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Considerations for Making Steel Plants CCS-Ready in China

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ABSTRACT

The steel sector is one of the largest industrial sources of CO_2 emissions, contributing around 28% of the global industry sector's direct greenhouse gas emissions. One crucial technological option for decreasing emissions is carbon capture and storage (CCS). 'CCS readiness' or 'CO**2** Capture Readiness (CCSR)' is a design concept requiring minimal up-front investment in the present to maintain the potential for CCS retrofit in the future. As such, capture readiness avoids a carbon lock-in effect in the steel industry. This report outlines the essential technical and design requirements to ensure that a steel plant is capture-ready. Through a case study for a hypothetical CCSR project for capturing 0.5 million tonnes of CO_2 using ASPEN Plus, a conceptual design for meeting the requirements of a carbon capture-ready steel plant is developed. The space required for the capture unit at a 0.5 million tonnes level is estimated at around 4,000m^2. The comprehensive utilisation of waste heat would be advantageous for CCS applications in China's steel production. It is recommended that back-pressure steam turbines are used to drive multi-stage CO_2 compression instead of electric-motor-driven compressors with huge power loads of 7,100kW. Potential pre-investment options are identified to ease future capture retrofit.

Keywords: Carbon Capture and Storage, CCS, Carbon Capture Readiness, CCS Readiness

1. INTRODUCTION

The steel sector contributes approximately 5% of global anthropogenic greenhouse gas (GHG) emissions and, since 2012, China has accounted for over half of global steel production (World Steel Association, 2019). This renders it critical to explore ways to decarbonise the steel sector, particularly in China. On average, an integrated blast furnace steel plant produces approximately 2 tonnes of carbon dioxide (tCO_2) per tonne of crude steel (Chandler, 2013).

Some low-carbon technologies and plant upgrade options exist for steel plants. Ren et al. (2019) has formulated a marginal abatement cost curve (MACC) to show that the application of all possible negative marginal abatement cost (MAC) technologies (i.e. otherwise known as cost-saving or 'no regrets' technologies) could contribute to a reduction of more than 0.45 tCO_2 per tonne of crude steel produced. Compared with these negative MAC options, the immediate large-scale deployment of Carbon Capture, Utilisation and Storage (CCUS) technologies – a high positive cost technology – remains challenging.

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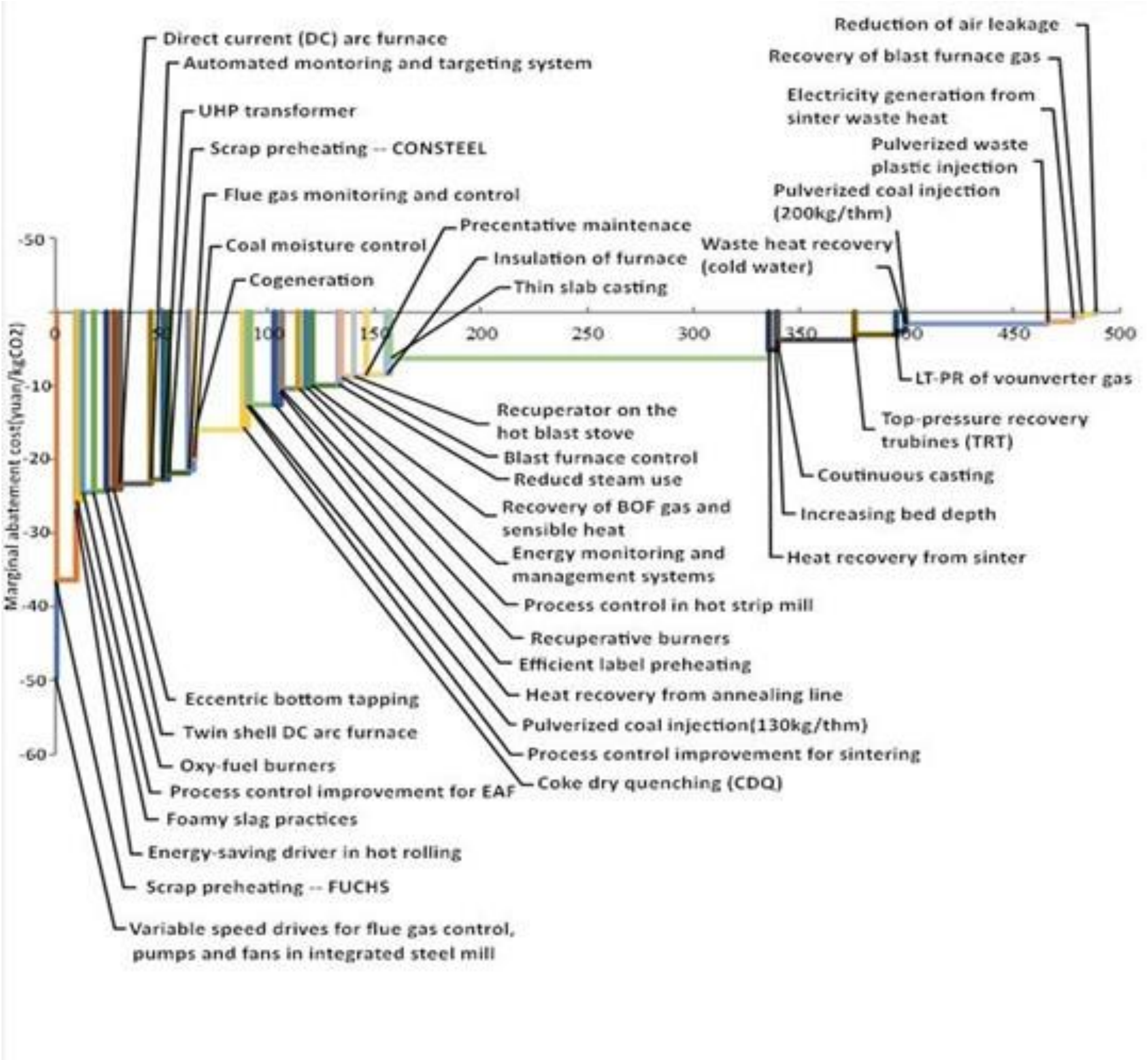

Fig 1 Marginal Abatement Cost Curve for Negative-Cost Emission Reduction Technologies in the Steel Sector (Ren et al., 2019)

However, even the deployment of all possible negative MAC technologies could only reduce CO_2 emissions in crude steel production by at most 25%. Over time, lower MAC opportunities will be exploited and will, therefore, no longer be available, and a lower emission performance standard or a higher carbon pricing scenario could be applicable in the distant future. While a steel plant built today could operate for 25 to 40 years, establishing carbon capture readiness (CCR & storage CCSR)[1] of steel plants could prove a low-cost technical approach to ensure plants could be retrofitted with CCS, to achieve deep cuts in greenhouse gas emissions in the future.

Therefore, this study discusses and outlines the technical and design requirements for CCS-ready steel plants, based on a hypothetical CCR project capturing 0.5 million tonnes of CO_2 in a steel plant in China. Detailed technical and design requirements are highlighted. The paper is organised as below: Section 2 reviews existing literature on CCS readiness, followed by a section illustrating the ASPEN Plus simulation model. Section 4 outlines the design considerations necessary for CCR. Based on the simulation results of the case study, requirements for capture readiness in steel plant design are listed in Section 5. Conclusions and suggestions are summarised in the last section.

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

2. LITERATURE REVIEW

Gibbins (2004) defined capture readiness as a '*plant designed to have CO_2 capture added at some time in the future with minimal impact on lifetime economic performance'*. Aside from technical design, a critical element in any capture readiness proposal is the need for physical space to accommodate the additional plant needed. The concept was further developed in subsequent years (IEA GHG, 2007, Gibbins et al., 2006). Wilson and Gibbins (2005) raised a broader concept of capture readiness in early 2005. Their suggestions included making new fossil fuel plants have capture facility retrofitted in the future, improving the technologies for converting capture-ready plants to capture CO_2, making sure additional technologies are also developed and developing proven- and socially acceptable CO_2 storage options.

In 2006, in a paper published by HM Treasury, 'capture readiness' was given a broad and simple explanation, where the key aim for a capture-ready plant was identified as needing to eventually be less expensive to retrofit the plant (HM Treasury, 2006). Bohm et al. (2007) defined capture readiness in that *'at some point in the future [the plant] could be retrofitted for carbon capture and sequestration and still be economical to operate'*. Moreover, capture readiness does not entail a specific plant design, but rather a spectrum of investments and design decisions that a plant owner would undertake during the design and construction of the plant.

In 2007, Scott Brockett from DG Environment within the European Commission suggested that all new coal-fired power generation plants built before 2020 must be capture-ready, and should be retrofitted soon after 2020 (Brockett, 2007). Later that year, a capture-readiness study by the Institution of Chemical Engineers (IChemE) warned that the '*lack of clear definition will hamper a low carbon economy*' (IChemE, 2007). However, the European Commission has chosen not to provide a detailed definition of the requirements for capture readiness. Intending to have capture facilities retrofitted on all coal plants beyond 2020, Commission officials have probably anticipated that firms will be penalised at a later date for any corners cut, and as such there would be no need for an explicit definition.

The Global CCS Institute (GCCSI) (2010) further developed the capture-readiness concept and promoted CCS readiness with more consideration of storage and transport readiness. Capture readiness was adopted by the UK Government in the revision of Electricity Act 1989. The concept was brought to China in 2003, and an option value concept was introduced by (Liang et al., 2009).

In summary, the concept of capture readiness has evolved from a narrow appreciation of the basic physical requirements needed for future retrofit of capture technologies, to a broader understanding of the necessity to anticipate and support a variety of future CCS-related needs.

Based on Liang et al.'s study, Jia et al. (2011) proposed a regional 'CCS Ready' strategy by simulating a dynamic top-down simulation model, and their results showed that financing 'CCS Ready' at regional planning level rather than only at the design stage of the individual plant (or project) is preferred since it reduces the overall cost of building integrated CCS systems.

The establishment of the China Low-carbon Energy Action Network (CLEAN) in 2010 indicates the first CCS network in China. In a three-year project Guangdong, China's First CCS Ready Province (GDCCSR), Zhou et al. (2013) demonstrated the benefits of adopting CCR by modelling a planned ultra-supercritical pulverised coal power plant in Guangdong. They believed these benefits would be enlarged if planned a regional CCR hub. The Asian Development Bank (ADB) (2014) made a recommendation for capture-ready design in 2016. The concept was first practically applied to China Resources Power's Units 3 & 4 of its Haifeng Project (GDCCUSC, 2014).

Studies on the application of the concept of CCS-Ready also spread in other countries other than China, Vatalis et al. (2014) also provide a preliminary assessment on how CCS-Ready technology can contribute to reducing CO_2 emissions from new fossil fuels coal-fired power plants and to describe what is its current status in the region of Western Macedonia in North-western Greece.

However, most existing studies focus on fossil fuels power plant, and there is only one study that focuses on steel plant by assessing the economic cost of Capture Readiness design in a generic steel plant in China (Ding et al., 2020). This work differs from previous studies by providing a compressive technical and design element on capture ready in steel plant planning.

3. METHODOLOGY

The study uses ASPEN (Advanced System for Process Engineering) software to perform process simulation, which is then used to develop a conceptual design for

CCR requirements. ASPEN is a proven chemical process simulation software that has been widely applied for R&D, design of large chemical systems, and production operation optimisation of the whole chemical plant. As a robust engineering design tool, ASPEN can provide engineering design parameters, chemicals consumption and utility requirements. The unit design and estimation of the operation cost can be performed based on the outcome of ASPEN simulation, as a starting point for further technical and economic analysis. The overall approach is illustrated in Figure 2.

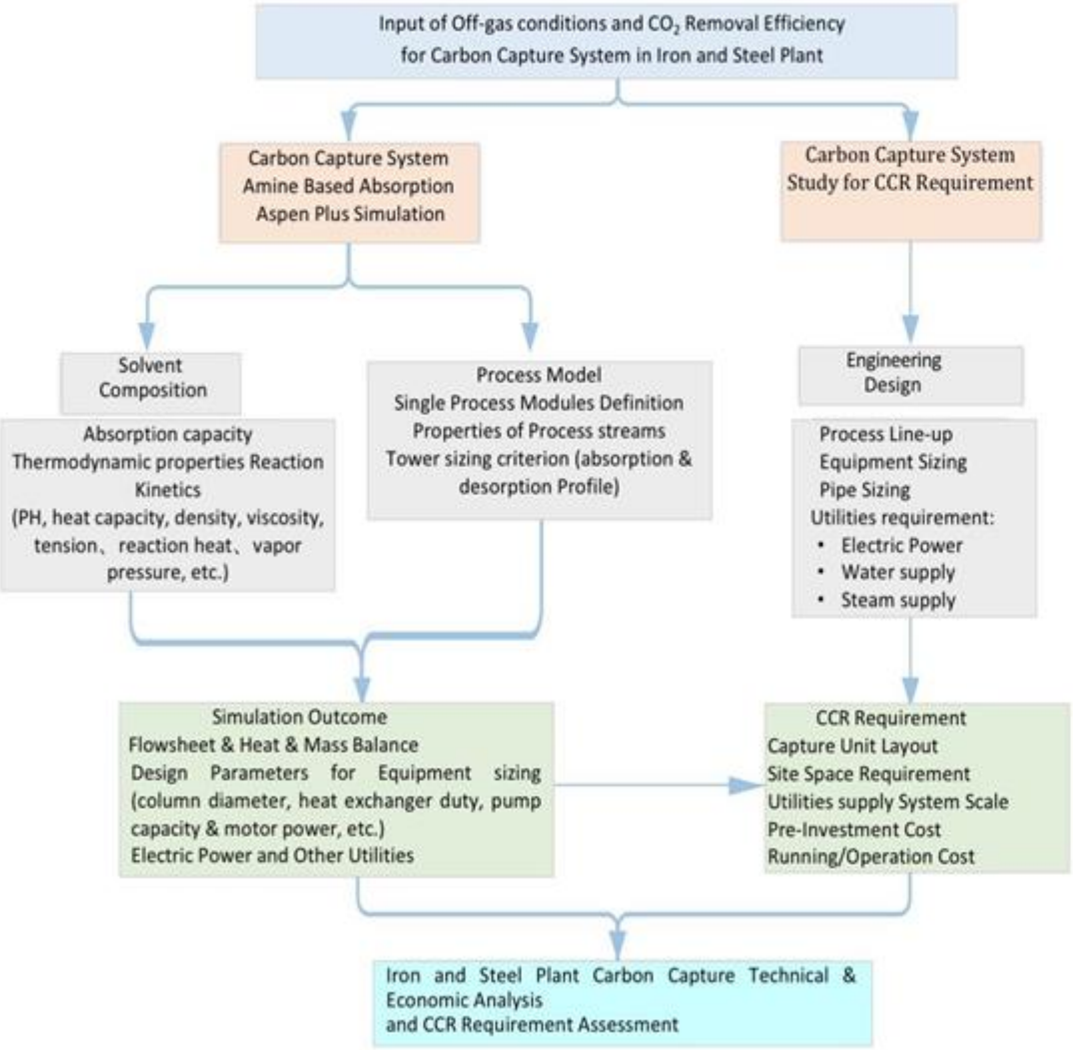

Fig 2 Methodology for the hypothetical capture readiness study

ASPEN Plus has imbedded a wide range of unit process modules, including mixing and separation, flash evaporation and heating/cooling, distillation, and reactor, pressure changer, pumps, compressors, pipes drop, etc. The models were developed using an equilibrium-based mass transfer approach.

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

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

$$CO_2 + 2H_2O \leftrightarrow HCO_3{}^- + H_3O^+ \qquad [2]$$

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

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

$$MEACOO^- + H_2O \leftrightarrow MEA + HCO_3{}^- \qquad [5]$$

The main purpose of the absorption simulation is to discharge of a 0.1-mole-fraction of CO_2 in the purified gas at the top of the absorber. By adjusting the parameters of the solution, including the composition of the solution, the absorption temperature, and solvent circulation rate, the expected carbon capture performance can be achieved. The regeneration simulation aims at reaching the desired regenerative degree of the rich solvent by adjusting the regeneration pressure, temperature and the heat load of the reboiler. The temperature of the tower top condenser is adjusted to achieve a CO_2 mole fraction >90% in the regenerated gas CO_2 emitted from the top of the tower to meet the requirements of further compression.

4. TECHNICAL AND DESIGN REQUIREMENTS FOR CCS-READY STEEL PLANTS

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

4.1 Locational considerations

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

- ***Proximity to CO_2 storage and/or other CO_2 user location***; this will enable ease of transport and reduction in transportation cost;
- ***Proximity to other existing or planned carbon capture facilities***; this could enable sharing of CO_2 infrastructure, leading to lower CO_2 transport costs. Furthermore, risks associated with public opposition to building new plants are generally lower for sites with an established industrial presence;
- ***Safe transportability*** and consideration of the potential for shared CO_2 pipelines, shared road transport facilities or ship transport for coastal sites; and
- ***Health and safety issues*** related to CO_2 transportation, handling of oxygen, amines, and CO_2-rich flue gas and CO_2 compression.

4.2 Carbon capture technology options for different flue gas streams

4.1.1 Iron/steel making processes and CO2 emission sources

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

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

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

Typical CO_2 emission sources of a steelmaking plant are illustrated in Figure 3, featuring CO_2 concentration ranges and emission indices per tonne of rolled coil steel production.

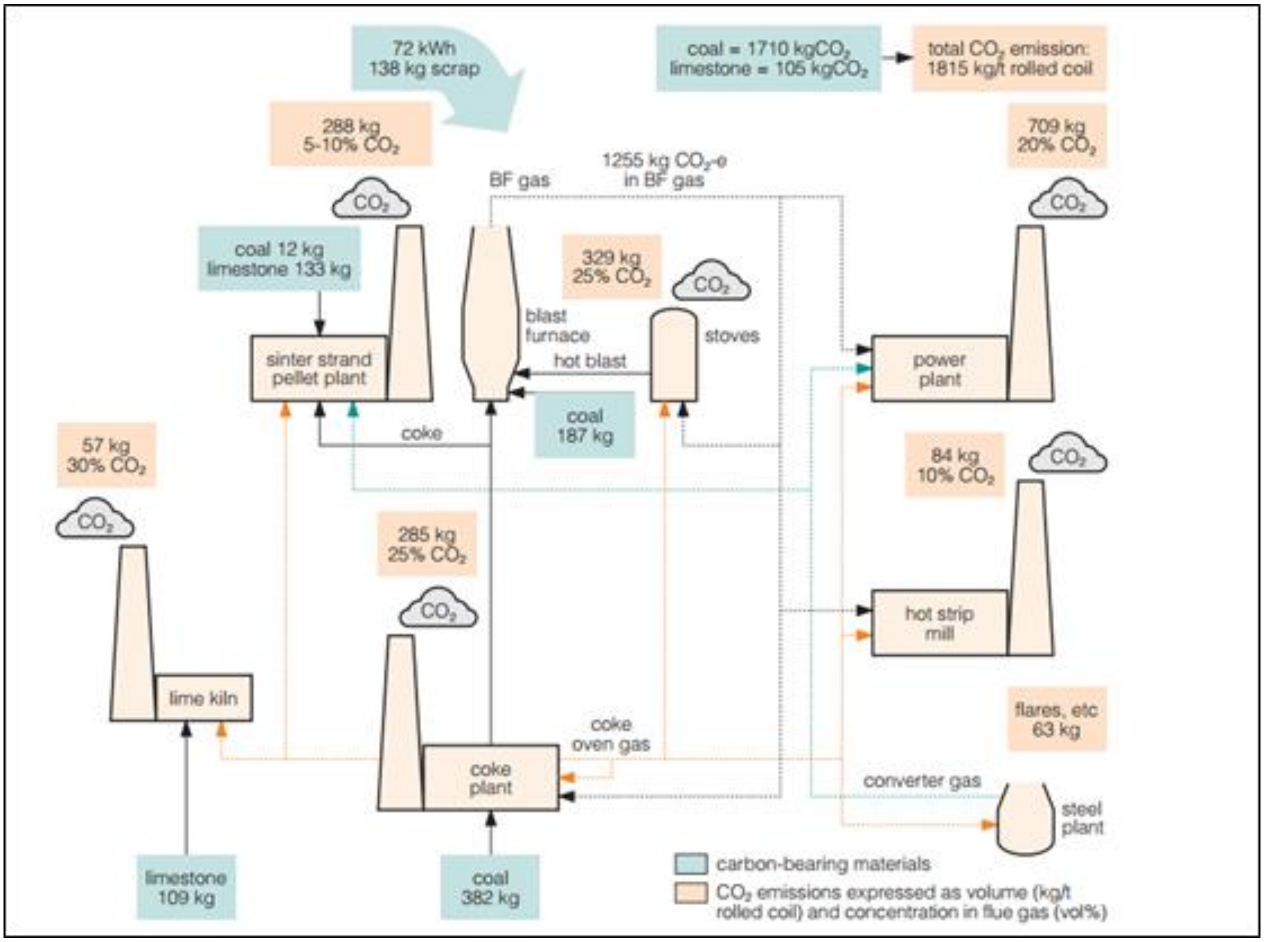

Fig 3 Typical CO2 emission sources of a steelmaking plant. Source: UNIDO (2010)

The CO$_2$ emission sources of Chinese iron and steel plants are identified according to the 'Guidelines to Ironmaking and Steelmaking Enterprises for Accounting Methods and Reporting of Greenhouse Gas Emissions in China', which was issued in 2013 by the Chinese National Development and Reform Commission (NRDC).

4.2.2. Carbon capture technology options

Pre-combustion and post-combustion CO$_2$ capture technologies have been significantly more researched than other approaches and are at a mature stage of development in the form of commercially available amine-based solvents. However, the large-scale implementation of a carbon capture project still faces various challenges, such as its high energy consumption, amine degradation, amine loss and other environmental issues, and the subsequent rise in the cost of capture. More emerging technologies are under development for solving these problems, including new solvents, physical and chemical solid sorbents, membranes, cryogenic processes, etc.

As per Section 2 above, capture readiness also involves ensuring that any additional technologies that may not be as competitive until CO$_2$ capture becomes the norm are also developed for rapid deployment when they will be needed. As such, the CO$_2$ capture technologies are screened from a diverse range of gas separation technologies based on their current capacity for capture, but other potential technologies are also included in the scope of concept design for capture readiness.

4.2.3. Essential requirements for a capture-ready plant

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

Following IEAGHG's (2007) definition of 'capture readiness', developers of capture-ready plants are responsible for ensuring that all known factors under their control and which could prevent the installation and operation of CO$_2$ capture are identified and eliminated. This includes:

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

The key issues for capture-ready plants are the inclusion of sufficient space and access for the additional facilities that would be required, and identification of reasonable route(s) to the storage of CO_2. Pre-investment in these essential capture ready features is expected to be relatively inexpensive. Further optional pre-investments could be made to reduce the cost and downtime for CO_2 capture retrofit.

4.2.4 Additional space for CCS in steel plants

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

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

4.2.5 Possible capture ready pre-investment options

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

- Flue gas desulphurisation (FGD) equipment
- $DeNO_X$ equipment
- Particulate removal unit (bag filter likely to be better for post-combustion capture than an electrostatic precipitator, due to improved aerosol removal)
- Steam sources and waste heat recovery options
- Water-steam condensate cycle
- Compressed air system
- Cooling water system
- Raw water pre-treatment plant
- Desalination plant
- Wastewater treatment plant
- Electrical equipment
- Chemical dosing systems and steam water analysis system
- Plant pipe racks
- Control and instrumentation
- Safety equipment
- Firefighting and fire protection system
- Plant infrastructure
- Steam turbine options for CO_2 compression

Some capture ready pre-investments are expected to have low costs and high potential benefits. However, there are two major reasons for not making primary capture ready pre-investments: economic discounting and uncertainty. Discounting is a well-established economic principle which means that economic resources in the future are worth less than at present. Also, due to uncertainty regarding future regulations and the value of carbon credits, it is uncertain if – or when –

capture would be required. It is also uncertain how capture technologies will develop in future. The costs of capture technologies are expected to decrease in the future due to 'learning by doing' and incremental technological improvements. If a plant is made capture ready for only one existing technology, it may become locked-in to a technology which becomes obsolete, and the pre-investment might become worthless. Capture-ready plants should thus be designed to accommodate anticipated future technological improvements, as far as reasonably possible. Nevertheless, it is difficult to predict future technology developments, and the risk of obsolescence is a major reason for not making substantial technology-specific pre-investments.

5. REQUIREMENTS FOR CAPTURE READINESS IN STEEL PLANT DESIGN

The conceptual design of the CO_2 capture and compression unit has been fully discussed earlier. These will be further used for developing the conceptual design of the CO_2 capture-ready steel plant. The capture readiness requirements discussed in this section are the 'essential' requirements which aim to ease the capture retrofit of steel plants with amine-scrubbing-technology-based CO_2 capture. The capture readiness features discussed require small additional investments and also have a low impact on plant performance whilst operating without capture.

5.1 Space requirements

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

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

- CO_2 capture equipment: according to the description in Section 5.4.3, the lot space reserved for the capture unit is estimated at ~4000m^2 (100m x 40m), which includes the pre-treatment unit, amine unit, operation control building, as well as CO_2 compression unit for CO_2 transportation and storage.
- The utility supply facilities are estimated at ~1200m^2 (30m x 40m).
- Hot stoves additions and modifications: the space for routing the flue gas duct between a pre-planned connection point at outlet of the induced draft (ID) fan on the hot stoves and the amine scrubber should be reserved, the duct diameter is approximate 1.5mx1.5m.
- Space reserved for a fan to overcome the pressure drop in a post-combustion capture absorber unit.
- Waste Heat Boiler (WHB) additions and modifications: there is a need to consider the space in WHB for routing large steam pipe (approx. 1m) to amine scrubber unit.
- Extension and addition of balance of plant systems to cater for the additional requirements of the capture equipment.
- Additional vehicle movement (amine transport etc.).
- Space allocation based on hazard and operability (HAZOP) management studies, considering storage and handling of amines and handling of CO_2.

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

5.2 Flue gas desulphurisation (FGD) unit

In recent years, the steel plant emission standards of particulate matter, sulphur dioxide and nitrogen oxides in China have been reduced from 40, 180 and 300mg/m^3 to stricter 20, 50 and 100mg/m^3 standards respectively. However, to minimise solvent degradation due to reaction with SO_2, the flue gas desulphurisation (FGD) unit has to be designed to reduce SO_X in the flue gas to very low levels, i.e. 10 to 30 mg/Nm^3 – even lower than the limits imposed by current environmental regulations.

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

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

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

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

5.3 *Water-steam-condensate cycle*

During the plant's operation with CO_2 capture, the steam from the WHB is required for the amine scrubbing plant reboiler (based on current amine-based solvents). The condensate system arrangement in a steel plant often consists of either 2x100% condensate pumps or 3x50% condensate pumps. This arrangement will lead to pump operation at non-optimum conditions after the capture retrofit. To enable condensate pumps to operate at optimum conditions before and after capture retrofit, pre-investment can be considered in using a 3x60% condensate pumps arrangement in the condensate system.

5.4 *Cooling water system*

As noted earlier, the cooling water of 12500t/h in total (assuming supply and return temperature of 32/40^{o}C) will be required for cooling equipment, the amount of cooling water may vary with local weather conditions, as well as with the water cooling system type. The additional cooling tower and additional cooling water piping requirements depend on the type of cooling water system envisaged (closed-loop cooling or once-through cooling with seawater/freshwater). The following pre-investments can be made to ease the CO_2 capture retrofit:

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

5.5 *Compressed air system*

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

5.6 *Raw water pre-treatment plant*

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

- Including estimated future additional raw water treatment plant capacity in sizing and selection of capture ready plant's raw water pre-treatment plant;
- Increasing the storage capacity of raw water tank to cater to future increase in storage requirements; and
- The make-up of the cooling water system may need to be taken into account for future increase in demand.

A raw water flowrate of 4m^3/h is estimated to meet the needs of water make-up in the off-gas pre-treatment system, but it does not include the raw water make-up of cooling water system.

5.7 Demineralisation/desalination plant

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

5.8 Wastewater treatment plant

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

5.9 Electrical

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

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

As discussed in Section 5.4.2, additional electrical loads of 9200kW in total are estimated to be required to operate the carbon capture and compression plant. If the motor power exceeds 250kW, the pumps equipped with high voltage motors would be selected. The power distribution system should consider two kinds: low and high voltage motors.

The application of waste heat recovery, as discussed in Section 5.4.4, could reduce the electric power consumption by approximately 7100kw by employing CO_2 compressors driven by back-pressure steam turbines. Pre-investments in this option would be considered for reserved flexibility in installation place and connection port to waste heat boiler to ease the CO_2 capture retrofit.

5.10 Chemical dosing systems and steam water analysis system

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

5.11 Plant pipe racks

Consideration of pre-investment in the areas listed below will ease the addition of new pipework required for the retrofit. Refer to Figure 7 for an illustration of the pipework required for capture retrofitting.

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

5.12 Control and instrumentation

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

- Designing the plant control system including the estimated additional I/Os required in the future; and

- Sizing the plant network (data highway) to handle (estimated) additional future signals.

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

5.13 Safety

No capture-ready pre-investment is foreseen.

5.14 Firefighting and fire protection system

No capture-ready pre-investment is foreseen.

5.15 Plant Infrastructure

No capture-ready pre-investment is foreseen for plant infrastructure, such as a public service facility.

5.16 Steam supply sources options

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

5.17 Laboratory analysis

- To support the CCS plant's activities, real-time laboratory solvent analysis is essential. The analysis item for amine process may be very different from steelmaking production. Special apparatus needs to be purchased for future CCS, and a laboratory must be built in the CCS section. It is however, an excellent option to share lab-equipment and laboratory rooms with the steel plant. Therefore, pre-investment is only expected for extra lab rooms reservation in the building design.

6. CONCLUSIONS

The study has reviewed the development course of the concept of 'capture readiness', put forward the capture readiness concept and promoted CCS readiness with more consideration of storage and transport readiness.

The study focuses on key elements of rendering steel plants CCS-ready in China. These are:

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

A preliminary GIS analysis indicated that 51 of 142 steel plants in China are within a 200km radius from a CO_2 storage site, opening the opportunity for further research on CO_2 storage for steel plants. A review of the essential requirements of various carbon capture technology for nine types of flue gas streams was undertaken to provide the basis for down selection, ascribable to complex flue gas contents and components from iron- and steelmaking production and relatively dispersed emission sources from different parts of the steel plant. An update to this review would be beneficial to track the progress of emerging capture technologies. Equally as important is ensuring that plants can accommodate any additional technologies that may not be as competitive until CO_2 capture becomes the norm, and that can be developed for rapid deployment when needed.

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

- A high-level basis of capture plant design was developed in this case study, including an indicative amine-based absorption process flow diagram showing major streams and the main equipment, Heat and Mass Balance, preliminary equipment size, utility consumption and other key engineering performance parameters;

- The space for the capture unit at 0.5 million tonnes level is estimated at ~4000m^2, which includes the pre-treatment unit, amine unit, operation control building, as well as CO$_2$ compression unit for CO$_2$ transportation and storage. The utility supply facilities are estimated at ~1200m^2;
- The comprehensive utilisation of waste heat would be advantageous for CCS applications in China's steel production. It is recommended that back-pressure steam turbines are used to drive multi-stage CO$_2$ compression instead of electric-motor-driven compressors with huge power loads of 7100kW. The steam recovered from waste heat boilers is fed to the steam turbine, exhaust steam at low pressure from the back-pressure turbine is then flown back to the reboilers of carbon capture unit to offer approx. 75% of amine regenerating heat source (without MVR process heat recovery option); and
- Potential pre-investment options are identified to ease future capture retrofit.

Furthermore, research & development (R&D) programmes related to CCS in the steel sector are reviewed to shed light on how its application may evolve in the future. Generally, this study provides the analytical approach and engineering principles in CCR plant design. It may be adopted to develop a more rigorous conceptual CCS-readiness design of steel plants at the FEED stage.

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