and informal dinners in the US, Canada, China and Australia. The ultimate goal of the Steel MAC is to serve as a ‘handy man’ for carbon dioxide emissions reduction in the steel sector.

The tool will help researchers identify and develop solutions for reducing carbon dioxide emissions in the steel sector by enhancing engagement between policymakers, industry participants and researchers. It will aid researchers in informally collecting advice from the public on a variety of technologies and/or project proposals. The tool will further serve as a bilingual platform to advance communication between English-speaking and Chinese communities where translation will be provided by the project partners.

Platform overview:

Technical Inputs:
a) Top-down choice of technologies used in each stage (i.e. sintering, coking, BF, BOF/EAF, casting)
b) Energy source for each stage
c) Electricity/fuel usage and intensity
d) Project location

Outputs:
1. Optimal technological development pathways
a) Energy-efficiency improvement
b) Waste heat recovery (WHR)
c) Carbon Capture and Storage (CCS)
d) Alternative fuels
2. CO2 abatement potentials - top 5 cheapest abatement options,
3. Costs - top 5 cheapest alternatives

列表 饼状图 点状图

选择	工艺	技术	节省燃料 (GJ/吨钢)	节省电力 (GJ/吨钢)	二氧化碳减排总量 (kgCO2/吨钢)	技术总投资成本 (元/吨钢)	年运营成本（元/吨钢)	节能成本现值 (元/吨钢)	节能收益现值 (元/吨钢)	CO2减排成本（元/吨CO2)
☐	烧结	烧结余热-生产蒸汽	0.32	0.32	57.6510	5.00	9.00	52.98	28.61	0.4228
☐	烧结	烧结余热-生产蒸汽	0.23	0.31	48.6430	5.00	6.00	35.43	27.12	0.1709
☐	烧结	烧结余热-生产蒸汽	0.50	0.50	90.0790	7.00	8.00	47.27	44.70	0.0285
☐	炼焦	煤调湿技术（CMC)	0.01	0.01	1.8020	4.00	4.00	23.67	0.89	12.6375
☐	高炉炼铁	顶燃式热风炉及热风炉换热器	0.02	0.02	3.6030	5.00	5.00	29.58	1.79	7.7145
☐	高炉炼铁	顶燃式热风炉及热风炉换热器	0.28	0.28	50.4440	5.00	5.00	29.58	25.03	0.0902

Stakeholder Engagement – Workshops

Enable Carbon Capture and Storage in China's Steel Sector

Station Master's Office, St Pancras Renaissance Hotel
27 July 2018

Our project investigated existing policy and financial instruments for CCUS (in China and globally), conducted a series of techno-economic analyses of CCUS and identified investment requirements and policy priorities. We focused on defining the most applicable policy and financial incentives for large-scale CCUS in China's steel sector, as well as understanding the technical needs to establish CCS-ready plants. Complementing our research were wide-ranging consultations with key stakeholders in industry, academia and government aimed at generating new thoughts and collect suggestions. On 27th July 2018, experts from the World Steel Association, Sheffield University and IEA Clean Coal Centre participated in an experts' workshop in London, and held an in-depth discussion on how to effectively enable CCS in China's iron and steel sector with Liang Xi and Lin Qianguo from the University of Edinburgh Business School.

Financing Carbon Capture and Storage in China

University of Edinburgh Business School
30 November 2019

China is the largest greenhouse gas emitter in the world. China has played a key role in driving rapid cost reductions of emerging energy technologies, such as onshore wind, solar, and coal-fired power plants. The estimated capital expenditure to build a new carbon capture and storage (CCS) project in China is estimated to only be around one fifth of that in OECD Europe. In this, on 30th November 2019, jointly with the UK CCS Research Centre, we held a workshop to explore the feasibility of developing and co-financing an open-access CCS project in China. Speakers from IEA GHG, UK International Climate Fund, and ADB, amongst others, shared their experiences of support policies for CCS activities. Panelists from the US

National Carbon Capture Center, International CCS Knowledge Centre, Scottish CCS, TCM, BP, and CNOOC held in-depth discussions on feasibility of an Open Access CCS project.

BHP Industry Carbon Capture and Storage Project Peer Review Workshop

Peking University Lakeview Hotel
29 May 2019

The aim of the workshop was to invite experts from the iron steel sector and experts in climate finance and green finance to provide detailed reviews on draft outputs from the BHP funded industry CCS research project in China. The project outputs reviewed by experts include:

- Low-carbon options in the iron and steel sector in China
- The techno-economic analysis of amine capture in the iron and steel sector
- The techno-economic analysis of membrane capture in the iron and steel sector
- Feasibility study of 100,000 tonne per annual scale steel CCS pilot with enhanced oil recovery
- Proposals for 500,000 tonne per annual commercial demonstration project
- CCS readiness in the iron and steel sector
- Policy options for CCS in the iron and steel sector
- Options to include steel CCS in the ETS in China
- Business models for incentivising CCS in the iron and streel sector

Iron and Steel CCUS Technology and Business Model

Suzhou Research Institute, North China Electric Power University
10 October 2019

Experts from the Ministry of Ecology and Environment, Baowu Steel Research Institute, Suzhou Environmental Protection Administration, Sinopec, GCCSI and NCSC, amongst others, attended a workshop in Suzhou, analysed the technological and policy development status of CCUS and discussed a potential CCUS roadmap in the iron and steel sector in China.