Recent Sustainability Developments in the Iron and Steel Industry

An overview of some of the recent steel industry carbon emission reduction innovations will be provided, including: (1) Reduction in blast furnace production and the trend toward electric arc furnace steelmaking with scrap or direct reduced iron; (2) Hydrogen use in direct reduced iron processes with hydrogen created via green electricity; (3) Hydrometallurgical-based electrolysis of iron ore; (4) Molten oxide electrolysis (Boston Metals); (5) European developments under the Ultra-Low CO₂ Steelmaking (ULCOS) program (blast furnace top gas recycling, HiSarna); (6) Chemical production from waste gases; and (7) Slag use in the cement industry.

The iron and steel industry is one of the biggest global emitters of carbon dioxide, accounting for 7–9% of total global CO₂ emissions and approximately 30% of industrial CO₂ emissions.¹ Fig. 1 depicts the global crude steel production, which has continuously increased since the modernization of the blast furnace in the late 1800s. In 2018, global crude steel production reached just over 1.8 billion metric tons, which increased by 4.6% compared to 2017.³

If steel production continues to grow, reducing the CO₂ intensity of crude steel will become increasingly important for lowering the global emissions of the iron and steel industry. To stay on track with the Sustainable Development Scenario (SDS), the International Energy Agency’s initiative to meeting the Paris Agreement objectives, the iron and steel industry must decrease the CO₂ intensity of crude steel by 1.9% annually between 2017 and 2030.⁴ As shown in Fig. 2, the CO₂ intensity of crude steel has been declining since 2009 (in 2017 the annual decline was 1.8%); however, more efforts and continuous technology advancement in the iron and steel industry will be required to meet these targets.

Figures 1 & 2

Global crude steel production in millions of metric tons of steel.²

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there are necessary to lower the per-metric-ton emissions of steel product.

There are several recent developments that are aiming to reduce the environmental footprint of the steel industry. Many of these programs, technologies or innovations fall into one of the following categories:

1. Hydrogen reduction of iron ore.
2. The use of green power.
4. End of pipe technologies.

This paper discusses the current iron and steel process routes and their CO₂ emissions. This paper also reviews existing as well as up-and-coming low-emission technologies (LETs) which could radically change the iron and steel industry.

**Main Iron and Steel Process Routes** — There are three main manufacturing routes for steel production:

1. The integrated route, which uses blast furnaces (BF), basic oxygen furnaces (BOF) and coke ovens.
2. Direct reduced iron (DRI) production for steelmaking in an electric arc furnace (EAF).

The most common route is the traditional integrated steelmaking route, which uses the BF for ironmaking and the BOF for steelmaking (Fig. 3). Approximately 70% of global steel production relies on the BF and BOF route. Iron ore is used as the primary iron source, and metallurgical coke is used for the reduction of iron ore in the BF. The second and third routes for steel production involve an EAF with scrap and/or DRI as an iron source. Approximately 30% of the world’s steel production is produced by the EAF route. Typically, 50–100% of the feed to an EAF contains recycled steel scrap, with alternative virgin iron ore units (DRI or hot briquetted iron (HBI)) added to dilute scrap residuals or replace purchased scrap. Significant amounts of electricity are required to operate an EAF; however, the direct CO₂ emissions are typically lower for the EAF route.

Hatch has calculated the CO₂ emissions per metric ton of hot-rolled coil (HRC) produced for the three manufacturing routes. The traditional integrated BF and BOF route, a 100% DRI-fed EAF, and a 100% scrap-fed EAF. To calculate the emissions for the integrated BF and BOF steelmaking route, the following operational assumptions were used:

1. 90%/10% sinter/pellet ratio.
2. 1,600 kg/metric ton hot metal (HM) sinter + pellet into the BF.
3. 325 kg/metric ton HM coke rate.
4. 1.1 metric tons steel/metric ton HM output.
5. 0.98 metric ton hot-rolled coil (HRC)/metric ton steel.

The best 10% benchmark values of the Western European iron and steel industry were used to estimate the CO₂ emissions from coke and sinter plants, as 0.33 metric ton CO₂/metric ton coke, and 0.191 metric ton CO₂/metric ton coke. Excluding emissions from the lime kiln, and electrical demand after the slab caster, the CO₂ emissions from the BF and BOF route are approximately 2.05 metric ton CO₂/metric ton HRC. A Sankey diagram following the CO₂
emissions in the integrated BF and BOF steel mill is shown in Fig. 4.

Since large amounts of electricity are necessary for EAF steelmaking, calculated emissions per metric ton of HRC vary depending on the region where the EAF is operating (and its respective grid electricity emission factor). Grid electricity emission factors can be as low as 0.08 kg CO₂/kWh in France, and greater than 1.0 kg CO₂/kWh in China and India. To calculate the emissions for the two EAF scenarios, the Japanese national grid electricity emission factor of 0.47 kg CO₂/kWh was used. Emissions for DRI production were found to be approximately 0.5 metric ton CO₂/metric ton DRI assuming natural gas (NG)-based DRI production.

The resulting CO₂ emissions from a 100% DRI-fed EAF, and a 100% scrap-fed EAF are approximately 0.96 and 0.26 metric ton CO₂/metric ton HRC, respectively. Typical EAFs, which use a portion of both virgin iron units and scrap, will have emission values somewhere between the 100% DRI and 100% scrap-based routes. A summary of the calculated CO₂ emissions for the three scenarios is shown in Fig. 5.

**Regional Differences by Process Route** — Precursors to the modern-day BF and BOF steelmaking route have existed for hundreds of years; however, steelmaking using the EAF first began in the early 20th century and its use only began to take off in the 1960s when large quantities of scrap became available. Limitations to early EAFs were the lack of electrical power availability — particularly inexpensive electricity, lack of scrap availability, and their ability to only produce low-grade steel products. Improvements to EAFs over the last 50 years have now allowed nearly 80% of all steel products to be produced by EAFs. Countries with cheap electric power and available scrap or natural gas for DRI production typically produce a large amount of steel in EAFs. In 2018, 68% of all steel produced in the U.S. was produced via this process, compared to 12% in China, where scrap and cheap power continues to be a limiting factor. Fig. 6 shows the percent of crude steel produced in EAFs since 1985, highlighting the difference between U.S. and Chinese steelmaking.

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**Table 1: Typical BF-BOF Steel Mill Mass Balance**

<table>
<thead>
<tr>
<th>Process</th>
<th>CO₂ Emissions [kg/t HRC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power plant</td>
<td>185.0</td>
</tr>
<tr>
<td>Converter</td>
<td>171.0</td>
</tr>
<tr>
<td>Finishing</td>
<td>63.0</td>
</tr>
<tr>
<td>Coke Plant</td>
<td>450.0</td>
</tr>
<tr>
<td>Lime Kiln</td>
<td>270.0</td>
</tr>
<tr>
<td>Blast furnace</td>
<td>90.0</td>
</tr>
<tr>
<td>Soves</td>
<td>270.0</td>
</tr>
<tr>
<td>Total CO₂</td>
<td>1425.0</td>
</tr>
<tr>
<td>CO₂ from DRI</td>
<td>99.0</td>
</tr>
<tr>
<td>CO₂ from EAF</td>
<td>255.0</td>
</tr>
<tr>
<td>BOFG</td>
<td>827.0</td>
</tr>
</tbody>
</table>

Sankey diagram depicting a mass balance around a typical integrated blast furnace (BF)/basic oxygen furnace (BOF) steel mill, and the CO₂ emission points. The total CO₂ emissions are 2.05 tCO₂/t hot-rolled coil (HRC).
Current CO₂ emissions in the steel industry (in tCO₂/t HRC) for the traditional BF/BOF route compared to the direct reduced iron (DRI)/electric arc furnace (EAF) and scrap/EAF routes.

**Figure 5**

<table>
<thead>
<tr>
<th>Process Route</th>
<th>CO₂ Emissions (tCO₂/t HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ironmaking (BF)</td>
<td>1.452</td>
</tr>
<tr>
<td>Steelmaking (BOF)</td>
<td>0.171</td>
</tr>
<tr>
<td>Cokemaking</td>
<td>0.099</td>
</tr>
<tr>
<td>Sinter Plant</td>
<td>0.255</td>
</tr>
<tr>
<td>Pellet Plant</td>
<td>0.015</td>
</tr>
<tr>
<td>Steelmaking (EAF)</td>
<td>0.259</td>
</tr>
<tr>
<td>DRI Production</td>
<td>0.487</td>
</tr>
<tr>
<td>Finishing</td>
<td>0.063</td>
</tr>
<tr>
<td>Pellet Plant</td>
<td>0.148</td>
</tr>
<tr>
<td>Steelmaking (EAF)</td>
<td>0.193</td>
</tr>
</tbody>
</table>

**BF-BOF Route Total:** 2.05  
**DRI-EAF Route Total:** 0.96  
**Scrap-EAF Route Total:** 0.26

All values are in t CO₂/t HRC

**Emission Reduction Strategies**

**Process Route Selection — Integrated Steelmaking, EAF Steelmaking and DRI —**

Using the Japanese electricity emission factor, it is apparent that emissions from the EAF steelmaking route, particularly when scrap is used, are lower than the traditional BF and BOF route. To move toward greener steelmaking, a global transition toward the EAF route could significantly reduce CO₂ emissions in the iron and steel industry. If 60% of steel is produced via the BF and BOF route, and 40% is produced via the EAF route (using a 100% NG-DRI feed), emissions can be reduced by approximately 20% to 1.62 metric ton CO₂/metric ton HRC.

**Figure 6**

Production of crude steel in electric arc furnaces (% total of crude production).^8

**Figure 7**

World DRI/hot briquetted iron (HBI) production by region and year.^^9

*References:*

^8 Current CO₂ emissions in the steel industry for the traditional BF/BOF route compared to the direct reduced iron (DRI)/electric arc furnace (EAF) and scrap/EAF routes.

^9 Production of crude steel in electric arc furnaces (% total of crude production).

^^9 World DRI/hot briquetted iron (HBI) production by region and year.
Emissions could potentially be further reduced if higher scrap ratios are used in EAFs.

For EAF steelmaking to be a viable alternative to the traditional BF and BOF route, low-carbon electricity and scrap is necessary. Additionally, the EAF must become a suitable method for producing all grades of steel, which is only possible with the addition of virgin iron ore units to an EAF (i.e., DRI/HBI). A major constraint to DRI/HBI production is natural gas availability and cost. In regions where natural gas is an abundant resource (i.e., the U.S.), the favorability of DRI/HBI production for DRI/EAF steelmaking is high. Therefore, in regions with low-carbon electricity, and scrap and natural gas availability, it is feasible to assume that the DRI/EAF route could eventually replace the BF and BOF route, and produce a lower-
CO₂-emitting steel. A graph of DRI/HBI production by region and year is shown in Fig. 7. Globally, DRI/HBI production has significantly increased in recent years.

EAF steelmaking is currently constrained in China, the world’s largest steel-producing country, due to electricity limitations and low-cost DRI and scrap availability. Over the past decade, China has been importing steel scrap; however, in 2017 China’s steel scrap exports surged and China stopped importing scrap shortly after. In the coming years, China’s domestic steel scrap availability is expected to increase (Figs. 8 and 9) due to the fast growth of China’s steel industry in the 21st century, and electricity will become more abundant. It is therefore likely that the substitution of some BOFs with EAFs will become a global reality.

**Blast Furnace Improvements** — Since 70% of steel is currently produced using the BF and BOF route, a short-term strategy to reduce the carbon intensity of steel would be to apply incremental modifications and improvements to the existing BF route which reduce the emissions per metric ton of steel. Improvements to the BF and BOF route include technologies that make use of electrical energy, such as hot blast superheating, top gas recycling, stove or cokemaking process improvements, natural gas injection to the blast furnace to partially offset coke requirements, and the use of alternative fuels such as biomass.

Employing electrical technologies at the BF can reduce CO₂ emissions, provided the electrical energy is obtained from renewable power or a green national electric grid. Plasma torches, whose reliability and maintainability have improved significantly since their introduction to the BF in the 1980s, use electrical energy to generate a high-temperature, high-velocity plasma stream. Hatch’s hot blast superheating technology uses plasma torches to superheat the hot blast air to the BF, which decreases the coke consumption and increases the productivity of the furnace.¹¹ IGAR, a technology currently being developed by ArcelorMittal and Eurometa, utilizes a plasma torch reactor to reform the BF top gas and recycle the syngas containing CO back to the BF through the tuyeres, reducing carbon consumption.¹² Similarly, the top gas of a BF can be recycled using vacuum and pressure swing adsorption (VPSA and PSA) to separate and capture CO₂ and recycle CO back to the BF. The technology, which is being developed through the Ultra-Low CO₂ Steelmaking (ULCOS) program, is expected to lead to 35% reduction in coke rate, reducing the overall emissions of the BF and BOF route by approximately 18%.¹³

Coke dry quenching is an improvement to the existing cokemaking technology, which employs a heat recovery system...
from red-hot coke using inert gas. The recovered heat is used to produce steam in a boiler for other uses such as power generation, and the dry-quenched coke has a very low moisture content which leads to coke savings in the BF. Coke dry quenching technology is owned by Nippon Steel and Sumikin Engineering, and the technology is commercially available. As of March 2018, 126 units have been constructed, and they have 5–10% CO₂ savings compared to conventional coke ovens.14

Many blast furnace improvement projects have focused on the use of biocarbon as a replacement for metallurgical coal/coke. Similar to other fossilized carbon sources, biocarbon releases CO₂ to the atmosphere; however, the CO₂ released is considered to be balanced by the CO₂ absorbed during the growth period of the biomass, and thus biocarbon is considered to be greenhouse gas (GHG) neutral. Canadian Carbonization Research Association (CCRA) in partnership with CanmetENERGY’s Metallurgical Fuels Lab (MFL) aims to substitute fossilized carbon with biocarbon in existing iron and steel facilities. Their 2030 goals include a 10% substitution of metallurgical coal in cokemaking, 100% replacement of pulverized coal injection (PCI) in BF ironmaking and 100% replacement of carbon in EAF steelmaking.15 Torero, a project initiative by ArcelorMittal, uses torrefaction to convert waste wood into biocoal. A large-scale demonstration plant is currently under construction at ArcelorMittal Ghent in Belgium, which aims to convert 120,000 metric tons of waste wood per year into 50,000 metric tons of biocoal.12 Tecnoled, a new furnace developed by Vale, aims to use charcoal as a carbon source. The furnace is similar to a moving bed shaft furnace, which is charged with self-reducing briquettes and a solid carbon source to generate liquid pig iron, similar to the product of the blast furnace. Currently, a 75,000-tpy demonstration plant exists in São Paulo, Brazil, which has been operating since 2011.16

A major problem with the use of biomass as a carbon replacement in the blast furnace is that biocarbon is highly reactive, which leads to a significant reduction in coke quality. Steinmetzger et al. studied the use of sugarcane bagasses as a biomass material for biocoal production and found that the biocoal produced could not reach the same efficiency rates as fossilized coal.17 Experiments carried out by Ng et al. found that densifying the biocarbon with cokemaking coal in a briquette improved the quality of the resulting coal, however for these experiments, the coal blend only contained 10% biocarbon.18 Due to this reduction in coal quality, the complete replacement of fossilized coal with biocoal in the blast furnace is an unlikely reality.

Figure 10

Energy Transitions Commission’s (ETC) illustrative energy mix in a zero-carbon economy.19
In November 2018, The Energy Transitions Commission (ETC) published their “Mission Possible” report with an illustrative pathway presenting their view of the final energy mix in a zero-carbon economy for hard-to-abate industrial sectors. ETC predicts that only 5% of the energy mix in the iron and steel industry will be provided through bioenergy and bio-feedstocks (Fig. 10), and places a large role on green electricity and hydrogen technologies to obtain a zero-carbon iron and steel future.

Hydrogen-Based Steelmaking Projects — A long-term solution to mitigate CO₂ emissions in iron and steel is to promote technologies that replace carbon by hydrogen as a reducing agent of iron. The use of hydrogen avoids the generation of CO₂ and produces water instead. There are two ways hydrogen reduction can be employed:

1. Hydrogen injection into the BF reduces the amount of required coal/ coke.
2. Hydrogen can be used to produce H₂-DRI as an alternative to NG-DRI in EAF steelmaking.

Although the use of hydrogen in crude steel production could theoretically reduce CO₂ emissions to nearly zero in steelmaking, a global CO₂ emission reduction benefit will only be achieved if green hydrogen is used. Hydrogen can be produced by way of steam methane reforming, which is a reaction between hydrocarbons and steam under high pressure to produce hydrogen and carbon monoxide, an inherently non-green process, or electrolysis, which uses electricity to split water into hydrogen and oxygen. Hydrogen production via electrolysis requires between 55 and 86 kWh of electricity, and 15 L of water per kg of H₂ produced. Therefore, to generate green hydrogen, electrolysis technologies that use renewable electricity sources must be employed.

To completely replace carbon with hydrogen and produce the 1.8 billion tons crude steel generated via all process routes in 2018, 64 Mtpa of hydrogen is required, and 4,150 TWh/year of green electricity is needed to generate this amount of hydrogen. To put this into perspective, the electrical power needed to replace carbon with hydrogen and produce completely green steel amounts to about two times the annual Australian power consumption, or 10% of the 2018 annual Chinese electricity consumption. voestalpine has calculated that it would need approximately 33 TWh of external renewable electricity to produce enough hydrogen to operate its Linz and Donawitz BF and BOF production facilities. This corresponds to approximately half the current production of electricity in Austria, or about 4,000 wind turbines with a capacity of 4 MW each. The production of green hydrogen is therefore very costly compared to coal/ coke or natural gas production methods.

Despite the large amounts of hydrogen required to replace carbon as a reducing agent, and the high cost of hydrogen, many steelmakers have initiated projects for the exploration of hydrogen in blast furnaces. thyssenkrupp has partnered with Air Liquide in an aim to reduce the amount of pulverized coal in the blast furnace with steam-reformed hydrogen injection at the tuyeres. The project, which was set to begin in the fall of 2019, plans to inject 25,000 Nm³/hour of H₂ at its Duisburg BF9, saving approximately 19% CO₂/tHM produced. GrInHy2.0 and H2Future are technologies funded by EU Horizon 2020 that aim to produce green hydrogen for use as a reductant in the blast furnace via solid oxide electrolysis fuel cell technology. H2Future is currently building the world’s largest proton exchange membrane (PEM) electrolysis plant with a capacity of 6 MW to produce 1,200 m³/hour of green hydrogen at voestalpine Linz steel plant in Austria. Currently, the maximum amount of hydrogen replacement in blast furnaces for acceptable operation is unknown; however, it is unlikely that complete replacement of carbon with hydrogen using the existing blast furnace technology is achievable.

Perhaps a more promising application of hydrogen as a reducing agent exists with H₂-DRI production. NG-DRI production currently operates with approximately 55% H₂ in the reducing gas; therefore, the process has the potential to gradually introduce additional H₂ up to a composition of 100%, as H₂ becomes more economically feasible to utilize. According to Muller et al., H₂-DRI has the potential to reduce CO₂ emissions by 91% when compared to NG-DRI. DRI production technologies that aim to use H₂ as a reducing agent include H₂Hamburg, HYBRIT and SALCOS. H₂Hamburg is a new furnace technology owned by ArcelorMittal that uses H₂ generated from the recycling of waste gas, and green hydrogen as a reducing agent to produce 0.55 Mtpa of DRI. The process requires 685 m³STP H₂/metric ton HBI produced. The HYBRIT project (Fig. 11) is a H₂-DRI-EAF process owned by SSAB, LKAB and Vattenfall which uses H₂ produced via electrolysis for DRI production. A pilot plant is currently being constructed for this project in Luleå, Sweden. Salzgitter is spearheading the SALCOS study to produce DRI for feeds in both the BF and EAF.

Smelting Reduction Technologies — Smelting reduction is an alternative coal-based ironmaking process that is dependent on the gasification of coal in molten iron. The smelting reduction process consists of two zones: a pre-reduction zone and a smelting reduction zone. Coal enters the smelting reduction zone where it is gasified to produce heat and CO-rich hot gas. The heat melts the iron in the smelting reduction
zone whereas the hot gas is transported to the pre-reduction zone. The hot gas then pre-reduces the iron oxides before they enter the smelting reduction zone for the final reduction to take place. Smelting reduction technologies avoid the cokemaking process and tend to avoid iron ore agglomeration processes, significantly reducing CO₂ emissions. A disadvantage of most smelting reduction processes is the requirement of large volumes of O₂, which can be expensive. Currently less than 1% of steel is produced via smelting reduction processes.

The two most common smelting reduction technologies are HISARNA and FINEX. HISARNA is a part of the ULCOS program, which has the objective to achieve a 50% reduction of the CO₂ emissions in steelmaking. Since 2007, Tata Steel, Rio Tinto and ULCOS have been developing the HISARNA technology, which directly converts iron ore and coal into iron without any pre-treatment of the ore and coal (Fig. 12). This reduces CO₂ emissions by 20% compared to the conventional ironmaking route, and the use of biomass or steel scrap in the HISARNA furnace can further reduce emissions by 50%. Pure O₂ is used instead of hot air in the furnace, which produces a top gas with a high concentration of CO₂, making the HISARNA process ideal for carbon capture. The program has been collaborating with TNO to develop carbon capture and storage (CCS) methods such as...
greenhouse plant production, or enhanced oil recovery, to be used in conjunction with the HISARNA plant, reducing emission by 80%. Currently, a 60,000 tpy pilot plant exists at Tata Steel in IJmuiden, Netherlands, and a second plant of 400,000 tpy was expected to begin construction at the time of this writing.

FINEX consists of a series of fluidized bed reactors to reduce the ore to DRI in three or four stages, and then this is compacted and charged in the form of HBI to a melter-gasifier unit, reducing it to metallic iron. The FINEX furnace combines the sinter plant, cokemaking plant and blast furnace into a single unit. Currently three plants exist at POSCO Pohang Works in Korea, the largest being a 2.0-Mtpa industrial plant. The FINEX process has been reported to have 4% lower CO₂ emissions compared to the blast furnace route.

Carbon Direct Avoidance Options

There are two pilot-stage projects that are working on totally new process routes and have the potential to completely transform and nearly decarburize the steel industry: molten oxide electrolysis (MOE) and electrowinning of iron ore, which are both green electrical technologies.

Molten Oxide Electrolysis — Boston Metal is developing a process for carbon-free production of steel from iron ores. The process is at the small pilot-scale level of development. The MOE process takes iron ores and selectively reduces iron via an inert anode and a more stable molten oxide electrolyte layer. The pure iron is periodically tapped from the cells, alloying for additions, and then the steel is processed and cast as per typical downstream steelmaking equipment. The molten oxide layer is formed by gangue components of the iron ore combined with fluxes in order to maintain the target chemistry and basicity. The equipment employed in the process is similar to aluminum production electrolysis cells and is therefore scalable and suitable for incremental steel production at existing plants right through to direct replacement of large integrated steel plants. Boston Metal’s key innovation that allows for carbon-free steelmaking is the development of the inert anode such that oxygen (rather than CO or CO₂) is the main gas emitted from the cells. The MOE process will be a major consumer of electricity and requires a green power grid in order to reduce steel industry carbon dioxide emissions.

Siderwin Project Electrowinning of Iron Ore — The Siderwin process is a European steel industry initiative led by ArcelorMittal that uses an electrolytic bath to produce metallic iron. When the iron ore is introduced to the bath and an electrical current is run through the electrodes, iron is attracted to the cathode and oxygen is attracted to the anode. The project, funded by EU Horizon 2020, is at the piloting stage, and at the time of this writing, a 3-m industrial cell was under construction for the testing of various iron sources as feed materials, including iron waste sources.

Three main process steps are involved to produce metallic iron are:

1. Chemical reaction of hematite with soluble ferrous iron to form magnetite:

   \[ \text{Fe}_2\text{O}_3 + \text{HFeO}_2^- \rightarrow \text{Fe}_3\text{O}_4 + \text{OH}^- \]

2. Galvanic coupling of magnetite with iron:

   \[ \text{Fe}_3\text{O}_4 + \text{Fe} + 4\text{OH}^- \rightarrow \text{HFeO}_2^- \]

3. Electrocrystallization of iron under cathodic polarization:

   \[ 3\text{HFeO}_2^- + 3\text{H}_2\text{O} + 6\text{e}^- \rightarrow 3\text{Fe} + 9\text{OH}^- \]
The Siderwin process is designed to operate with a high energy efficiency and aims to have a flexible production rate, which will be ideal for operation on power grids that have intermittent renewable power. Tests at the Research and Development Laboratory in Maizières, France, have shown that less power is needed to operate the electrolytic cell compared to the power required to produce hydrogen from electrolysis. The Siderwin technology has been cited as having an 87% reduction of the direct CO₂ emissions compared to the traditional BF and BOF route.²⁹

### Waste to Product Processes

Carbon capture storage and utilization could also play a role in moving toward low-emission steel production. Carbon capture storage and utilization processes capture CO₂ from waste streams and reuse it as a feedstock for the generation of various chemical products, avoiding the use of coal or natural gas feedstocks. Captured CO₂ from iron and steel waste streams could be used as-is to enhance oil recovery in wells or can be converted to higher-value products such as bioethanol, biomethanol or polymers. CO₂ can also be stored in cement or utilized as a feed for algae growth; however, significant amounts of cement or algae are necessary to completely remove the current CO₂ emissions of the iron and steel industry, making scaling up of these technologies challenging.

Bioethanol is typically produced from the yeast fermentation of sugars from biomass, such as corn or sugarcane, and it is used as a substitute for petrol. Bioethanol is attractive as it is obtained from renewable resources, has lower toxicity and produces slightly less CO₂ emissions compared to fossil fuels. The increasing demand for bioethanol, as well as the biomass feedstocks, means the price of bioethanol has been increasing; therefore, sourcing bioethanol from an alternative feedstock would be ideal. LanzaTech, an American company, owns the biotechnology behind the separation of blast furnace top gas for bioethanol production. In partnership with LanzaTech, ArcelorMittal has been working on developing this technology through its Steelanol/Carbalyst projects. Blast furnace gas is passed through a reactor to capture the waste CO gas and biologically convert it to bioethanol. A life cycle analysis of this process determined that there is an 87% reduction in CO₂ emissions compared to fossil transport fuels.¹² A demonstration plant is currently being constructed in Ghent, Belgium, which plans to capture 15% of the waste gas from the plant and produce 80 million L of bioethanol per year.¹²

Carbon2Value is a similar project led by ArcelorMittal that uses pressure swing absorption to separate the blast furnace gas and convert it into bioethanol and ethylene for chemical production using the Fischer-Tropsch process.¹²

Methanol can be produced from blast furnace top gases or coke oven gas, reducing CO₂ emissions by avoiding the use of fossil fuels. The syngas for methanol synthesis can be a mix of H₂, CO₂ and CO; however, compounds such as N₂ must be removed from the gas before it is viable for methanol production.³⁰ Carbon2Chem, an initiative led by thyssenkrupp, consists of several subprojects that convert steel gas emissions into methanol, which can then be used to produce various methanol derivatives such as plastics, ammonia or oxymethylene. A pilot plant at thyssenkrupp’s Duisburg site began operation in 2018, and when the project is fully implemented, it aims to
reduce 20 million metric tons per year of steel plant emissions in Germany.31 FReSMe, a similar project funded by EU Horizon 2020, aims to convert CO₂ from blast furnace gas into methanol to primarily be used as a fuel in the ship transportation sector.32

A major problem with applying existing carbon capture storage and utilization technologies to the flue gas streams of an integrated steel mill is the existence of undesirable compounds. Before blast furnace gas or coke oven gas can be used as a feedstock, CO and CO₂ must be isolated. CO₂ Solutions, a Canadian company, has developed a process that uses the IT1 enzyme to accelerate CO₂ capture, generating a pure CO₂ stream (>99%) that is ideal for reuse or sequestration. Currently, a 30-metric-ton-per-day capture unit is being commissioned at a kraft pulp mill in Quebec, Canada.33

Conclusions

It is apparent that the iron and steel industry is putting significant investments into the research and development of technologies that will reduce its carbon footprint. Short-term solutions, such as incremental blast furnace improvements, or the transition to EAF steelmaking, can help reduce the per-metric-ton emissions of steel production; however, if a large reduction in CO₂ emissions is to be made, advancements in new alternative processes such as using hydrogen as a reductant or green smelting reduction technologies are necessary to decarbonize the industry (Fig. 13). Furthermore, government initiatives to support green energy and phase out fossil industries are crucial to advance these breakthrough technologies and make them both a sustainable and cost-effective alternative to the existing process routes.

References

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