CHAPTER 11

CCS in the Iron and Steel Industry

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NB Books in the Issues in Environmental Science and Technology series do not have chapter numbers.
Section headings should follow the numbering: 1 Main section heading; 1.1 Sub section heading; 1.1.1
Abstract

The iron and steel industry has played a large part in global industrialization and now accounts for about 7% of global anthropogenic CO₂ emissions. As thorough progress has already been made in minimizing carbon footprint through process optimization efficiency increases, further emissions reductions could be achieved through carbon capture and sequestration (CCS). In an analysis of existing production capacity around the globe, most production facilities will likely continue to run in the coming decades, presenting an opportunity to install retrofit CCS technologies onto existing plants, like absorption and oxyfuel top gas recycling. More advanced CCS technologies such as hydrogen direct reduction and smelting reduction should be installed within the upcoming production plants being constructed. Current international initiatives like ULCOS and HYBRIT, evolving government policies and incentives, and pilot projects are helping to improve process economics and shedding light on industrial viability.
1 Introduction to Iron and Steel

Steel is an alloy of iron and carbon that is used in many building and process materials due to its low cost and high tensile strength.\(^1\) The production of steel can be broken up into two main categories: primary and secondary steel production. Primary steelmaking is the most common form of steelmaking, accounting for approximately 65% of steel production worldwide.\(^2\) Primary steelmaking follows two main processes: 1) blast furnace with basic oxygen furnace (BF/BOF) and 2) direct-reduced iron with the electric arc furnace (DRI/EAF). Of these two process pathways, the BF/BOF process currently dominates the iron and steel industry.

The BF/BOF process typically involves five parts: coking, iron ore agglomeration, blast furnace (BF), basic oxygen furnace (BOF), and manufacturing the final steel product (rolling, casting, etc.).\(^3\) An overview of the BF/BOF process for steelmaking is shown in Figure 1-1. The initial part of the process, coking, iron ore agglomeration, and sintering, refer to the preparation of raw materials for the steelmaking process. In the coke-making process, coke (carbon) is produced in the coke oven. During this process, the coal is carbonized at a high temperature to create the coke.\(^4\) In some cases, the coke oven gas (COG) is collected and utilized by the steel plant. This gas can be cleaned, leaving light hydrocarbons which can be used for subsequent heating of the oven or can be burned without cleaning for heat recovery or electricity generation.\(^4\) The second raw material preparation step is iron agglomeration, or iron ore preparation, where the iron ore fines (obtained from the mining process) are heated (1300-1480 °C) and melted into pellets to be fed into the BF.\(^5\) In sintering, the fine ore is heated, but not melted, with coke breeze and flux (typically limestone). This results in agglomeration into large granules that are sent to the BF.

Following raw material preparation, iron ore, sintered iron ore, coke, and limestone are fed into the top of the BF, where iron ore is reduced to what is known as “pig iron,” which is either an intermediate product in steel production or is sold as a product. In the BF, hot air is fed through the bottom and oxygen from the air
reacts with coke, forming reducing gases (namely CO and H\textsubscript{2}). These gases then react with iron ore, reducing the ore to iron by removing oxygen.\textsuperscript{4,5} Reactions in the BF occur in the following sequence:\textsuperscript{6,7}

Reaction of coke with oxygen and further reaction of coke with carbon dioxide:

\begin{align}
C + O_2 & \rightarrow CO_2 \\
CO_2 + C & \rightarrow 2CO
\end{align}

\text{(1.1)} \text{(1.2)}

Reduction of iron ore with carbon monoxide:

\begin{align}
Fe_2O_3 + 3CO & \rightarrow 2Fe + 3CO_2
\end{align}

\text{(1.3)}

Limestone decomposition to produce slag:

\begin{align}
CaCO_3 + \text{heat} & \rightarrow CaO + CO_2 \\
CaO + SiO_2 & \rightarrow CaSiO_3
\end{align}

\text{(1.4)} \text{(1.5)}

In the limestone decomposition step, limestone combines with iron ore impurities to produce a major byproduct from the steelmaking process known as steel slag. This byproduct is subsequently removed from the molten iron before it is fed into the BOF. The gas from the BF (containing large amounts of CO and CO\textsubscript{2}) is typically collected and combusted for heat before being vented to the atmosphere.\textsuperscript{4}

Molten iron from the BF is subsequently fed into the BOF. In this step, the pig iron and any recycled steel are fed into the BOF and reacted with pure oxygen. This process removes any other impurities in iron to produce molten steel and off-gas mainly composed of CO (which can also be used to recover heat from the process). From the BOF, molten steel can be processed through refining, casting, rolling, etc. to produce the final steel products.
The DRI/EAF process, shown in Figure 1-2, typically utilizes a similar process to the BF/BOF process. The main difference between the BF/BOF and DRI/EAF processes occurs during the reduction of iron ore to crude iron and the furnace used for steel production. In the DRI/EAF process, iron ore is directly reduced, using natural gas or, more often in India, using coal, resulting in higher process emissions. In this process, iron does not melt, but instead undergoes a direct reduction. Traditionally, the reduction reaction occurs in a CO environment, however recent technological developments consider an iron reduction in the presence of H₂ to reduce CO₂ emissions. The reaction occurring in the DRI reactor ultimately depends on the reducing agent used. The following expressions detail the reduction of iron with CO and H₂ as reducing gases:

**Reduction of iron with CO:**

\[
3\text{FeO}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \\
\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2 \\
\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2
\]

**Reduction of iron with H₂:**

\[
3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightarrow 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \\
\text{Fe}_3\text{O}_4 + \text{H}_2 \rightarrow 3\text{FeO} + \text{H}_2\text{O} \\
\text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O}
\]

There are many deviations in this process, mainly based around the type of reactor used, including: shaft
furnaces, rotary kilns, rotary hearth furnaces, and fluidized bed reactors. Additionally, many DRI/EAF plants will capture CO₂ from the DRI reactor to improve the recycle gas quality. After the iron is reduced in the DRI reactor, it is fed to the EAF. In addition to the DRI, limestone and recycled steel can also be added to the furnace depending on the steel grade and required furnace fluxes. Once the reactor is charged, the electrodes contact the metal and produce a high-temperature arc which initiates melting. The reactor is then fed with pure oxygen that can react with any impurities present in the raw materials. From the EAF, molten steel can be processed through refining, casting, rolling, etc. to produce the final steel products.

![Image: DRI/EAF Process for Steel Production]

In addition to the BF/BOF and DRI/EAF processes, there also exist open hearth furnaces (OHF) and induction furnaces (IF). OHFs makeup less than 2% of overall steel production and are considered an outdated technology. IFs also account for a small percentage of processes, but are illegal in many places throughout the world. Most of the world’s IFs are located in China and are quickly being updated to more energy-efficient technologies.

Secondary steel production mainly uses recycled steel or ‘scrap’ steel and accounts for approximately 32% of world-wide steel production. While there are multiple furnace configurations for primary steel production, secondary steel production typically uses electric arc furnaces (EAF). In an electric arc furnace,
the recycled steel is fed to the furnace where it is heated by means of an electric arc. This process melts the steel and removes impurities that may have been present in the feedstock. After the EAF, the steel is cooled and manufactured into the final product. The secondary steel production process using a BF and EAF are outlined in Figure 1-1 and above Figure 1-2 with the introduction of recycled steel.

While the secondary steelmaking process allows for significant increases in energy efficiency and overall emissions reduction, the existence of these steelmaking plants is limited by the amount of scrap steel available for recycling. Additionally, it is more common for countries such as the Unites States and Europe to have scrap steel available for recycling processes as opposed to countries like China where secondary steelmaking makes up a small percentage of overall steel production.

1.1 Process CO\textsubscript{2} Emissions

Approximately 24% of global CO\textsubscript{2} emissions (8.3 GtCO\textsubscript{2}) stem from the industrial sector\textsuperscript{11}. The iron and steel industry accounts for roughly 28% of industrial emissions, equating to 6.7% of global anthropogenic CO\textsubscript{2} emissions or 2.3 Gt CO\textsubscript{2}\textsuperscript{12}. Specifically within the iron and steel production process, CO\textsubscript{2} emissions originate from various process units, as shown in Figure 1-3.

Figure 1-3 and Table 1-1.

<table>
<thead>
<tr>
<th>Primary BF/BOF Facility</th>
<th>Secondary EAF Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8-2.2 tCO\textsubscript{2}/t crude steel\textsuperscript{13}</td>
<td>0.5-0.7 tCO\textsubscript{2}/t crude steel\textsuperscript{13}</td>
</tr>
</tbody>
</table>
Figure 1-3: GHG emission distribution within a) primary secondary EAF facility. Data adapted for average of facility emissions based on (a) 17 and (b) 87 US facilities; Not accounting for coke production where facility is standalone from BF/BOF facility\textsuperscript{14}

Table 1-1: Conditions and concentrations of emissions from major emitters in iron and steel production. Adapted\textsuperscript{15} All emissions occur at atmospheric pressure (101.3 kPa)

<table>
<thead>
<tr>
<th></th>
<th>Coke Oven</th>
<th>Sinter Plant</th>
<th>BF</th>
<th>BOF</th>
<th>EAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>tCO\textsubscript{2}/t-product\textsuperscript{14}</td>
<td>0.21-1.23</td>
<td>0.2</td>
<td>0.65</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>Primary Point of Emissions</td>
<td>Combustion Stack</td>
<td>Exhaust Stack</td>
<td>Stove Stack</td>
<td>BFG*</td>
<td>Exhaust Stack</td>
</tr>
<tr>
<td>T (°C)</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>375</td>
<td>300</td>
</tr>
<tr>
<td>Flow (m\textsuperscript{3}/s)</td>
<td>132</td>
<td>14</td>
<td>14</td>
<td>240</td>
<td>194</td>
</tr>
</tbody>
</table>

\textbf{Volumetric Composition (%):}

<table>
<thead>
<tr>
<th></th>
<th>CO\textsubscript{2}</th>
<th>CO</th>
<th>N\textsubscript{2}</th>
<th>H\textsubbox{2}O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>0</td>
<td>67</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
<td>70</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>0</td>
<td>68</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>20</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>70</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0</td>
<td>56</td>
<td>1</td>
</tr>
</tbody>
</table>

For the integrated BF/BOF process, the majority of emissions originate from the BF. This presents two options for point sources highly suitable for CCS. The majority of emissions associated with the BF are released by the hot blast stoves, where BF gas (BFG) is cleaned, cooled, and burnt as a fuel in the hot blast stoves after leaving the BF. Emissions could be captured post-combustion directly from the BF, with the benefit of upgrading gas quality, or from the stoves to avoid causing large changes with the facility. The BOF contributes less to emissions than the BF, and BOF gas (BOFG) highly varies in temperature and composition. The BOFG can be very dirty, causing many plants to flare it\textsuperscript{5} However, it is released to the
atmosphere at a rather high flow rate and presents another possible point source for CCS. Emissions from the EAF, which are only 10% of the facility’s emissions, are emitted from a baghouse after removal of particulate matter. Emissions from the baghouse are highly concentrated in CO₂ making this an additional target for CCS.

In both the BF/BOF and DRI/EAF processes, a high percentage of GHG emissions result from miscellaneous combustion units, which include process heaters, boilers, flares, dryout heaters, and several furnace types. However, the emission intensity for combustion units within BF/BOF facilities is much higher, as they burn a combination of natural gas, COG, BF gas (BFG), and other fuels, while those within EAF facilities solely burn natural gas (Table 1-2). These units are scattered throughout the plant without a common emission point source. Therefore, installation of small CCS modules for each unit would be cost prohibitive due to economies of scale.

Electricity indirectly accounts for a significant portion of emissions in both process routes. Several small units, like roller mills for product finishing, require electricity in both steelmaking routes. Electrodes within the EAF are powered by electricity, accounting for the majority of emissions in this route. Since most iron and steel plants source their electricity from the grid, emissions due to electricity are typically out of the facility’s control in terms of CCS. As of 2012, only 8 of the 104 US steel plants generated their own electricity with a combined capacity of 1087 MW. This is in addition to 5 coke plants with a combined 363 MW capacity. It is important to keep in mind that Figure 1-3 is based on US data, and the share of emissions from electricity would be higher for countries like...
China, who burn more coal, and lower for countries like Germany, who have employed more renewable energy into their grid.

Table 1-2: Energetic Data for Relevant Gases in Steel Production\textsuperscript{16-19}

<table>
<thead>
<tr>
<th></th>
<th>Energy Density kWh/m\textsuperscript{3}</th>
<th>Emission Intensity (kgCO\textsubscript{2}/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>10.62</td>
<td>0.20</td>
</tr>
<tr>
<td>COG</td>
<td>6.20</td>
<td>0.14</td>
</tr>
<tr>
<td>BFG</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td>BOFG</td>
<td>2.64</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The emissions from iron and steel production are not evenly distributed across the globe. Table 1-3 shows the top 6 steel producers in the world. As shown, China holds the vast majority of steel production. However, by examining the emission intensity of processes in different regions in Figure 1-4, a more complete picture is painted of global emissions from steel production.

Table 1-3: Top Global Steel Producers, 2017\textsuperscript{20}

<table>
<thead>
<tr>
<th>Country</th>
<th>Mt Steel</th>
<th>Global Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>831.7</td>
<td>49%</td>
</tr>
<tr>
<td>Japan</td>
<td>104.7</td>
<td>6%</td>
</tr>
<tr>
<td>India</td>
<td>101.4</td>
<td>6%</td>
</tr>
<tr>
<td>United States</td>
<td>81.6</td>
<td>5%</td>
</tr>
<tr>
<td>Russia</td>
<td>71.3</td>
<td>4%</td>
</tr>
<tr>
<td>South Korea</td>
<td>71.0</td>
<td>4%</td>
</tr>
</tbody>
</table>
A few interesting interpretations can be drawn from Figure 1-4. About 75% of steel is produced through the BF/BOF process worldwide, indicating that capture of CO$_2$ from the BF would have a significant impact on the industry’s carbon footprint. Additionally, the advantage of EAF use is clear as the countries with more EAF installations all have fewer emissions relative to steel production. Though China dominates the market in steel production, they have primarily invested in BF/BOF rather than EAF facilities, further increasing the already high magnitude of carbon emissions from their iron/steel industry. Finally, the countries within CIS have worked to phase out OHF facilities, but those that are still in operation significantly increase the region’s emissions.

### 1.2 Iron and Steel Plant Lifetimes

A standard estimate for the service life of a steel production equipment is 15-20 years. However, based on data from Steel Institute VDEh illustrated in Figure 1-5, many of the currently functional iron and steel plants around the world have lasted far longer. The age data, comprising 1994 of the 2437 functional production plants, show an average age for BF/BOF and EAF plants of 25-30 years. While the median age for such plants is closer to the standard estimate of 20 years, several plants still exist with initial start-up dates from more than 45 years ago.
From Figure 1-5, aside from some earlier-built BF s which predate oxygen steelmaking (popularized in the 1960s), the more modern BF plants correlate with start-up of BOF plants. The OHF plants are well on their way to full closure, with only 9 still remaining within the CIS region. The median and average age of EAF plants is almost equivalent to BF/BOF, but the more recent inception of their installation results in a more well-distributed box plot.

1.2.1 Expected Growth

Global steel production grew almost 5% per year in the period of 2004-2013, largely due to the accelerated growth of China’s economy. Although demand peaked in 2013, steel production capacity continued to expand for 3 more years, resulting in a high excess of capacity relative to demand. The utilization rate of installed steel production capacity has been 70-75% since 2013. While some expansion is planned around the globe, especially in developing countries like India with high demand and insufficient infrastructure, much work is being done to shrink the gap between demand and capacity.\(^9\)
With moderate (at best) demand growth in the coming years, companies are either closing facilities or altering business models to increase the overall capacity utilization rate. In China, where the capacity more than doubled between 2006 and 2015, the shutdown of illegal induction furnaces and uneconomic BF/BOF facilities has brought a slight decline in capacity. Some companies worldwide are turning to the pursuit of new high-value products in various sectors. The automotive sector’s shift to lightweight materials has created demand for high-strength steel substitutes; the energy sector’s increase in renewables has given way for the development of steel products for photovoltaic mounting systems.

Overall, the steel industry is expected to have several volatile years; demand is slowly picking up but will not approach the enormous levels of the past, instead equating to about 0.8% growth per year. However, while global growth in facilities will be nearly net-neutral, countries like India and Iran have several projects in the works. The Indian government reported the need to reach 300 Mt production levels by 2030 from 125 Mt in 2017; Iran is the biggest player in the Middle East’s growth, with aspirations to increase capacity to 55 Mt by 2025 from 28 Mt in 2016.

### 1.2.2 Committed Emissions

It is useful to evaluate the amount of committed emissions from iron and steel production plants in the coming decades, i.e., emissions from plants that are unlikely to halt production in the foreseeable future. Due to the lack of specific data on age of plants at closure and the varying age of currently functional plants, it is difficult to accurately predict how soon plants will close. The third quartile of functional BF plants is the year 1972, or 47 years old in 2019. Choosing 1972 as a conservative cut-off for plants still functional in 2030 results in the shutting down of 284 BF, BOF, and EAF plants. An additional assumption is made that all currently remaining OHF plants will close prior to 2030. Finally, it is assumed that all plants continue production with business as usual, without the addition of the CCS retrofit that could significantly further reduce committed emissions, which is to be discussed later. This results in 1.75 GtCO₂ of annual committed emissions from
the remaining functional BF/BOF and EAF plants in 2030. The closure would result in a total decrease in steelmaking capacity of 239 Mt crude steel, or 14% of current capacity recorded by VDEh. Table 1-4 shows estimates for committed emissions for 2040 and 2050 based on the same criteria (e.g., in 2040 all functional plants will have a start-up date after 1982, etc.).

Table 1-4: Committed Emissions from Currently Functional Iron and Steel Production Plants

data from Steel Institute VDEh;
(based on closure of plants older than 58 years at years 2030-2050 and closure of all OHF plants by year 2030; emission intensities assumed: BF/BOF=1.6, EAF(scrap)=0.4, EAF(DRI)=1.75 tCO₂/t crude steel)

<table>
<thead>
<tr>
<th>Year</th>
<th>BF/BOF Capacity (Mt crude steel)</th>
<th>EAF Capacity (Mt crude steel)</th>
<th>Committed Emissions (GtCO₂)</th>
<th>Capacity Reduction</th>
<th>Emission Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>1089</td>
<td>592</td>
<td>2.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2030</td>
<td>872</td>
<td>581</td>
<td>1.75</td>
<td>14%</td>
<td>21%</td>
</tr>
<tr>
<td>2040</td>
<td>702</td>
<td>532</td>
<td>1.12</td>
<td>27%</td>
<td>49%</td>
</tr>
<tr>
<td>2050</td>
<td>604</td>
<td>452</td>
<td>0.97</td>
<td>38%</td>
<td>57%</td>
</tr>
</tbody>
</table>

Closure of the plants according to the criteria estimated here results in a 21% decrease in CO₂ emissions within the next decade. The reduction in emissions compounds even further in the following decades, especially in 2040, where the sharp increase in reductions is due to a larger magnitude of EAF plants affected by the estimated closures.

Emission values in Table 1-4 only correspond to the emissions society has committed to with the current technology in place. Mabashi\textsuperscript{26} reported in 2018 that by 2020, new facilities could account for an additional 90 Mt of crude steel production, equating to 40-160 MtCO₂ depending on technology used (without CCS deployment). Further emissions will likely continue to ensue from the production capacity increases in developing countries, especially those aspired by India.

With the currently low capacity utilization rate (75%) and the rather low forecast of demand growth (0.4%), a drop of 14% production capacity by 2030 without large compensation by new instalments is not unreasonable. While the resultant estimated decrease in CO₂ emissions of 21% is a good start, the UN states that global CO₂ emissions should be reduced by at least 25% by 2030 to avoid warming of 2 °C.\textsuperscript{27} For the
iron and steel industry to meet the 25% reduction mark, or possibly surpass to aid in emission reductions from other industries and sectors, further measures to reduce emissions, like CCS must be deployed.

1.3 Energy Efficiency

The steel industry has been making strides to increase energy efficiency and decrease CO₂ emissions for years. With new initiatives, technologies have been developed that push BF technology towards its theoretical limit of energy efficiency. New initiatives focusing on process intensification and heat integration have decreased the overall energy consumption in the iron and steelmaking industry. Technological changes such as dry coke quenching, top pressure recovery turbines, and COG utilization technologies work to reduce fossil fuel consumption and recover wasted process energy. While increased process energy efficiency remains a primary goal to reduce overall carbon footprint, operating costs, and align with corporate sustainability initiatives, the overall emissions reductions become smaller as the process converges with benchmark performance. Hence, this chapter will focus on emissions reductions through the utilization and implementation of carbon capture technologies, as well as recently developed CO₂ emission reduction technologies for the iron and steel industry.

2 Post-Combustion Capture – Retrofit Technologies

Due to the longer lifetimes of steelmaking plants, the ability to retrofit existing steelmaking plants with carbon capture and sequestration (CCS) technology is increasingly important in decreasing the industry’s CO₂ emissions. Although emission points from the steelmaking process are numerous and diffuse, BF operation provides an opportunity to capture a large amount of the process CO₂ without having to alter the fundamental steelmaking process.

Carbon capture technologies work to separate concentrated CO₂ from an emissions source for sequestration or utilization. Based on this, carbon capture technologies for this industry can typically be divided into four categories: absorption (physical or chemical), adsorption, membrane separations, and mineral carbonation.
Each of these technologies and their application to the iron and steel industry will be discussed in more detail in the following sections.

In addition to the type of capture technology employed at iron and steel plants, there is another important consideration: the implementation of a water-gas shift reaction. The water gas shift describes the reaction of CO with steam to produce CO$_2$ and H$_2$ according to the following reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad (2.1)$$

Since BFG typically contains about 20% CO$_2$ and 23% CO, it is possible to first perform a water-gas shift reaction to convert some of the CO to CO$_2$. This increases the concentration of CO$_2$ in the exiting stream, thereby decreasing the work required to capture the CO$_2$. The addition of the water-gas shift reaction can make different CCS techniques advantageous that do not exhibit the same advantage at lower CO$_2$ concentrations. Current initiatives focus on developing effective water-gas shift technology paired with CCS technologies. This includes the Stepwise project’s sorption-enhanced water-gas shift (SEWGS) technology. The SEWGS technology and pilot scale initiatives are discussed further in Section 4.5.

### 2.1 Absorption

Absorption is the most mature and industrialized of CCS technologies. In this process, CO$_2$ is separated using a chemical or physical solvent. Both solvent types are industrially available and offer unique advantages and challenges for the iron and steel industry.

#### 2.1.1 Chemical Absorption

Chemical absorption refers to the process by which CO$_2$ from a waste gas stream is separated through the selective formation of a chemical bond with the absorbing solvent. Following this absorption process, this chemical bond is broken and CO$_2$ is evolved at a higher temperature and lower pressure, thereby regenerating the solvent and producing high-purity CO$_2$. Of the absorption technologies, chemical absorption via amine scrubbing is the most industrialized carbon capture technology with applications dating back 60 years.\textsuperscript{19}
Typically, this process uses alkanoamines, such as monoethanolamine (MEA) or methyldiethanolamine (MDEA), on account of their high capture efficiency and selectivity. However, these amines are sensitive to a range of contaminants, including dust and sulphur compounds present in BFG. In this case, the stream must be pre-processed to remove any necessary contaminants. While desulphurization is already a part of the process, there is typically no step to remove dust compounds from BFG, indicating that an additional gas cleaning step may be necessary to implement absorption technologies.

For traditional amine absorption with MEA, CO$_2$ is absorbed at lower temperatures ranging between 40-60 °C and evolved at higher temperatures between 100-120 °C. A comparative simulation tested the capture conditions and capacity of three different solvents (MEA, MDEA/Piperazine (Pz) 50% mixture, and 2-amino-2-methyl-1-propanol (AMP)) for CO$_2$ capture from BFG. It was found that all three solvents are capable of achieving similar CO$_2$ capture rates (~85%). However, the solvents required 3.18, 2.48, and 2.2 MJ steam/kgCO$_2$ for MEA, MDEA/Pz, and AMP, respectively. This being said, traditional amines have some obvious disadvantages, including equipment corrosion, solvent degradation, low CO$_2$ loading, and high energy consumption for regeneration. The main consideration with the implementation of any absorption system is the associated energy penalty.

New advanced solvents have also been developed to combat the problems seen in traditional MEA absorption processes, particularly to address the high energy requirements for solvent regeneration. Some of these solvents have shown advantages specifically for capturing CO$_2$ from BFG. Under the COURSE50 program (discussed further in Section 4.4), Japan has tested new absorbents made of secondary amino-alcohols. Pilot scale testing with real BFG has taken place at the Nippon steel plant where researchers tested BFG streams at both 1 tCO$_2$/day and 30 tCO$_2$/day. Both trials showed a reduction in the required regeneration energies from the MEA baseline at around 2-3 GJ/tCO$_2$. Finally, some research has been focused on alternative solvents to traditional amine-based processes. The
most notable of these initiatives in the iron and steel industry is the development of ammonia-based solvents. Aqueous ammonia was chosen as an alternative to amine absorption due to high CO₂ loading capacity, low regeneration temperature, low regeneration energy consumption, and low corrosivity. A pilot-scale plant in Korea has demonstrated this solvent with a BFG stream of 10 tCO₂/day with ~23% CO₂. The results showed that the CO₂ could be captured at 90% recovery with a purity of 99% in the product CO₂ stream. Additionally, the regeneration energy for this solvent was determined to be 2.5 GJ/tCO₂. These researchers also confirmed that waste heat integration to the absorption process could mitigate the external energy requirement for the capture process.

2.1.2 Physical Absorption

At the conditions of the blast furnace (~20% CO₂ at 3 bar), physical absorption can also be utilized on account of the high CO₂ concentration. Physical absorption systems operate where CO₂ is absorbed at a high pressure and low temperature, and have subsequently evolved using a lower pressure and higher temperature (similar to chemical absorption). However, in physical absorption, no chemical reaction occurs between the CO₂ and the solvent. Similar to chemical absorbents, physical absorbents can also be sensitive to a range of contaminants. Once again, since desulphurization is often included as a part of the process, only one additional BFG cleaning step may be necessary to implement this technology.

Many commercial processes and physical absorbents exist, including: Purisol®, Selexol™, Rectisol®, and Fluor Solvent™. These solvents tend to be less corrosive and less toxic than those used for chemical absorption. Lampert et al., studied the effectiveness of Selexol™ (dimethyl ethers of polyethylene glycol) as an absorption solvent for BFG. This process was designed to capture CO₂ with 90% recovery at 80 bar. From this analysis, the energy requirements for the separation of CO₂ was estimated to be between 0.8-1 GJ/ton CO₂. Additional studies show Selexol™ being a more economical solvent than amines and other physical absorbents. However, Purisol® is shown to have lower energy requirements and Rectisol® is
favoured when dealing with streams that could contain sulphur. Therefore, both of these solvent processes could prove advantageous.

### 2.2 Adsorption

Adsorption is the process by which CO\textsubscript{2} molecules adsorb to the surface or within the micro and mesopores of a solid adsorbent material. Although a number of configurations are possible, for ease one could consider this taking place in a packed bed where the waste stream flows through the bed until the adsorbent becomes saturated with CO\textsubscript{2}. At this point, CO\textsubscript{2} is evolved by one of three methods: 1) reducing the pressure, known as pressure swing adsorption (PSA) or vacuum swing adsorption (VSA), 2) increasing the temperature, known as temperature swing adsorption (TSA), or 3) applying a low voltage current, known as electric swing adsorption (ESA). A combination of these approaches is also an option. In the iron and steel industry, only PSA and VSA have been used commercially. Activated carbon, zeolites, and metal-organic frameworks have all been studied as potential adsorbents.

Adsorption technologies, specifically PSA and VSA, have been integrated into many of the existing pilot scale initiatives in the iron and steel industry. A pilot-scale plant as a part of the COURSE50 initiative tested the concept of VSA CO\textsubscript{2} capture from the BF. The pilot plant processed 3 tCO\textsubscript{2}/day and verified the ability to scale up the VSA system to industrial scale. The researchers also confirmed that the process receives significant economies of scale, as the process scaled up for 63\% of laboratory costs. Additionally, the electricity requirements for a PSA unit operating in a Finex® plant has been estimated around 0.71 GJ/tonne hot metal. Assuming 90\% capture at the BF, this corresponds to about 0.5 GJ/tCO\textsubscript{2}.

Another form of adsorption is calcium looping (CaL), where calcium-based sorbents are used to adsorb CO\textsubscript{2} molecules, similar to reactions discussed later in Section 2.4. Calcium oxide, typically from limestone, reacts with CO\textsubscript{2} in flue gas to form calcium carbonate, where the reaction can later be reversed through calcination to produce a high-purity CO\textsubscript{2} stream. An advantage of CaL is its utilization of fluidised beds, which have
already been demonstrated at industrial scale and do not need a vast scale-up like amine scrubbing towers.\textsuperscript{34} In an industrial scheme, flue gas is passed through a fluidised bed carbonator, where CO\textsubscript{2} is captured by the Ca-based sorbent, and the reacted sorbent is sent to a second fluidised bed calciner to regenerate the sorbent.\textsuperscript{35} Research on this method has been primarily focused within the cement industry, likely due to the limestone available at cement production facilities, but work has been done to apply this in steel production. Cormos\textsuperscript{36} used simulation to compare amine absorption and CaL, and found that CaL presents significant advantages in terms of both performance and economics, reducing steel mill emissions by 73\% (compared to 60\% for absorption) at approximately 50\% of the specific investment costs required for absorption. A possible limitation of CaL is the feasibility of sorbent regeneration, as CaO becomes less reactive over many cycles due to pore blockage and sintering.\textsuperscript{37} However, the spent sorbent could easily be used in the iron and steel industry as feed for sinter production, BOF, and ladle metallurgy, decreasing the necessary carbon-intensive lime kiln output.\textsuperscript{36}

### 2.3 Membranes

Membrane operation depends on the differences in physical and chemical properties between gases in a waste stream and the membrane material. These differences allow for one component to pass through the membrane at a higher rate than others. Membranes are traditionally a good technology for carbon capture as they are easy to scale up, require little energy input, and are typically easy to incorporate into existing processes.\textsuperscript{38} Although membranes provide many benefits, there are a few additional considerations when incorporating membranes as a capture technology in the steelmaking process. First, many membranes are easily poisoned by sulphur and sulphur-containing gases. To ensure operability and lifetime of the membrane, these gases must be removed before being fed to the membrane module. This may require additions to the plant process, however most iron and steel plants already treat BFG for sulphur compounds before it is vented. However, it should be noted that typical wet flue gas desulphurization scrubbers remove 80-90\% of SO\textsubscript{2}, while an SO\textsubscript{2}
polisher pre-capture technology might have an SO₂ outlet concentration of 10 – 25 ppmv. Second, membranes operate based on the existence of a partial pressure differential between the feed and the permeate stream sides. This often means that the feed gas entering the membrane module is at a high pressure or requires pressurization. Since BFG leaves the process at ~3 bar, an additional compression step may be required to achieve higher CO₂ separation using membrane technologies.

A study by Lie et al. showed that 97% CO₂ recovery was possible from oxygen-blown BFs using fixed site carrier membranes. Additionally, they showed that 83% of CO₂ could be recovered from a traditional BF with two membrane stages. Another study by Ramirez-Santos et al. modelled two membranes to capture CO₂ from BFG: 1) H₂-selective polyimide membrane from UBE industries and 2) CO₂ selective rubbery composite membrane from MTR Inc. The rubbery membrane showed noticeably better results than the polyimide membrane with CO₂ recoveries of 80% and 62% respectively (achieving 90% CO₂ purity in each case). Additionally, these studies note that increasing the feed pressure improves the overall process separation, levelling-off at higher feed pressures.

A final process consideration involves the incorporation of the water-gas shift reaction. Membrane CCS technology is specifically advantageous for systems operating with the post-combustion water-gas shift reactions. Since membranes operate on the principle of partial pressure differentials, the increased concentration of CO₂ in the gas stream works to increase the driving force for the membrane separations, possibly resulting in increased CO₂ recovery. Additionally, the water-gas shift reaction is carried out at elevated pressures, improving the separation process and recovery while eliminating the need for subsequent feed compression. Commercially available membranes already exist for separation of H₂ and CO₂.

2.4 Mineral Carbonation

Another form of CCS that has gained popularity is mineral carbonation (MC). Originally proposed by Seifritz, it involves exploiting the natural process in which alkaline silicate minerals uptake CO₂. While the
process typically occurs on geologic timescales, researchers have been working towards accelerating the rates to make it practical and economical on the large-scale.

The overall process chemistry of mineral carbonation has been discussed at length elsewhere\(^4\) and essentially involves the carbonation of alkaline materials containing divalent cations, e.g., \(\text{Mg}^{2+}\) and \(\text{Ca}^{2+}\). While carbonation can be done via a gas-solid reaction, it is more efficient with dissolved \(\text{CO}_2\) in aqueous solution.

The basic reactions are shown below,

\[
\text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 = \text{HCO}_3^- + \text{H}^+ = \text{CO}_3^{2-} + 2\text{H}^+ \\
\text{M}^{2+} + \text{CO}_3^{2-} \rightarrow \text{MCO}_3(s)
\]

where \(\text{M}\) is \(\text{Mg}\) or \(\text{Ca}\). The basic requirements for this CCS method are \(\text{CO}_2\), water, and an alkalinity source, where increases in efficiency come through suitability of the alkalinity source (particle size, silicate structure, composition) and process conditions (temperature, \(\text{CO}_2\) partial pressure, solid/liquid ratio, pH). Industrial byproducts like steelmaking slags have become a popular candidate for MC due to their already small particle size, high alkaline content and reactivity, and proximity to \(\text{CO}_2\) sources such as flue gas.\(^4\)

The amount of slags produced per tonne of steel depends on the steelmaking route. On average, there are 200-400 kg of byproducts per tonne of steel produced, including slag, dust and sludge. Of the byproducts produced, slags constitute 90% by mass, totalling to more than 400 Mt per year. The BF, BOF, and EAF produce approximately 275, 126, and 169 kg slag per t crude steel product.\(^4\)

Similar to the production amount, the composition of slags varies with the type of furnace used. From Table 2-1\(\text{Error! Reference source not found.}\), one can see that the alkaline content is in the range of about 25-45\%, mostly in the form of hydroxides, oxides, and silicates.\(^4\) In terms of \(\text{CO}_2\) sequestration potential, based on the values reported here with total Ca and Mg, the sequestration capacity would be a minimum of 0.29 kg \(\text{CO}_2\) per kg slag to a maximum of 0.52 kg \(\text{CO}_2\)/kg slag. Taking a median value of 0.41 kg \(\text{CO}_2\)/kg slag with the 400 Mt of slag produced per year gives an approximate maximum of 163 Mt \(\text{CO}_2\) that could be captured
each year with steelmaking slags globally. This accounts for about 6% of the industry’s emissions.

<table>
<thead>
<tr>
<th></th>
<th>Ca + Mg</th>
<th>Total CO₂</th>
<th>Global Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>32.1</td>
<td>0.39</td>
<td>154.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>45.2</td>
<td>0.52</td>
<td>209.7</td>
</tr>
<tr>
<td>Median</td>
<td>33.5</td>
<td>0.41</td>
<td>163.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>24.8</td>
<td>0.29</td>
<td>116.0</td>
</tr>
</tbody>
</table>

There already exists a market for slags, primarily as supplementary cementitious materials (SCM) for concrete mixtures to replace a portion of carbon-intensive cement. Further, 11 US states consider it a product rather than a waste, and it has become the preferred aggregate in road surface applications where high wear and tear are frequent. Perhaps this brings an additional hurdle to CCS through MC of slags, or a higher emphasis on the market value of carbonated steel slag products. However, while many developed countries have slag utilization rates at or near 100%, developing countries like China are still catching up to that mark. China is only using slags at a rate of about 30%, and nearly 300 Mt had accumulated in landfills as of 2016.

If carbonation can improve the properties of slags, it could become an intermediate treatment step between the slag producers and consumers. The Ca/Mg oxides and hydroxides present in slags can cause long-term uncontrollable expansion problems in concrete. However, such components can be eliminated through MC. Indeed, there are a number of beneficial changes that slags undergo when carbonated, and the tuning of carbonates towards higher-value products will improve process economics. In addition to eliminating expansion risk, MC can neutralize the environmentally relevant amounts of hazardous heavy metals like Ba, Cr, V, and Mo that can be found in steelmaking slags. Decreases in porosity, particle size, and density can also occur.
2.4.1 State-of-the-art Slag Carbonation Processes

Over the last 15 years, there has been significant effort toward the optimization of the carbonation of steel slags. Some successful endeavours are listed in Table 2-2. One of the first to investigate MC of steel slags, Huijgen et al\textsuperscript{47} (1) used direct carbonation and maximized Ca carbonation at 74\% in 30 minutes under 19 bar $P_{\text{CO}_2}$ and 100 °C, where the slag particles were < 38 μm. Although their work is somewhat outdated, it is included here to illustrate the field’s progress. As demonstrated in Table 2-2, obtaining an optimal process, where high overall efficiency and product purity are achieved with practical conditions, is difficult. Those with higher efficiencies (Chang\textsuperscript{60}, Wang\textsuperscript{61}, Hollen\textsuperscript{62}) require expensive equipment or impractical conditions, while those with milder conditions (Eloneva\textsuperscript{63}, Chang\textsuperscript{46}) lack efficiency in terms of yield or reaction time.
Table 2-2: Summary of Parameters from Various MC Processes in Literature

<table>
<thead>
<tr>
<th>First Author</th>
<th>Particle Size (um)</th>
<th>Additives Used</th>
<th>Max Temp (°C)</th>
<th>CO₂ Introduction</th>
<th>Duration (min)</th>
<th>Efficiency %*</th>
<th>Purity %</th>
<th>Practicality Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huijgen⁴⁷</td>
<td>&lt;38</td>
<td>n/a</td>
<td>100</td>
<td>P&lt;sub&gt;CO₂&lt;/sub&gt;=19 bar</td>
<td>30</td>
<td>74o</td>
<td>&lt;100</td>
<td>XRD</td>
</tr>
<tr>
<td>Eloneva⁶³</td>
<td>&lt;10</td>
<td>CH₃COOH, 20 vol%</td>
<td>70</td>
<td>1 L/min</td>
<td>255</td>
<td>~65o</td>
<td>100</td>
<td>Energy intensive; small particles</td>
</tr>
<tr>
<td>Chang⁶⁰</td>
<td>62</td>
<td>n/a</td>
<td>65</td>
<td>P&lt;sub&gt;CO₂&lt;/sub&gt;=1 bar</td>
<td>30</td>
<td>93.5o</td>
<td>100</td>
<td>Expensive equipment</td>
</tr>
<tr>
<td>Said⁴⁹</td>
<td>0-125</td>
<td>NH₄NO₃, 1M</td>
<td>30</td>
<td>1 L/min</td>
<td>10+</td>
<td>73e</td>
<td>unknown</td>
<td>High raw material usage</td>
</tr>
<tr>
<td>Chang⁴⁶</td>
<td>&lt;44</td>
<td>n/a</td>
<td>25</td>
<td>1 L/min</td>
<td>120</td>
<td>89.4o</td>
<td>100</td>
<td>Long time, small particles</td>
</tr>
<tr>
<td>Wang⁶¹</td>
<td>&lt;100</td>
<td>(NH₄)₂SO₄, H₂SO₄</td>
<td>350</td>
<td>Rxn with NH₄HCO₃</td>
<td>300+</td>
<td>92.6e, 82.1o</td>
<td>61.7% &amp; 95.6%</td>
<td>Several steps; acidic</td>
</tr>
<tr>
<td>Hollen⁶²</td>
<td>63-125</td>
<td>8% HCl</td>
<td>90</td>
<td>6.6 L/min</td>
<td>180+</td>
<td>97e, 67.5c</td>
<td>97</td>
<td>Acidic, long time</td>
</tr>
<tr>
<td>Ragipani⁴⁸</td>
<td>&lt;75</td>
<td>n/a</td>
<td>25</td>
<td>P&lt;sub&gt;CO₂&lt;/sub&gt;=12.4 bar</td>
<td>180</td>
<td>57o</td>
<td>81.5</td>
<td>Low efficiency, high P</td>
</tr>
</tbody>
</table>

*Efficiency types reported as: o (overall), e (extraction), c (carbonation)
2.4.2 Overall Analysis

Although carbonation efficiency values in the literature have reached acceptable levels, the practicality for large-scale implementation is still lacking. Success in terms of yield and economics depends highly on the starting material, process used, and materials available. A full-scale economic analysis on a case-by-case basis may aid in the decision to install MC at an iron/steel plant. Locations that produce slags with higher CaO and/or heavy metal content can benefit more greatly from MC of steel slags. China may especially be a good location, as there exists less market competition for slags, making the feedstock cheaper and bringing the added benefit of neutralizing landfills. The authors expect great opportunities to arise when considering MC implementation on a per-plant basis.

2.5 Oxyfuel Top Gas Recycled Blast Furnace (TGRBF) with CCS

One of the most promising technologies for retrofitting older iron and steel plants is oxyfuel top gas recycled blast furnaces (TGRBF) with CCS. Oxyfuel TGRBF with CCS operates by separating the BFG into two streams: a CO$_2$-rich stream and a CO-rich stream. The CO-rich stream is recycled back into the BF, improving the reduction reaction and reducing coking rates. The addition of this recycle stream also increases the concentration of CO$_2$ in the BFG to near 35%, making the subsequent CO$_2$ separation less energy intensive. The CO$_2$ from this stream can be captured and sequestered or utilized to mitigate process CO$_2$ emissions. Overall, the oxyfuel TGRBF process, shown in Figure 2-1, can be broken down into four distinct steps: 1) the oxyfuel technology, 2) CO$_2$ separation, 3) top gas recycling, and 4) CO$_2$ sequestration or utilization.
Figure 2-1: Oxyfuel TGRBF with CCS Example Process Schematic. Example illustrates a typical 2-stage CO₂ capture unit.

2.5.1 **Oxyfuel Technology**

The idea behind the oxyfuel BF mirrors that of the oxyfuel combustion cycle proposed for carbon capture at traditional coal and natural gas-fired power plants. In traditional BF configurations, oxygen-enriched air is used as a feed gas; however, in oxyfuel BFs, the BF is fed with pure oxygen, removing unwanted and inert nitrogen from the process. This leads to an exit stream that is more concentrated in CO₂ and subsequently requires less energy to separate CO₂ from the gas stream.

In introducing an oxygen BF, additional equipment and process modifications may be required. For example, to feed a stream of pure oxygen to the BF, the iron and steel plant needs to be equipped with an air separation unit that can produce the required amount of oxygen to fuel the BF.⁶⁶ New equipment or modifications may be necessary for this route. The products of the oxyfuel BFG contain CO, CO₂, H₂, H₂O.⁶⁷ Therefore, in addition to any process modifications, a CO₂ separation process is necessary for the BFG to prevent further CO₂ emissions and purify the recycle stream for recirculation to the BF.

It is important to note that the TGRBF can also be modified without including the oxyfuel technology. In
this case, the BF is still fed with the oxygen-enriched air, meaning that there is a lower concentration of CO$_2$ in the BFG stream. While this increases the energy requirements for separation, the process is still feasible and may be retrofit to existing iron and steel plants. However, the oxyfuel TGRBF is the recommended technology for new builds.

2.5.2 CO$_2$ Separation

Following the blast furnace, BFG must be cleaned and dehydrated to remove any dust particles and water that are initially present. The stream is then compressed and may be fed to the CO$_2$ separation unit. The specific CO$_2$ separation unit can vary based on implementation requirements, where any of the aforementioned separation technologies can be incorporated. Laboratory- and pilot-scale CO$_2$ separation processes for TGRBF have ranges from VSA to MEA absorption.$^{66}$ However, the TGRBF has traditionally been tested with VSA or PSA technologies.$^{19,68}$ Finally, the CO$_2$-rich stream can be compressed and sequestered geologically or utilized in industrial applications.

2.5.3 Top Gas Recycling

Following the CO$_2$ separation, the CO-rich stream is reheated to a temperature between 900 °C and 1250 °C (depending on the desired re-injection conditions) and recycled back into the base of the BF.$^{68}$ In recycling the CO-rich stream, the carbon input to the BF can be reduced by 30%.$^2$ Additionally, the TGRBF can mitigate up to 65% of the process CO$_2$ emissions and decrease the coke rate by 35%.$^{69}$

3 New Builds and Technology Changes

Another important aspect of reducing the CO$_2$ emissions from the iron and steel industry is the development of new technologies. Since many of these new technologies include metallurgical changes to the process, it is often better to implement these technologies in new iron and steel plants rather than retrofitting existing plants. Many of the technological innovations for iron and steel emissions reduction have focused on BF, EAF, and process intensification. There are many disadvantages to the traditional BF setup, including
dependence on coke feedstocks, environmental constraints on coke ovens and iron feedstocks, and high capital and operational intensity. To tackle these issues, technology has been developed to help reduce the carbon-intensity of BF and increase the implementation of EAFs.

3.1 Hydrogen Direct Reduction Technology

To produce iron from steel, the iron ores must be fully reduced in the BF/BOF or by direct reduction. This reduction is traditionally performed in an oxygen-rich environment. However, in the case of the DRI/EAF process, this reduction can be carried out with hydrogen. When the reduction takes place in a pure hydrogen environment, the reaction produces water vapor as opposed to CO$_2$. This water can easily be separated from the waste stream, leaving the emissions related to hydrogen production to be the lone emissions in this process.

H$_2$ is produced in a variety of ways, including from fossil fuels, water electrolysis, and biomass gasification. The two that have received a lot of attention recently are biomass gasification and water electrolysis (despite significant electricity requirements). Recent initiatives have explored performing on-site electrolysis to produce the necessary H$_2$. This process, utilizing water electrolysis and an EAF, is detailed in Figure 3-1. In the process, water is initially sent to an electrolyzer operating at 70 ºC where it is split into O$_2$ and H$_2$ gases at the anode and cathode, respectively. From here, H$_2$ is fed into a condenser where any remaining water vapor from electrolysis is condensed and recycled to the electrolyzer. After the condenser, the H$_2$ stream is heated before being injected into the reduction shaft operating around 800 ºC. Alternatively, iron and steel plants also have the opportunity to perform a water-gas shift reaction on the COG to produce H$_2$. This allows the iron and steel plant to convert CO in the waste stream to CO$_2$ and H$_2$ using steam. The CO$_2$ from this reaction can be subsequently captured by any of the previously mentioned post-combustion methods and H$_2$ can be recycled into the reactor to maintain the H$_2$ environment.
Figure 3-1: Hydrogen direct reduction with water electrolysis.

Implementation of this process at iron and steel plans would include changes too large to retrofit to existing plants. Changes for this process would include the addition of a H₂ production unit, the need for an EAF, and potential changes to the way the carbon and iron ore are introduced into the process. Since only 25% of iron and steel plants are operating with EAF capabilities, the hydrogen reduction technology is best suited for new builds.

### 3.2 Smelting Reduction Technologies

Smelting reduction technologies perform a direct reduction of iron to pig iron without the need for coke production. These technologies can be divided into multiple subcategories based on the process organization, two of which have been highly studied. The first process consists of a preliminary reduction of iron ore to direct reduced iron in the solid state followed by a final reduction and smelting into the liquid phase. This approach is seen in processes such as the Finex® and Corex® processes. The second process of interest consists of a complete reduction and smelting of iron oxides in a molten slag bath. This approach is seen in processes such as the HIsarna process. Both process types will be discussed further in the following sections.
3.2.1 Finex® Technologies

The Finex® technology was developed in a joint venture between Siemens (Germany) and POSCO (South Korea). The Finex® process has two main units: a four-stage reactor system of bubbling fluidized beds and a melter-gasifier. The iron ore is fed into the fluidized bed reactors with a fluxing agent, such as limestone. In these reactors, the iron ore is heated and reduced by reaction with hot reducing gas. The product of this process is DRI that is subsequently compressed and transferred to the melter-gasifier. In the melter-gasifier, the iron is melted at high temperature to the liquid product, which mirrors that of the BF and can continue through the traditional steelmaking cycle.72 Figure 3-2 displays the Finex® process flow diagram.

![Finex® process flow diagram](image)

The Finex® technology allows for the utilization of low-cost iron ore fines that could not be used in previous processes. Additionally, the process uses less energy and produces less emissions than traditional steelmaking technologies without compromising the integrity of the iron and steel produced.73 Under initiatives by POSCO in South Korea, this technology has been proven successful on the industrial scale.
3.2.2 **HIsarna Technology**

The HIsarna technology is being developed by the ultra-low CO₂ steelmaking (ULCOS) initiative of European organisations, which will be discussed in more detail in Section 4.2. The HIsarna process uses a bath smelting technology that combines three new technologies: 1) preheating coal with partial pyrolysis in a reactor, 2) melting and reduction of iron ore in the cyclone converter section, and 3) final reduction and iron production in the smelt reduction section. For this process, the iron ore and oxygen are injected into a cyclone converter furnace where the iron is reduced at a high temperature using the recycled off gas from the Smelt Reduction Vessel. After the cyclone furnace, iron ore moves into the smelt reduction vessel where it undergoes a final reduction at 1400-1450°C. A process diagram for the HIsarna process is shown in Figure 3-3.

![Figure 3-3: HIsarna process flow diagram](image)

The HIsarna process offers quite a few advantages over traditional BF/BOF processes. Similar to the Finex process, HIsarna technology has the ability to use lower quality iron ore feed materials. Compared to the
BF/BOF process, the HIsarna technology does not require the energy- and carbon-intensive sintering or coking processes and requires a significantly lower coal input.\textsuperscript{74} This leads to 20% energy savings and can reduce CO$_2$ emission by up to 70% from traditional BF/BOF processes.\textsuperscript{68}

3.3 Direct Reduced Iron with Natural Gas

Direct reduction of iron with natural gas employs advanced direct reduction technology, partnered with a CCS system (amine absorption, membrane, etc.). This process was first developed as a part of the ULCOS initiatives as a process known as ULCORED. The process uses a reducing agent derived from partially oxidized natural gas, replacing the traditional coal-derived reducing agent (or coke). Additional process modifications have explored the use of coal, biomass, or bio-waste gasification for producing the reducing agent. Following the BF, the off gas from DRI production is recycled in a similar manner to the TGRBF. By recycling this CO-rich stream to the direct reduction reactor, less of the reducing agent is used. After the direct reduction reaction, the solid iron pellets are fed into the EAF and processed according to the DRI/EAF process route.\textsuperscript{68}

A major advantage of this process is decreasing the dependence on traditional coke ovens, which significantly reduces overall process emissions. However, the ULCORED process requires higher quality iron ore than traditional BF processes. Additionally, this process is similar to the TGRBF with a higher energy demand.\textsuperscript{19} Ultimately, the ULCORED technology partnered with a traditional CCS system has the potential to reduce CO$_2$ emissions by 70% when compared to traditional BF processes.\textsuperscript{68}

Research is currently focused on developing technology for the partial oxidation of natural gas to reduce the process natural gas consumption by 15-20%.\textsuperscript{68,75} They expect this change to reduce overall capital and operating expenditures.

3.4 Direct Electrolysis of Iron

When iron is directly reduced via electrolysis, the process takes in iron ore and converts it into iron and
oxygen. This eliminates the needs for coke as a reducing agent and for conventional BF technology. This can also eliminate any CO₂ emissions from process operation. For the ULCOWIN process, iron ore is suspended in a solution of alkaline electrolyte (in this case NaOH) at temperatures around 110 °C. The solution is then electrolyzed by an electric current. The positively charged iron ions precipitate as iron at the cathode. The negatively charged oxygen ions are attracted to the anode where they recombine to produce O₂. Initial tests for this technology were not promising with the production of 5 kg iron/day. Additionally, iron purity levels of 99.98% were achieved from this process.

A variation of this process named ULCOLYSIS was developed to improve the process production capacity. In this process, a molten oxide solution at 1600 °C is used as the electrolyte medium. This allows the process to surpass the melting point of iron. In this process, liquid iron is produced at the cathode and O₂ gas is produced at the anode. This process is still being developed on the laboratory scale. Currently, these projects are facing challenges related to economic and process efficiency.

4 Technology Development Initiatives and Pilot Scale Projects

As previously discussed, there exist pilot-scale projects and technology initiatives that highlight the state of carbon capture and low carbon emissions technology in the iron and steel industry. The most notable of these
initiatives are described in the following sections. Table 4-1 outlines the most recent CO2 emissions reduction initiatives worldwide and the current scale of operation. Additionally, Table 4-2 outlines the average avoided emissions for some of the pilot scale technologies. These values are based on the average CO2 emissions from an BF/BOF process plant at 1850 kg CO2/thm (thm = tonne hot metal).

Table 4-1: Location and Description of Pilot Scale Initiatives

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Technology</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYBRIT76</td>
<td>Sweden</td>
<td>Direct reduction with hydrogen gas</td>
<td>-</td>
</tr>
<tr>
<td>ULCOS28,77–79</td>
<td>Sweden</td>
<td>1a. TGRBF</td>
<td>12 kt iron/year*</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td>1b. TGRBF without CO2 storage</td>
<td>700 kt iron/year</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>1c. TGRBF with CO2 storage</td>
<td>1.38 kt iron/year</td>
</tr>
<tr>
<td></td>
<td>Netherlands</td>
<td>2. HiSarna Technology</td>
<td>65 kt steel/year</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>3. ULCORED - novel direct reduction with natural gas derived reducing agents</td>
<td>8 kt iron/year*</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>4. ULCOLYSIS - direct electrolysis of iron</td>
<td>1.7 kt iron/year*</td>
</tr>
<tr>
<td>POSCO5,68,80</td>
<td>South Korea</td>
<td>1a. Finex® process development</td>
<td>900 kt steel/year</td>
</tr>
<tr>
<td></td>
<td>South Korea</td>
<td>1b. Finex® process development</td>
<td>1500 kt steel/year</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>2. CCS using VSA</td>
<td>0.18 kt CO2/year**</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>3. Pure H2-based blast furnace</td>
<td>Laboratory</td>
</tr>
<tr>
<td>COURSE 5019,28,77,81,82</td>
<td>Japan</td>
<td>1. Direct iron reduction with hydrogen</td>
<td>Laboratory</td>
</tr>
<tr>
<td></td>
<td>Japan</td>
<td>2. Reforming coke oven gas though hydrogen amplification</td>
<td>Laboratory</td>
</tr>
<tr>
<td></td>
<td>Japan</td>
<td>3a. CCS from BFG using amine absorption</td>
<td>0.33 kt CO2/year*</td>
</tr>
<tr>
<td>Country</td>
<td>Initiative</td>
<td>Technology Description</td>
<td>Avoided Emissions (kt CO2/year*)</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------------</td>
<td>-------------------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Japan</td>
<td>3b. CCS from BFG using amine absorption</td>
<td>10 kt CO2/year*</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>3c. CCS from PFG using PSA</td>
<td>1 kt CO2/year*</td>
<td></td>
</tr>
<tr>
<td>Emirates Steel Industries(^{19,83})</td>
<td>Abu Dhabi</td>
<td>DRI with CCS for enhanced oil recovery</td>
<td>800 kt CO2/year</td>
</tr>
<tr>
<td>Stepwise Initiative(^{84})</td>
<td>Sweden</td>
<td>Sorption-enhanced water-gas shift technology</td>
<td>4.7 kt CO2/year*</td>
</tr>
<tr>
<td>United States</td>
<td>AISI(^{85,86})</td>
<td>1. Molten Oxide Electrolysis</td>
<td>0.024 kt iron/year*</td>
</tr>
<tr>
<td>United States</td>
<td></td>
<td>2. Suspension reduction of iron ore concentrates using hydrogen</td>
<td>Bench Scale</td>
</tr>
</tbody>
</table>

*For pilot scale initiatives with production capacity given in per hour or per day basis, a pilot scale operation of 8000h/year was used.

**Volume of processed blast furnace gas given as 50 m³/h\(^{87}\)**

Table 4-2: Avoided Emissions for Pilot Scale Technologies Based on Reduction from Average BF/BOF Process Emissions (1850 kg CO2/thm)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Avoided Emissions (kg CO2/thm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Direct Reduction(^68)</td>
<td>1550</td>
</tr>
<tr>
<td>TGRBF with VSA CCS(^68)</td>
<td>1270</td>
</tr>
<tr>
<td>BF/BOF with MEA CCS(^88)</td>
<td>927 - 1116</td>
</tr>
<tr>
<td>Oxy-blast furnace with MDEA/Pz CCS(^88)</td>
<td>851</td>
</tr>
<tr>
<td>HISarna(^89)</td>
<td>370</td>
</tr>
<tr>
<td>HISarna with CCS(^89)</td>
<td>1480</td>
</tr>
<tr>
<td>ULCORED(^89)</td>
<td>93</td>
</tr>
<tr>
<td>ULCORED with CCS(^89)</td>
<td>1018</td>
</tr>
<tr>
<td>SEWGS(^89)</td>
<td>1570</td>
</tr>
</tbody>
</table>

### 4.1 HYBRIT
In February of 2018, the Swedish companies SSAB (steel), LKAB (mining), and Vattenfall (energy) announced the intent to build a plant to produce steel via the HYBRIT process. The goal of HYBRIT is to place the traditional coke reducing agent with $\text{H}_2$ (similar to the process discussed in the hydrogen direct reduction technologies section). The pilot plant is estimated to cost $20 million and will be supported in part by the Swedish Energy Agency.\textsuperscript{76} The feasibility study phase of this project was completed in 2017. This pilot phase is anticipated to last until 2024 when the technology will move into the demonstration phase.\textsuperscript{90} The main challenges are developing efficient and economic methods to produce hydrogen on an industrial scale.

4.2 ULCOS

Among the initiatives to develop new low-CO$_2$ technologies, the ULCOS program has the broadest scope. ULCOS is a consortium of European companies invested in research to develop CO$_2$ reduction technologies for steel production. Established in 2004, the initiative was developed to reduce the industry’s CO$_2$ emissions by at least 50%.\textsuperscript{28} The ULCOS initiative can be divided into four main projects all focused around reducing CO$_2$ emissions from the iron and steel industry: TGRBF, HIsarna smelter, direct-reduced iron with natural gas (ULCORED), and direct electrolysis of iron ore (ULCOWIN/ULCOLYSIS). Of the processes developed by the ULCOS program, the TGRBF, HIsarna, and UCORED technologies have been demonstrated on the pilot scale. The first experiment using TGRBF under ULCOS was started in 2007 at MEFOS in Lulea, Sweden, where it ran efficiently and reduced CO$_2$ emissions by 24\%.\textsuperscript{64,68} As a result, EU invested hundreds of millions of euros for a TGR-BF that has the potential to mitigate 1.5 MtCO$_2$/year, which is about 1/3 of a BF’s emissions.\textsuperscript{28}

In 2010, a HIsarna pilot plant was established by TATA Iron and Steel group. This facility has the capacity to produce 65 kt of steel annually.\textsuperscript{68} During pilot scale operations, researchers estimated that the technology will not be industrially available for at least 10 to 20 years.
4.3 Pohang Iron and Steel Company (POSCO)

In 2014, POSCO began operation of their largest Finex® plant after already having successfully operated two other plants. This plant has the capacity to process 2 Mt CO\(_2\) and employs a 3-stage approach to mitigate CO\(_2\) emissions.\(^6^8\) This design adopted a new, compact design and reduced the initial investment by 15%. Since the process’ inception in 1992, two commercial Finex® plants have operated under POSCO, capable of processing 0.9 Mt and 1.5 Mt of hot metal per year, respectively.\(^9^1\)

At its Pohang location, POSCO has built a pilot plant to process 50 m\(^3\)/h of BFG. This project uses an ammonia-based absorption/stripping process, and reported a recovery of over 90% with a 9 wt% ammonia solution at a regeneration temperature of 78 °C.\(^5\) Additionally, the regeneration energy was supplied using low temperature waste heat from the power plant stacks. In addition to the ammonia absorption process, POSCO has tested PSA processes at its Pohang location. This process removes CO\(_2\) using a fluidized bed reactor and recycles the low-CO\(_2\) stream back into the reactor (in a similar configuration to the TGRBF).\(^5\)

4.4 CO\(_2\) Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE50)

With the goal of reducing CO\(_2\) emissions by 30%, COURSE50 operates through three technology initiatives: reducing BF emissions through direct hydrogen reduction, developing CCS technology for BFG, and reforming COG with hydrogen.\(^8^0\) Of these initiatives, the developed pilot scale processes have surrounded primarily CCS technology development, testing both amine absorption and PSA.

Pilot-scale initiatives investigating the use of secondary amino alcohols for absorption CCS technologies were performed at the Nippon steel plant. These operations used real BFG from the plant to process 1 tCO\(_2\)/day and 30 tCO\(_2\)/day. The project showed new absorbents had lower regeneration energies than traditional MEA absorbents.\(^1^9\) Additional projects include development of a PSA system with JFE steel. This PSA process uses zeolite ZEOLUM F-9H to recover CO\(_2\) from the BFG stream. A subsequent step recovers
CO from the process. The results of this investigation showed recoveries around 80% with 99% CO₂ purity in the product stream.³³

4.5 Stepwise SEWGS

The Stepwise project works to develop and scale-up sorption-enhanced water-gas shift technology specifically for CO₂ capture from BFs. The overall goals of this project are to decrease the carbon intensity of the BF by increasing the rate of carbon capture, increase the process energy efficiency by lowering energy consumption, and decrease CO₂ avoidance cost.⁹² The proposed SEWGS process mainly consists of a water gas shift converter and a SEWGS reactive separator. CO₂ and H₂ produced in the water gas shift converter are fed into the SEWGS reactive separator where CO₂ is adsorbed via PSA on potassium-promoted hydrocalcite, allowing for the production of high pressure H₂ in the same operation.⁹³,⁹⁴ This process is advantageous due to the high temperature (350-500 ºC) and pressure (25 bar) of the separation technology and the combination of the water-gas shift reaction and CO₂ adsorption, eliminating the need for an additional water-gas shift reactor.⁹²

Current pilot scale demonstration of the Stepwise SEWGS technology is occurring at the Swerea Mefos facility is Luluå, Sweden. This process is designed to capture CO₂ at a rate of 14 tCO₂/day. The test facility, which consists of a BFG compression section, a water-gas shift reaction section, and a SEWGS section, will receive untreated BFG via a 500-m long tie-in line.⁸⁴

5 Cost of CO₂ Capture from Iron and Steel Production

5.1 Costs per tonne CO₂

The recently reported costs per tonne CO₂ avoided are tabulated in Table 5-1 for the various CCS technologies discussed in this chapter, along with the amount of CO₂ emissions that were captured. Comparing economics of different processes is difficult due to several aspects, one being the variability in calculations and assumptions among different studies. Some publications report %CO₂ recovered from the
amount passed through the CCS technology, while others report a percentage of the entire plant’s emissions. Complications also arise due to differences in assumptions about facility characteristics and electricity costs.

Table 5-1: Cost of Capture from Various CCS Technologies in Recent Literature

<table>
<thead>
<tr>
<th>First Author</th>
<th>Year</th>
<th>Technology</th>
<th>Emissions Captured</th>
<th>Cost (2019 USD/tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td><strong>BF Post Combustion with Absorption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tsupari⁴⁵</td>
<td>2013</td>
<td>MEA Solvent</td>
<td>50-75%</td>
<td>126.21   171.29</td>
</tr>
<tr>
<td>Kim⁴⁶</td>
<td>2015</td>
<td>MEA Solvent</td>
<td>*90%</td>
<td>79.04    97.15</td>
</tr>
<tr>
<td>Cormos³⁶</td>
<td>2016</td>
<td>MDEA Solvent</td>
<td>50-60%</td>
<td>91.83    97.15</td>
</tr>
<tr>
<td>Dreillard⁹²</td>
<td>2017</td>
<td>DMX Solvent</td>
<td>*99%</td>
<td>32.47    48.10</td>
</tr>
<tr>
<td><strong>BF Post Combustion with Adsorption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim⁴⁶</td>
<td>2015</td>
<td>PSA</td>
<td>*90%</td>
<td>41.89    44.94</td>
</tr>
<tr>
<td>Cormos³⁶</td>
<td>2016</td>
<td>Calcium Looping</td>
<td>45-73%</td>
<td>42.89    44.94</td>
</tr>
<tr>
<td><strong>BF Post Combustion with Membrane Separation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramirez-Santos⁹⁸</td>
<td>2017</td>
<td>Rubbery Composite Membrane</td>
<td>*99%</td>
<td>27.66    39.68</td>
</tr>
<tr>
<td><strong>Oxyfuel Top Gas Recycled BF with CCS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEAGHG⁸⁸</td>
<td>2013</td>
<td>Absorption with MDEA/Pz solvent</td>
<td>47%</td>
<td>64.39    64.39</td>
</tr>
<tr>
<td>Chung⁹⁹</td>
<td>2018</td>
<td>Hybrid of Absorption (Pz) &amp; Membrane (Polaris)</td>
<td>69%</td>
<td>31.00</td>
</tr>
<tr>
<td><strong>Mineral Carbonation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stolaroff⁵⁴</td>
<td>2005</td>
<td>Steel Slag Direct Carbonation with Ambient Air</td>
<td>8%</td>
<td>14.69</td>
</tr>
<tr>
<td>Huijgen¹⁰⁰</td>
<td>2007</td>
<td>Steel Slag Direct Carbonation with Flue Gas</td>
<td>*84%</td>
<td>141.55</td>
</tr>
</tbody>
</table>

Table 5-1 is an updated version of one by Leeson et al.,⁶⁵ where the tabulated literature was published prior to 2014. Evident in the previous table and here is that the majority of research has focused on absorption, which is likely the option most equipped for deployment, especially that of Chung et al.,⁹⁹ who developed a hybrid system of amine scrubbing and membrane capture and incorporated heat recovery. Also notable is that the studies that only consider capture efficiency (or recovery) of the stream input to the CCS technology all are capable of achieving at least 90% capture. This is at least indicative of highly efficient technologies that should be ready for experimentation with scaling-up.

Studies that consider emissions avoided from the whole plant are reaching a maximum amount of about 70%. This may be approaching the theoretical maximum when considering the relationship of emissions to cost;
capturing more emissions throughout the plant would require installation of several CCS modules on smaller emitters like process heaters.\textsuperscript{95}

When studying membrane systems for CCS, costs differ depending on whether the feed is compressed or the permeate side is under vacuum. Systems under vacuum are most sensitive to membrane life and cost, while systems with feed compression vary more with electricity, equipment, and operation cost parameters. This can affect the decision of which conditions to implement depending on operational needs of the CO\textsubscript{byproduct}, i.e., operating with feed compression produces a high P\textsubscript{CO\textsubscript{2}} stream well suited for later utilization, while for cases where costs are more important and/or P\textsubscript{CO\textsubscript{2}} is not an asset, vacuum operation reduces costs and P\textsubscript{CO\textsubscript{2}}.\textsuperscript{98}

Cost information for MC of steel slags is limited. Most research has focused on optimizing the process, with less focus on actual large-scale feasibility. The high emissions captured reported by Huijgen et al. in Table 5-1 actually depicts the ratio of CO\textsubscript{2} avoided to CO\textsubscript{2} sequestered, accounting for additional CO\textsubscript{2} generated from the MC process. Besides, the costs and nature of the two MC processes listed here differ incredibly from each other: the process of Stolaroff et al. is a simplistic scheme with rather low capture efficiency, and that of Huijgen et al. (which is more indicative of a full-scale MC process) has nearly the highest costs within the table. While many MC results listed in Table 2-2 have higher efficiencies than listed here in Table 5-1, their economic viability is not reported, adding more emphasis on a deeper economic analysis as suggested in Section 0.

In an overall analysis of global costs of CCS for iron and steel, it was found that adding CCS to a blast furnace would result in a 30-41\% increase to levelized cost of production (LCOP). This is particularly larger than other industrial applications, like natural gas processing and fertilizer production, because CCS is not inherent in the design of a blast furnace. However, costs can decrease by up to 17\% as CCS continues to be implemented and technology develops, especially through the progression of the pilot projects detailed in
Section 4.101

CCS implementation costs vary in countries around the world (Error! Reference source not found. Figure 5-1), due by and large to the difference in labour and energy costs: of the countries with the lowest costs for instalment, most have cheap labour (Indonesia, China, Poland, Mexico) and/or energy (Saudi Arabia).101

![Figure 5-1: Cost of First-of-a-Kind CCS through Iron/Steel Industry in Several Countries, Adapted](image)

5.2 Capital, Operating and Maintenance Costs

The capital costs reported for CCS technologies vary, largely due to their slow implementation in the iron and steel industry. Kim et al96 compared the distribution of capital equipment costs for PSA and MEA systems. Capital costs for the PSA system were 13.7% higher than the MEA system, largely due to the higher feed compressor cost for use at 6 bar operation. This single component comprises 60% of the PSA capital cost. However, the MEA system requires $42.4 million per year in operating costs due to higher utility usage, compared to PSA at $18 million. As a result, the annual costs for PSA were found to be roughly 47% lower than those for MEA separation.

Irlam101 presented a capital cost breakdown including equipment, construction labour, materials,
contingencies, and fees. For a US a plant, the major contributor to total capital was equipment at 33%, followed by construction labour at 27% and materials at 11%. Since these values were based on US costs, significant reduction opportunities exist for countries with cheaper labour.

5.3 Policy considerations

Government incentivization of CCS can greatly accelerate implementation by improving economics. These can come in the form of tax credits, carbon prices or taxes, or government mandates. The recent US incentive 45Q gives $50 per tCO$_2$ sequestered in saline aquifers, and $35 per tCO$_2$ utilized in products (both in terms of tax credits). Wiley et al. suggest the need for a 65 A$/tCO$_2$ to make CCS instalment in iron/steel economically viable for Australia, and Van Ruijven et al. suggest a carbon tax between 20-100 US$/tCO$_2$ to bring atmospheric CO$_2$ below 2010 levels.

As nations continue to become stricter on emissions and offer tax incentives for CCS, MC may become a more competitive CO$_2$ abatement option for plants where installation of other CCS forms is less convenient due to practicality or economics. It would be interesting to treat MC as a method of CO$_2$ sequestration post-CO$_2$ capture from other technologies like absorption. While the sequestration cost for saline reservoirs is rather cheap, at 6-13 USD/tCO$_2$, sequestration as carbonate minerals requires significantly less monitoring, and if done well, can be sold as a product.

6 The Way Forward

To mitigate emissions from the industrial sector, it is imperative that CCS technologies are quickly implemented into the iron and steel industry. Due to the changing global economy and demand of iron and steel products, it is important to continue to develop CCS technology to both retrofit existing iron and steel plants and provide newer, lower CO$_2$ technologies to new builds. Since global capacity growth it expected to stay net-stagnant, the implementation of retrofit or new builds technology will vary by country. Retrofit technologies will be of interest to the most developed countries, such as those in the NAFTA, EU, and even
China (who is currently removing facilities). Other countries who are rapidly increasing production capacity, namely India and Iran, may install new build steel production and CCS technologies in their new production facilities and can additionally implement retrofit CCS technologies on existing production facilities to further eliminate CO\textsubscript{2} emissions. Without implementation of CCS technologies, climate change mitigation goals for upcoming years will not be met.

One driver to accelerate CCS uptake could exist in coupling CO\textsubscript{2} capture from iron and steel facilities to beneficial reuse. The conversion of CO\textsubscript{2} to a marketable product can yield revenue and – in some locations– tax credits to help offset CCS costs. For example, ArcelorMittal has partnered with the US-based LanzaTech to produce bioethanol from BFG for use in the transportation sector or plastic production. Such partnerships can help overcome early economic barriers allowing for the construction of iron and steel CCS operations and, in turn, driving down costs through learning.

Current progress in emissions reduction in the iron and steel industry is highlighted by several pilot-scale initiatives in the past decade, as well as several successful laboratory-scale iron and steel production pathways and post-combustion technologies. While CCS and other mitigation technologies are becoming more well-developed and widely implemented, several hurdles present themselves for the future of these technologies, mostly relating to economics. Though process development has matured, a major issue is lack of industrial-scale experience with most of the technologies discussed. Processes will benefit greatly through learning from first-of-a-kind technologies, allowing future instalments to be more cost effective. Additionally, while it is relatively easy to capture CO\textsubscript{2} from BFG, there exist several other small-scale point sources scattered throughout the process that contribute 30-40% of the process CO\textsubscript{2} emissions. Further process intensification or recombination of gas exit streams could prove a useful strategy in mitigating the emissions from smaller combustion units.

Pilot scale initiatives, such as HYBRIT and ULCOS TGRBF with CCS, aim to demonstrate the pilot scale
operability of cutting-edge emissions reductions technologies. As these technologies mature, the economic risks and costs associated with them will decrease, encouraging more widespread implementation. Additionally, many of these pilot scale initiatives are supported (at least in part) by their respective country’s government. Government incentives for development and implementation of novel steel production and CCS technologies could greatly accelerate the implementation process by providing an economic incentive for technology deployment. Nonetheless, the success at the pilot scale level, advancement of novel technologies on the laboratory scale, and the continued deployment of governmental incentives worldwide demonstrate the opportunity to continue to advance the technologies.
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