# Technological Pathways for a Green Iron & Green Steel Supply Chain

Working paper for consultation | June 2024

**We welcome and seek stakeholder feedback on this report.**
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## Citation

P. Ellersdorfer, T.C. Leung, M.H.A. Khan, I. Canbulat, S. Saydam, I. MacGill, R. Daiyan (2024). *"Technological Pathways for a Green Iron and Green Steel Supply Chain"*. UNSW Sydney, Australia.

## Project Scope

This report outlines the technological pathways for a green iron and green steel supply chain between Australia and Germany. Both countries have significant clean energy and emission reduction targets, and key roles in the global steel industry. This report, focussing on technology pathways for a green iron and steel value chain between Australia and Germany, forms the second part of a series of reports for this feasibility and technical study.

## Acknowledgements

The authors thank the Australian industry and research stakeholders who generously shared their time and expertise during the preparation of this report. We also acknowledge the support of the Department of Climate Change, Energy, the Environment and Water (DCCEEW). While the insights and support provided were invaluable, the authors take full responsibility for the content and conclusions presented in the final report.

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# Executive Summary

Current steelmaking pathways involve the production of iron from iron ore, followed by the production of steel from iron using fossil fuels as both an energy source and reducing agent[1]. The most energy and carbon-intensive processes involve the conversion of iron ore to iron, accounting for over 88%[2] of direct $CO_2$ for current steelmaking pathways. Several technological pathways exist for the decarbonisation of the iron and steel industry, each at differing levels of development. Understanding the level of decarbonisation, material requirements and the current Technology Readiness Level (TRL) of each pathway are important factors in assessing the short-term and long-term viability of each process option.

The use of Carbon Capture, Utilisation, and Storage (CCUS) presents significant carbon abatement potential, only requiring capital expenditure for the integration of $CO_2$ capture and storage into existing processes. However, a major drawback of these pathways is their continued reliance on fossil fuels despite offering minimal disruption to existing supply chains. Apart from CCUS, carbon emissions can be decreased by incorporating low-carbon fuels into current processes. Examples include utilising biomass in blast furnace ironmaking or employing bio-syngas or pure hydrogen in the DRI process. These options not only reduce $CO_2$ emissions but also lessen our dependence on fossil fuels. In the gas-based DRI process, up to 100% of fossil fuel input can be substituted with bio-syngas or pure hydrogen, leading to significantly higher $CO_2$ reduction potential compared to the blast furnace process route with biomass substitution, where only a portion of the fossil fuel input can be replaced with biomass.

Outside of process modification, signification reductions in direct $CO_2$ emissions can be achieved by adopting new alternative process routes independent of existing methods. These include processes such as the Alkaline Iron Electrolysis, Hydrogen Plasma Smelting Reduction and Molten Oxide Electrolysis. However, these processes are at early stages of development, requiring significant investment and development before meeting commercial applications.

[1] In ironmaking, a reducing agent is a material that removes oxygen from iron ore, converting it to iron.
[2] Based on a blast furnace-basic oxygen furnace (BF-BOF) route and emissions intensity of 1476 and 193 $kg_{CO2}$/t for a blast furnace and basic oxygen furnace respectively.[1]

## Comparison of the Different Iron and Steel Technology Pathways

| Product Conversion | Base Technology | Energy Consumption[a] (GJ/t) | CAPEX[a] (AUD/t) | Decarbonisation Route | Current Technology Readiness Level[b] (TRL) | Net Direct $CO_2$ Emissions[c] ($kg_{CO_2}$/t) |
|---|---|---|---|---|---|---|
| Iron Ore to Iron | Blast Furnace | 15.28[2] | 228[3] | Base Technology | 11 | 1450[d] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 145[e] |
| | | | | Partially Replace Coke with Biomass | 7-10 | 1357[c,f] |
| | | | | Tuyere Injection Fuel Replacement | 7 | 926[c,f] |
| | Coal-Based Direct Reduced Iron | 21.9[4] 20[5] | 250[6] | Base Technology | 11 | 1048[1] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 105[e] |
| | Gas-Based Direct Reduced Iron | 12.16-13.0[2] | 310[2] 280-286[7] | Base Technology | 11 | 522[1] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 52[e] |
| | | | | Syngas Derived from Biomass | 7-8 | 0[c] |
| | | | | Electrolytic Hydrogen | 5-6 | 0[g] |
| | Electric Smelting Furnace | Data Unavailable | Data Unavailable | Base Technology | 9[h] | 0[i] |
| | Alkaline Iron Electrolysis | 9.9[2] | 755-970[2] | Direct Electrification | 4 | 0[j] |
| Iron to Steel | Basic Oxygen Furnace | 4.72-14.72[2] | 152[3] | Base Technology | 11 | 193[1] |
| | Electric Arc Furnace | 1.3-1.6[8,9] | 159[7] 172[3] | Base Technology | 11 | 50[k] [2] |
| Iron Ore to Steel | Hydrogen Plasma Smelting Reduction | Data Unavailable [l] | Data Unavailable | Hydrogen Plasma Reduction | 4 | 93[2] |
| | Molten Oxide Electrolysis | 14.76[2] | 1100-1150[2] | Direct Electrification | 4 | 0[m] [10] |

a. Energy consumption and CAPEX estimates refer to the base technology and do not account for any additional CAPEX or energy requirements where decarbonisation is performed through modification of the base technology. Any currency conversions were assumed at 0.7EUR:AUD and 0.7USD:AUD.

b. As determined by this report, according to Technology Readiness Scale (TRL) defined by the International Energy Agency (IEA).[11]

c. Net Direct $CO_2$ emissions only consider emissions arising from the process, this omits indirect emissions arising from electricity generation & raw material preparation. In cases where biomass is used, these fuels are assumed to have net-zero emissions and are hence deducted from the net direct CO2 emissions for that pathway.

d. Estimated based on a coke consumption rate of 0.32 $t/t_{Iron}$[12-14] and a pulverised coal (tuyere injection) consumption rate of 0.20 $t/t_{Iron}$[14] for a coke emission factor of 2895 $kg_{CO2}/t$[15] and anthracite emissions factor of 2617 $kg_{CO2}/t$[15]. Estimate aligns with literature reported value of 1476 $kg_{CO2}/t_{Iron}$.[1]

e. Assuming a $CO_2$ capture efficiency of 90%.[16]

f. Based on a coke replacement rate of 10% and a pulverised coal (tuyere injection) replacement rate of 100% (refer to **Section 4.1** for details), for a coke emissions factor of 2895 $kg_{CO2}/t$[15] and anthracite emissions factor of 2617 $kg_{CO2}/t$[15]. In both cases the replacement fuel is assumed to net-zero $CO_2$ emissions.

g. Although this process is reported as having direct carbon emissions of 25 $kg_{CO2}/t_{Iron,}$[2] this is due to carbon addition in the EAF process (if considering the use of H2-DRI coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[2]

h. Although the electric smelting furnace is currently under commercial operation in limited applications, further development is needed for the application of ESFs with DRI processes and on different ore types.[17]

i. The carbon emissions from the ESF process are assumed to be negligible. However, it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

j. Although this process is reported as having direct carbon emissions of 180 $kg_{CO2}/t_{Iron,}$[2] this is due to carbon addition in the EAF process (if considering the use of AIE coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[18]

k. Due to the injection of carbon in the EAF process and consumption of graphite electrodes.[2,19]

l. Large-scale or pilot-scale data unavailable. Energy requirements of a bench-scale demonstration for a 1kg sample of iron ore indicate a power consumption of 22-40kWh/$kg_{IronOre}$.[20]

m. Although the reported direct $CO_2$ emissions from this process are 0 $kg_{CO2}/t_{Steel}$ it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

## Synergy Between Australia and Germany

Regardless of which technological pathway is used, large amounts of renewable energy and iron ore are necessary to produce green iron and steel. The symbiotic relationship detailed in **Report 1** where the synergy of abundant renewable energy, iron ore resources and strong international relationships has the potential to establish a value-added supply chain between Australia, Germany, and Europe, fostering the production and export of green iron, steel, and related products. This suggests three possible roles that Australia could provide in the advancement of green steel production in Germany:

i) Export iron ore and renewable hydrogen (and derivatives) to enable the integrated production of green iron and green steel in Germany,
ii) Produce green iron locally in Australia and export green iron and renewable hydrogen (and derivatives) to support the production of green steel in Germany,
iii) Produce both green iron and green steel locally in Australia for export to Germany. The steel would still generally require further processing into the specialty steels used in German and European steel markets.

At present, we acknowledge that the first two options are likely the better fits for current industry arrangements in both Australia and Europe.

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# 1 What is Iron and Steel?

**Iron and steel are alloys comprised primarily of metallic iron (Fe) and carbon (C) seeing wide application in industries including construction, automotive, and aerospace industries. Currently, the iron and steel industry directly employs an estimated 6 million people, generating a total of US$2.5 trillion in revenue globally.**

The term "iron" can refer to various forms depending on the context. Iron in its pure form, often referred to as metallic iron (Fe), is one of the most abundant rock-forming elements, constituting around 5% of the Earth's crust.[21] However, in nature iron is not found in its pure form. Instead, it is found as mineral oxides in compounds such as hematite ($Fe_2O_3$) and magnetite ($Fe_3O_4$). These compounds contain iron in a chemical form that is not directly usable in most industrial applications. To make iron usable for manufacturing, it needs to be extracted from these ores and combined with other elements, such as **carbon (C**) and other alloying elements, to produce iron and steel.[21] Currently, the iron and steel industry directly employs an estimated 6 million people, generating a total of **US$2.5 trillion** in revenue globally.[11]

Iron and steel are commonly categorised according to their carbon content. Typical types of iron and steel include wrought iron, cast iron, ductile iron, pig iron and sponge iron, low-carbon steel, medium-carbon steel, high-carbon steel and alloy steel (**Figure 1**).

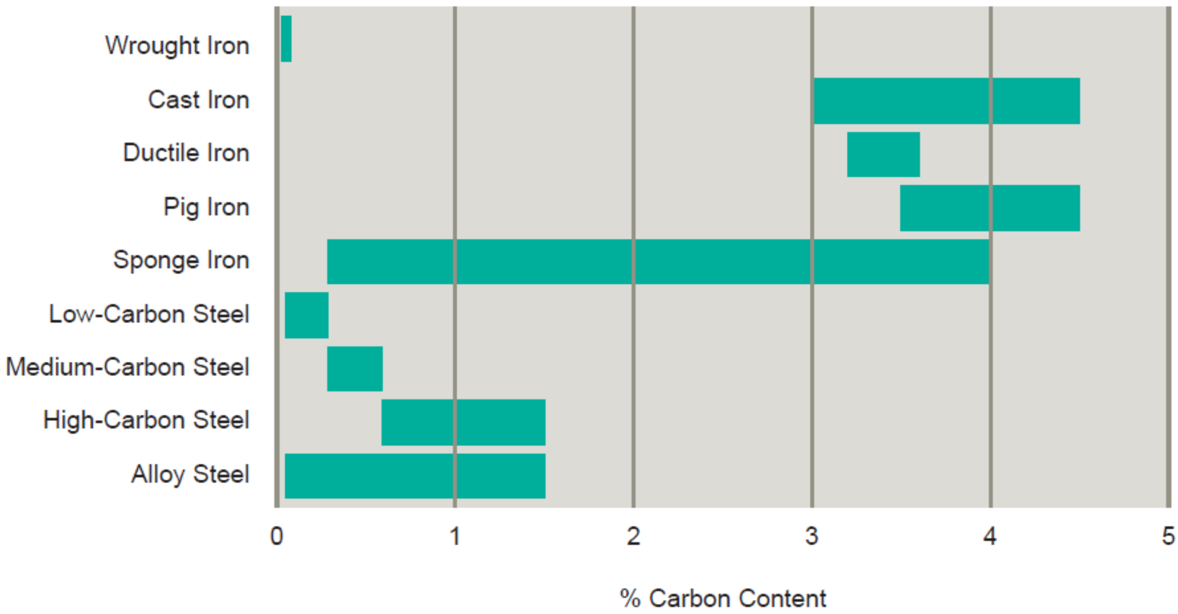


**Figure 1. Iron and steel categorised by carbon content**. In general, iron contains a much higher carbon content than steel. The level of carbon (and in the case of steel, other alloying elements) give rise to diverse range of properties exhibited by these materials.

**Wrought iron** was the most prevalent form of iron throughout the Iron Age and is characterised by a low **carbon content ranging from 0.02% to 0.08%.**[22] This is attributed to its formation at relatively low temperatures, where carbon is less able to absorb into the iron. Wrought iron is currently used for railroads, shipbuilding and in architectural applications such as iron grating and fencing.[23] **Cast iron** refers to iron that is formed at higher temperatures and has a **typical carbon content of 3% to 4.5%.** This higher carbon content leads to cast iron having an increased hardness and brittleness compared to other iron[22]. Cast iron is versatile, finding applications in kitchenware, electrical fittings, hand tools and also serving as a precursor to pig iron.[24] Cast iron can also take the form of ductile cast iron (often referred to as ductile iron). Ductile iron differs from cast iron due to the presence of nodular graphite resulting in enhanced ductility (resulting in its name).[25] **Ductile iron typically has a carbon content of 3.2% to 3.6%** and finds applications in the production of ductile iron pipe,[26] used for water and sewer lines.

In contrast to wrought and cast irons, which have direct applications, pig iron and sponge iron are produced as intermediate products used in the production of steel or steel alloys.[27] **Pig iron is formed in a blast furnace** and typically has a **carbon content of 3.5% to 4.5%**[27]. Pig iron typically takes the form of small ingots known as "pigs",[28] giving rise to its name. Conversely, **sponge iron** is formed through the **direct reduction of iron ore** and typically has a **carbon content of 0.3% to 4%**[27,29]. Sponge iron is porous in structure and has a lower density compared to the other irons.[27]

Like iron, steel is also comprised of iron and carbon. Steels that contain carbon as the main alloying element are referred to as **carbon steels**. Carbon steel is categorised as **low-carbon** (containing 0.05-0.3% carbon), **medium-carbon** (containing 0.3-0.6% carbon), and **high-carbon** (containing 0.6-1.5% carbon).[30,31] Carbon steel can be used for a variety of applications in the automotive and construction industries, and for the production of hand tools. Although carbon steel is regarded for its strength and durability, it is more susceptible to rust than alloy steels.[30]

Alloy steel refers to steel that contains alloying elements (e.g. aluminium, chromium, copper, manganese, nickel, silicon, and titanium) in addition to the carbon found in regular carbon steel.[30] Alloying content ranges from 0.01-0.1% (micro-alloyed) to over 5% (high-alloy steels).[32] High-alloyed steel includes stainless steel, which is characterised by at least 10.5% chromium,[32] along with nickel, silicon, manganese, and carbon.[33] Due to their desirable mechanical and chemical properties, alloy steels are widely used in a variety of applications including construction, automotive, and aerospace industries.[30]

### 1.1 Green Iron and Steel

As detailed in **Report 1**, the International Energy Agency (IEA) has established criteria for near-zero steel emissions by setting an emissions threshold ranging from **0.4 tonnes of $CO_2$ per tonne of steel for 100% primary steel production to 0.05 tonnes of $CO_2$ per tonne of steel for 100% secondary steel production** (i.e., using steel scrap).[34,35] Currently, primary steel production methods have an estimated emissions intensity of **2.33 tonnes of $CO_2$ per tonne of steel for the BF-BOF route** and **1.37 tonnes of $CO_2$ per tonne of steel for the DRI-EAF route**, with **secondary steel production methods** having an emissions intensity of **0.68 tonnes of $CO_2$ per tonne of steel**.[36]

The need to decarbonise commodities such as iron and steel, is further highlighted by the European Union's Carbon Border Adjustment Mechanism (CBAM), which will come into full effect from 2026.[37] CBAM targets carbon-intensive industries, including iron and steel, by imposing tariffs on imported goods based on their embedded emissions. This mechanism ensures that the carbon price for imported goods aligns with that of domestic production,[37] emphasising the growing importance of emissions reduction in globally traded commodities like iron and steel.

# 2 Current Technology Pathways for Ironmaking

**Ironmaking refers to the process of converting iron oxides, such as hematite ($Fe_2O_3$) and magnetite ($Fe_3O_4$), into iron. Currently, there are two main process pathways for the production of iron: the Blast Furnace, which results in the production of Pig Iron, and Direct Reduced Iron (DRI), which results in the production of Sponge Iron.**

Ironmaking and steelmaking are distinct processes, typically operated together to produce steel from iron ore (as detailed in **Report 1**), with more than **98%** of total iron production used for the production of steel.[38] Ironmaking refers to the process converting iron oxides, such as hematite ($Fe_2O_3$) and magnetite ($Fe_3O_4$), into iron. Currently, the primary pathways for iron production from iron ore include **Blast Furnace (BF)** and **Direct Reduction of Iron (DRI).**

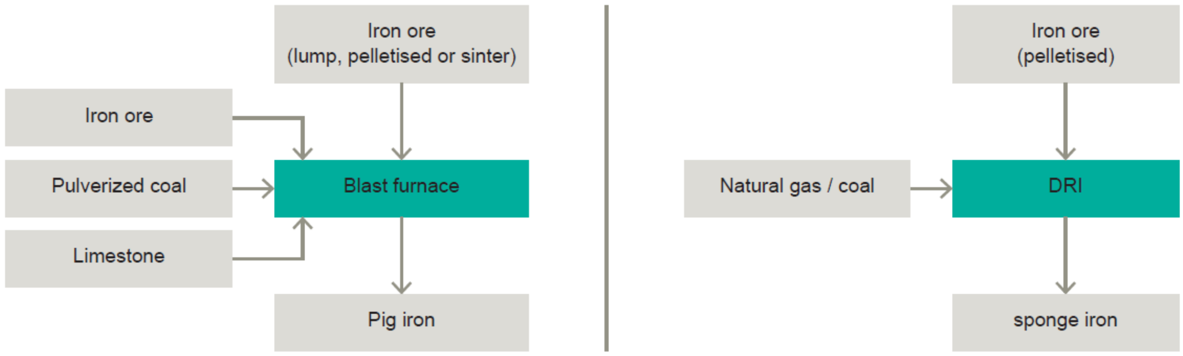


**Figure 2. Current technology pathways for ironmaking**. The blast furnace and direct reduction of iron processes are currently the 2 major processes used for ironmaking.

## 2.1 Blast Furnace

The Blast Furnace (BF) was first employed in the 12th century,[39] and became the conventional method of ironmaking from the 16$^{th}$ century onwards.[40] Pig iron is the main product of iron ore reduction in a blast furnace and represents the most produced form of iron in the world, with about 1301.1 million tonnes made in 2022.[41]

The BF operates by converting iron oxide into iron using coke (a form of coal) as the reducing agent.[42] In this process, the furnace is stacked with alternating layers of iron ore and coke.[27] Blast air is pre-heated through pre-heated chambers or "stoves",[43] which operate as regenerative heat exchangers, heated by process waste-heat through the blast furnace top-gas.[44] The pre-heated blast air and pulverised coal are then injected into the base of the furnace via tuyeres (forming regions in the furnace referred to as raceways), while pelletised iron ore, coke and flux (typically limestone) are loaded into the top of the furnace.[11,42]

The hot gases travel upwards through the layers of iron ore and coke, providing heat to the melt the iron ore pellets and resulting in the counter-current flow of descending iron ore to rising reducing gases.[11,42] Modern blast furnaces range in size from 20 to 110 m in height with diameters of 6 to 15 m.[45] A diagram of a typical Blast Furnace is provided in **Figure 3**.

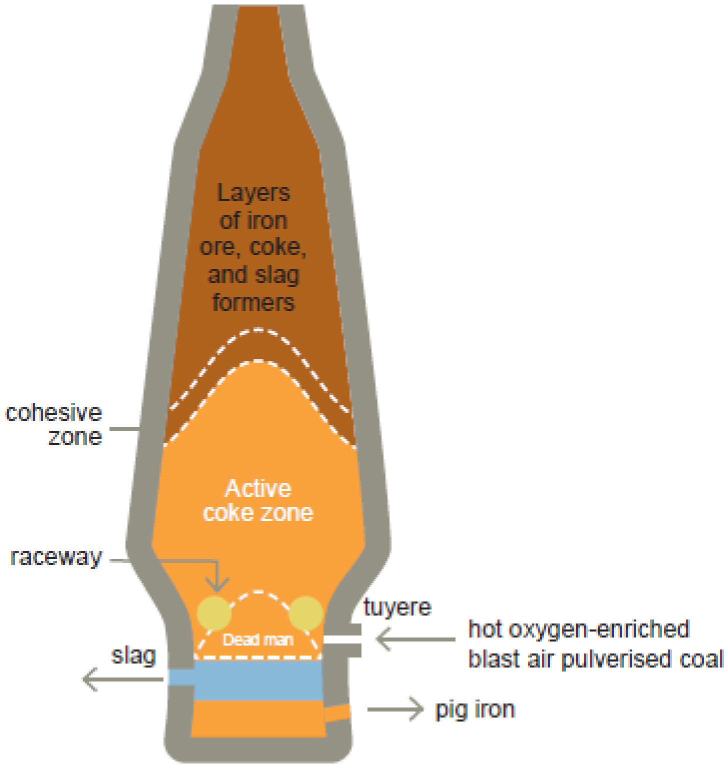


**Figure 3. Diagram of a blast furnace.** Image adapted from[46]. The blast furnace process reduces iron ore using coke. The reduction of iron ore occurs across 4 zones: Dead Man, Active Coke Zone, Cohesive Zone and Reduction Zone.

The operation of the furnace can be divided into four zones (moving from the base of the furnace to the top)[42]:

- **Dead Man** (otherwise known as the "Active Coke Zone"[42]): This is the zone of highest carbon concentration.
- **Active Coke Zone**: This is where blast air encounters hot coke, leading to combustion.
- **Cohesive Zone** (otherwise known as the "Fusion Zone"[42]): This is where iron ore pellets are melted.
- **Reduction Zone**: This zone extends up from the cohesive zone and is where iron oxide is reduced to iron.

Carbon monoxide is produced in the *active coke zone* and rises through the furnace, contacting the iron ore and reducing it to iron. The reduction sequence occurs in 3 steps, first, by converting hematite ($Fe_2O_3$) into magnetite ($Fe_3O_4$), then into wustite ($FeO$) and finally to iron ($Fe$).

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + O_2 \qquad \textbf{Eq 1}$$
$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2 \qquad \textbf{Eq 2}$$
$$FeO + CO \rightarrow Fe + CO_2 \qquad \textbf{Eq 3}$$

The resulting product, pig iron, has a high carbon content ranging from 4-5%,[47] and iron content ranging from 90-95.5%, depending on the ore and coke used.[48] The resulting pig iron can either be processed further to steel, although it may also be used directly as cast iron.

The following **Figure 4** and **Table 1** outline the major process inputs and waste products for the typical BF process.

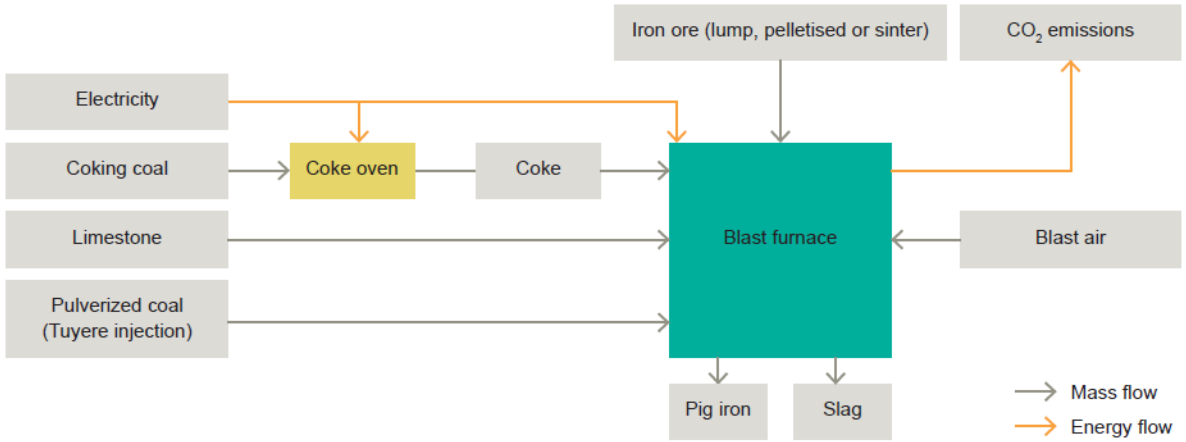


**Figure 4. Schematic of Blast Furnace Process**. Iron ore, coke, limestone, pulverised coal, and blast air are introduced into the blast furnace to produce pig iron and slag.

**Table 1. Major process inputs and outputs from a typical blast furnace process.**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | The iron ore used for the BF process is typically a mixture of pellet (62-66%Fe), sinter (55-58%Fe), and direct shipping ore (>60%Fe).[27,47,49] | 1.4-1.5[a] $t/t_{Iron}$ |
| Limestone | Limestone is the most common flux material used for ironmaking. Flux is used to react with and remove impurities form the iron ore (in the form of slag).[47] | 41-44 $kg/t_{Iron}$[3,12] |
| Coking Coal | Coking coal is used to produce coke in the coke oven. | 1.4[b] $t/t_{Coke}$ |
| Coke | Coke is used in the blast furnace to act as the reducing agent for the iron ore.[42] | 0.28-0.36 $t/t_{Iron}$[12-14] |
| Pulverised Coal (Tuyere Injection) | Fuel is injected into the tuyeres to provide heat to the blast furnace. Other fuels including natural gas or oil can be used in place of pulverised coal.[50] | 0.15-0.22 $t/t_{Iron}$[14,51] |

| | | |
|---|---|---|
| Electricity | Electricity is used to power blast furnace and ancillary equipment. | 0.10 $MWh/t_{Iron}$[8] |
| | Electricity is used to power coke oven and ancillary equipment. | 0.04 $MWh/t_{Coke}$[8] |
| Slag | Slag is produced as a waste product from the blast furnace, resulting from the impurities present in the iron ore.[47] | 0.21-0.28 $t/t_{Iron}$[52,53] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from blast furnace primary reactor. Omits indirect emissions including electricity generation and raw material preparation (this includes omittance of the 97 $kg_{CO2}/t_{Iron}$[1] generated by the coke oven.) | 1450[c] $kg_{CO2}/t_{Iron}$ |

a. Calculated based on an iron ore grade of 60-65% Fe(w/w) and a pig iron metallic iron content of 92% Fe (w/w).[28]

b. Assuming a coke oven yield of 70%.[54]

c. Estimated based on a coke consumption rate of 0.32 $t/t_{Iron}$[12-14] and a pulverised coal (tuyere injection) consumption rate of 0.20 $t/t_{Iron}$[14] for a coke emissions factor of 2895 $kg_{CO2}/t$[15] and anthracite emissions factor of 2617 $kg_{CO2}/t$[15]. Estimate aligns with literature reported value of 1476 $kg_{CO2}/t_{Iron}$.[1]

Modern BFs are designed to operate with minimal maintenance.[55] These processes are equipped with refractory lining to protect the shell from high temperatures and abrasive materials from inside the furnace. Historically the refractory lining was replaced every 6-7 years,[56,57] however modern blast furnaces are designed for the **refractory lining to be replaced every 10-12 years or more**.[57,58] Similarly, the blast furnace stoves require little maintenance, typically operating with a minimum service period of 15-20 years with maintenance work typically occurring during the shutdown period of the blast furnace.[56]

Outside of replacement of the refractory lining, there are instances where the blast furnace must be taken offline to perform other maintenance tasks such as replacement of the tuyeres, tuyere coolers or maintenance of peripheral equipment.[59] Tuyere replacement is a common part of blast furnace maintenance, with tuyere failure usually caused by crack formation, wear, and burn-throughs. The lifespan of a tuyere depends heavily on the stability of the blast furnace operation, where the average lifespan can be 5-7 months and up to 14-15 months under optimal operation.[60]

The following **Table 2** summarises some of the major global suppliers of BFs and related products.

**Table 2. Major suppliers of blast furnaces and related equipment**

| Equipment Supplier | Location |
|---|---|
| Primetals Technologies[61] | UK |
| Paul Wurth (SMS Group)[62] | Germany |
| MHeavyTechnology[63] | Portugal |
| CISDI Engineering[64] | China |
| Magnezit Group[65] | Russia |
| IHI Corporation[66] | Japan |

## 2.2 Direct Reduced Iron

The Direct Reduction of Iron (DRI) process gained prominence in the 20th century.[67] Application of this process began with the introduction of the rotary kiln for coal-based iron reduction in 1930, followed by the development of a gas-based process in 1932.[67] In general, the use of DRI processes emit only 30-57% of the carbon emissions produced in a traditional blast furnace.[2,68] This has led to the recent uptake in DRI processes around the world, with current production of direct-reduced iron reaching 125 million tonnes, up from 76.9 million tonnes 10 years ago.[41,68] **Globally, 70.1% of Direct Reduced Iron (DRI) processes utilise natural gas, while the remaining 29.9% rely on coal, predominantly in India**.[2,69]

The DRI process is a solid-state reduction method, meaning the ore does not melt, and impurities are retained throughout the process. Consequently, iron produced from a DRI process typically contains up to 1.4 times more bonded oxide impurities (gangue) than iron produced in a blast furnace.[27] These additional impurities must be removed during the steelmaking process, which can cause operational challenges.[70] Therefore, although DRI processes can operate with ore that has an iron content of 64-66%,[25,6471] the preferred feed for a DRI plant is ore with an iron content of 67% or greater, necessitating the beneficiation of lower-grade ores.[72,73]

There are currently two main DRI processes, one which relies on coal as the reducing agent and the other which relies on natural gas. The Iron produced in each of these DRI processes differs significantly from that produced in a blast furnace, producing an iron which is porous in structure, often referred to as sponge iron. Coal-based processes typically result in iron of low carbon content (<1%)[27]. However, coal can be charged at the end of the kiln to increase the carbon content to 3.5-4%.[74] Natural gas-based processes typically result in iron of slightly higher carbon content (>1%).[27] However, the reducing gas can be introduced as a coolant for the direct-reduced iron to increase the carbon content to 3-4%.[27] The process and operating requirements of the coal-based and gas-based DRI processes are outlined below.

### 2.2.1 Coal-based Direct Reduced Iron

Coal-based DRI processes can employ various reactor vessel types, such as fluidised bed, cyclone converter furnaces and smelting reduction vessels as observed in the HIsarna process.[2] However, the most used type is the rotary kiln.[27] A typical rotary kiln has a diameter of 4-6m and length of 60-125m (with an length/diameter ratio of 15-20).[27] The kiln also features an internal slope of 2-3% toward the end of the tube, which can be adjusted to accommodate different treatment capacities.[74] A diagram of a rotary kiln, such as what is used for the coal-based DRI is provided in **Figure 5**.

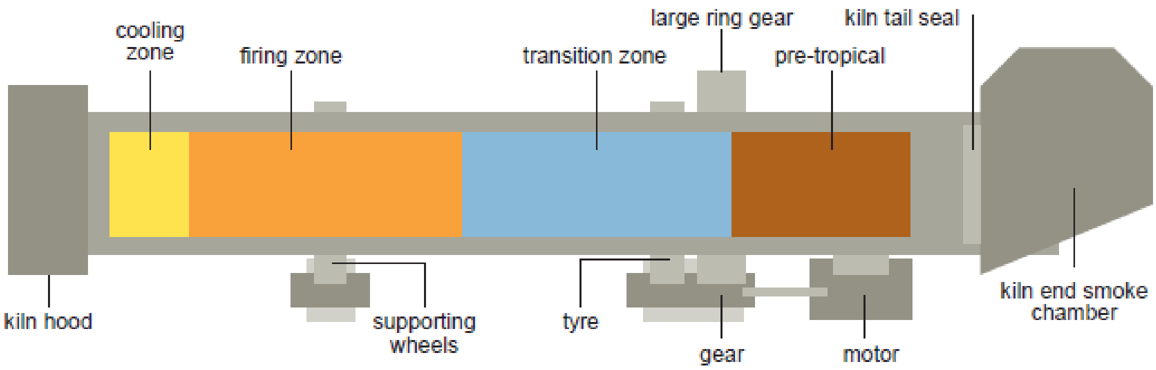


**Figure 5. Diagram of a rotary kiln**. Image adapted from.[75] Iron ore and coal are added to a rotary kiln where the addition of heat allows for the direct reduction of iron ore.

Coal-based DRI can use non-coking coal. However, the sulphur content must be low.[74] The coal provides the environment for iron to be reduced and the necessary heat for the reaction to occur.[74] Pre-heated air can also be charged into the kiln to maintain uniform temperature.[27] The coal-based reaction is performed by reacting carbon monoxide with iron ore by the following reactions: [27,71,76,77]

$$3Fe_2O_{3(s)} + CO_{(g)} \rightarrow 2Fe_3O_{4(s)} + O_{2(g)} \quad \textbf{Eq 4}$$

$$Fe_3O_{4(s)} + CO_{(g)} \rightarrow 3FeO_{(s)} + CO_{2(g)} \quad \textbf{Eq 5}$$

$$FeO_{(s)} + CO_{(g)} \rightarrow Fe_{(s)} + CO_{2(g)} \quad \textbf{Eq 6}$$

$$CO_{2(g)} + C_{(s)} \rightarrow 2CO_{(g)} \quad \textbf{Eq 7}$$

The following **Figure 6** and **Table 3** outline the major process inputs and waste products for the typical coal based DRI process.

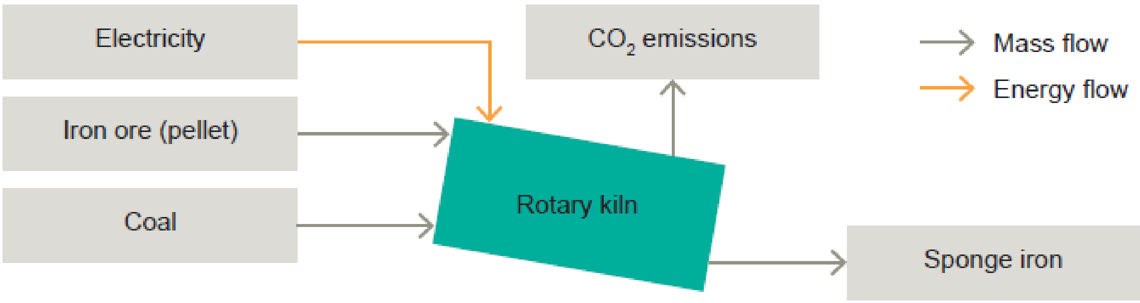


**Figure 6. Schematic of coal-based DRI process utilising a rotary kiln.** Iron ore and coal are introduced into a rotary kiln where the ore is directly reduced to sponge iron by the coal.

**Table 3. Major process inputs and outputs from a typical coal-based DRI process.**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | The DRI process requires high grade ore (64-66%Fe, >67%Fe preferred) and containing low levels of impurities (<4% $SiO_2$+$Al_2O_3$, 0.008% S, <0.05% P and <0.15% $TiO_2$, <1% moisture).[27,71] Coal based DRI processes typically require size graded or pelletised iron ore.[71] | 1.38-1.60$^a$ t/$t_{Iron}$[4,78] |
| Electricity | Electricity is used to power the process and ancillary equipment. | 0.05-0.10 MWh/$t_{Iron}$[4,79] |
| Coal | Coal is used as the reducing agent for coal based DRI processes | 0.5-1.6 t/$t_{Iron}$[4,79] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor, for coal based DRI process. Omits indirect emissions including electricity generation or raw material preparation | 1048 $kg_{CO2}$/$t_{Iron}$[1] |

a. The exact amount depends on the iron content and level of impurities of the iron ore.

To withstand high temperatures during operation, the inner section of a rotary kiln is comprised of one or multiple layers of refractory materials. This is necessary to shield the steel casing of the kiln, surrounding elements (including sensitive equipment and personnel), and to minimise heat losses, thereby reducing operational costs. Typically, these materials exist in the form of castables or bricks with various chemical compositions dependant on specific service conditions.[80]

The refractory lining in the upper, cooler sections of a rotary kiln can withstand a lifespan of **5-20 years**; however, in the reduction zone, where higher reaction temperatures are encountered, the lifespan significantly decreases.[81] In this area, **refractory lining replacement often aligns with the scheduled maintenance of the plant, occurring at intervals of 12 or 24 months.**[63,64]

The more shutdowns and stops the kiln experiences, the shorter its lifespan and the risk of refractory damage is closely tied to the rate of kiln cooldown, with the highest danger occurring during excessively rapid cooling.[81] Furthermore, abrasion of the refractory lining occurs along the entire length of the rotary kiln but becomes more pronounced towards the discharge end, where much of the iron ore has already been reduced into Direct Reduced Iron (DRI).[82] Outside of refractory lining, rotary kiln routine maintenance requirements include the following:[83]

- **Riding Ring:** Wraps the kiln shell, providing radial stiffness and a contact area for kiln rotation. This can wear from physical damage or contact wear between the retaining components and the riding ring. Tire griding, alignment or replacement can be performed to resolve these issues.
- **Kiln Shell:** Forms the outer structure of the rotary kiln. Kiln crank or ovality can occur along the shaft furnace, or refractory lining can come loose. If this occurs, those sections of the kiln can be replaced.
- **Carrying Station:** Located at the load piers, it includes the base frame and all support mechanisms (bearing assemblies and trunnions etc). These can wear out, resulting in excessive heat and vibrations / noise. Frequent alignments and lubrication are needed, as well as potential replacement if necessary.
- **End Seal:** Positioned at the point of transfer between the rotating element and the stationary hood or duct. Kiln seals are used to minimise the drawing of excess air and expulsion of kiln gases. These can wear out, resulting in replacement as necessary.
- **Drive System:** Responsible for kiln rotation, comprising the main gear, drive pinion, and a motor/reducer assembly. These can wear down or become unaligned, frequent lubrication and alignment is necessary.

The following **Table 4** summarises some of the major global suppliers of coal-based DRI processes and related equipment.

**Table 4. Major suppliers of coal-based DRI and related equipment**

| Supplier | Location |
| --- | --- |
| Electrotherm[84] | India |
| Innov Engineering[85] | India |
| Metso[86] | Finland |

### 2.2.2 Gas-based Direct Reduced Iron

There are currently two major technology providers for gas-based DRI processes: Midrex and Energiron.[87] Midrex currently dominates the market, providing approximately 80% of all gas-based DRI plants in 2022.[88] Both Midrex and Energiron DRI processes rely on shaft furnaces; however, other gas-based DRI processes, such as HIsmelt, COREX, FINEX, FINMET and FINORED utilise different reactor vessel arrangements like fluidised beds and smelting reactors.[2,76] Coal gasification or reformed natural gas serves as the reducing agent, with natural gas being reformed into carbon monoxide ($CO$) and hydrogen ($H_2$) in the presence of a nikel ($Ni$) or aluminum oxide ($Al_2O_3$) catalyst.[27,77] A diagram of the gas-based DRI process operating with a shaft furnace has been provided in **Figure 7**, the typical Midrex shaft furnace has a diameter of 4-7m.[89]

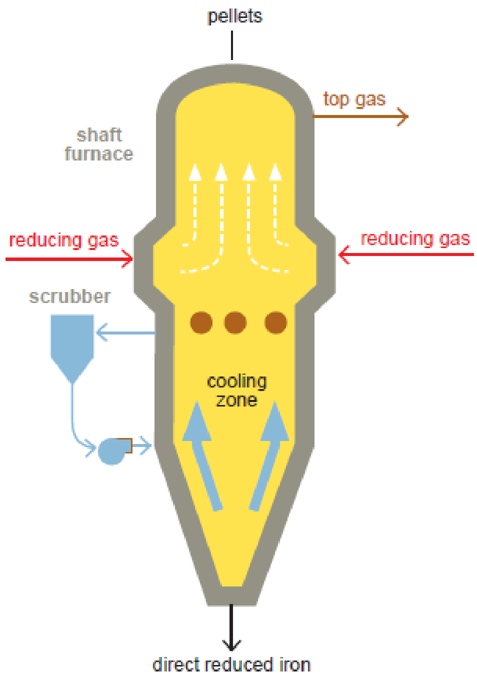


**Figure 7. Diagram of a gas-based DRI process (based on the Midrex process).** Image Adapted from.[90] Syngas and iron ore are introduced into a shaft furnace where the iron ore is directly reduced by the gas.

The reduction reactions in a DRI process occurs according to the following reaction, in addition to the reactions with carbon monoxide ($CO$) as described above in **Eq 4** to **Eq 6**.[77]

$$3Fe_2O_{3(s)} + H_{2(g)} \rightarrow 2Fe_3O_{4(s)} + H_2O_{(g)} \qquad \textbf{Eq 8}$$

$$Fe_3O_{4(s)} + H_{2(g)} \rightarrow 3FeO_{(s)} + H_2O_{(g)} \qquad \textbf{Eq 9}$$

$$FeO_{(s)} + H_{2(g)} \rightarrow Fe_{(s)} + H_2O_{(g)} \qquad \textbf{Eq 10}$$

Any water formed from the reduction of iron ore is rapidly reduced by carbon by the following reaction.[77]

$$H_2O_{(g)} + C_{(s)} \rightarrow CO_{(g)} + H_{2(g)} \qquad \textbf{Eq 11}$$

The Midrex process exhibits a metallisation rate[3] of 92-95%[89] and uses a ratio of 1.4:1 ($H_2$: $CO$) as the reduction gas. This ratio can go as high as 3.3-3.8:1 ($H_2$: $CO$) with the development of the FMO Midrex process, as a means to reduce carbon emissions and potentially integrate green hydrogen.[2] The Energiron (HYL) process is the second most popular DRI process.[91,92] This process offers an adjustable DRI carbon content and exhibits a metallisation rate of approximately 94%.[92] The Energiron (ZR) is the latest technology offering by Energiron and allows high efficiency and producing high carbon content direct reduced iron.[2,92]

The following **Figure 8** and **Table 5** outline the major process inputs and waste products for the typical gas-based DRI process operating with a shaft furnace.

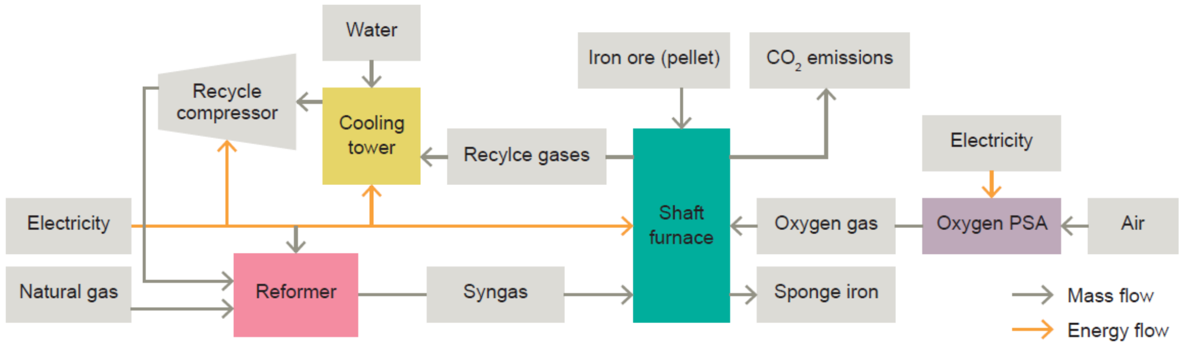


**Figure 8. Schematic of gas-based DRI process utilising a shaft furnace**. Natural gas is converted to syngas where it is introduced into a shaft furnace alongside iron ore and small amounts of oxygen gas. The syngas directly reduced the iron ore resulting in the production of sponge iron.

**Table 5. Major process inputs and outputs from a typical gas-based DRI process.**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | The DRI process requires high grade ore (64-66%Fe, >67%Fe preferred) and containing low levels of impurities (<4% $SiO_2$+$Al_2O_3$, 0.008% S, <0.05% P and <0.15% $TiO_2$, <1% moisture).[27,71] Gas based DRI processes typically use pelletised iron ore.[76,93] | 1.38-1.60[a] t/$t_{Iron}$[4,78] |
| Natural Gas | Natural gas is used as the reducing agent for gas based DRI processes | 0.19-0.23 t/$t_{Iron}$[4,8,78] |
| Oxygen Gas | Oxygen is typically injected into the furnace (or upstream of the shaft furnace) to raise the operating temperature of the shaft furnace, which improves reaction kinetics.[9] | 3 kg/$t_{Iron}$[9] |
| Water | Water for cooling tower operation. Amount of water depends on on-site water recovery.[78] | 1.0-1.3 $m^3$/$t_{Iron}$[9,78] |

[3] The metallisation rate refers to the amount of metallic Fe as a percentage of the total Fe content and is a measure of how effective the reaction is at converting iron oxides (from iron ore) to metallic iron.

| | | |
|---|---|---|
| Electricity | Electricity is used to power the DRI process and ancillary equipment. | 0.07-0.09 $MWh/t_{Iron}$[8,78] |
| | Electricity is used to power the pressure swing adsorption unit for oxygen generation. | 0.39 $MWh/t_{Oxygen}$[8] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor, for natural gas based DRI process. Omits indirect emissions including electricity generation and raw material preparation. | 522 $kg_{CO2}/t_{Iron}$[1] |

a. The exact amount depends on the iron content and level of impurities of the iron ore.

The following **Table 6** summarises some of the major suppliers of gas-based DRI processes.

**Table 6. Major suppliers of gas-based DRI processes.**

| Supplier | Location |
|---|---|
| Midrex[94] | USA |
| Energiron[95] | Italy |
| Primetals Technologies[96] | UK |

As mentioned, the Midrex and Energiron processes are the most widely used DRI processes. Both are regarded for their high reliability, requiring little maintenance.[78,92,97] Midrex plants commonly operate in **excess of 8000 hrs per year**,[97] with major shutdowns typically occurring every 8-12 months,[98] extending up to 18 months.[99]

Routine maintenance activities include maintenance of the auxiliary equipment such as the recycle compressor, natural gas reformer, oxygen PSA and cooling tower.

- **Recycle Compressor:** Routine maintenance includes oil changes, lubrication, filter inspection and replacement, oil level monitoring and adjustment, inspection of coolers and heat exchangers, cleaning inlet guide vanes regularly, and replacing seals and bearings as needed.[100]
- **Reformer:** Routine maintenance includes inspection of the furnace box and heater as well as cleaning of the steam methane reforming convection section.[101]
- **Oxygen PSA**: Routine maintenance includes inspection of the pipes and hoses for leaks or corrosion, inspection of the filter elements and calibration of the oxygen sensors. As well as routine maintenance of the PSA air compressors.[102]
- **Cooling tower**: Routine maintenance includes inspection of the water basin and strainers, water distribution and packing material. Lubrication of the fan shaft bearings and inspection of the fan blades.[103]

**Challenges with the Transportation of Direct-Reduced Iron (Sponge Iron)**

The DRI process results in the production of sponge iron pellets (or lumps), which get their name due to their porous structure.[27] Sponge iron is pyrophoric, meaning if left unprotected it can spontaneously catch fire in the presence of air.[104] Moreover, if sponge iron becomes wet, this can result in the generation of hydrogen resulting in the formation of an explosive atmosphere.[104] Therefore, if DRI is transported or shipped, it is typically done so in the form of cold moulded briquettes, or hot moulded briquettes (also known as hot briquetted iron (HBI)).

Cold moulded briquettes are sponge iron pellets that have been compressed into small briquettes with the intention of reducing the accessible surface area thus minimising the risk of reaction with air and moisture. One of the issues surrounding the use of cold moulded briquettes is they are relatively fragile and can fracture during normal cargo operations, increasing surface area and leading to similar issues surrounding the reaction with air and moisture as with sponge iron pellets.[104]

The other option is to form hot moulded briquettes (or HBI). These are formed by the compression of sponge iron pellets at temperatures exceeding 650°C and have an apparent density greater than 5g/cm$^3$.[105] This results in the formation of briquettes that are less porous than sponge iron, and less fragile than cold moulded briquettes making for safter transportation.[104] Both cold and hot moulded briquettes can be passivated to reduce reaction with air and moisture during transport.[104] DRI is currently a globally traded commodity with global shipments of DRI reaching 25.7 million tonnes in 2022.[106]

# 3 Current Technology Pathways for Steelmaking

**Steelmaking refers to the process of converting iron into steel. Currently, there are two main process pathways for the production of steel. The Basic Oxygen Furnace, which is typically coupled with a Blast Furnace; and Electric Arc Furnace, which is typically coupled with a Direct Reduced Iron process.**

Steelmaking involves the process of taking iron, often supplemented with steel scraps, and reducing the carbon and impurity content to produce steel. Additionally, alloying materials are introduced at this stage to form the desired steel composition. The primary pathways for steel production from iron include Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF).

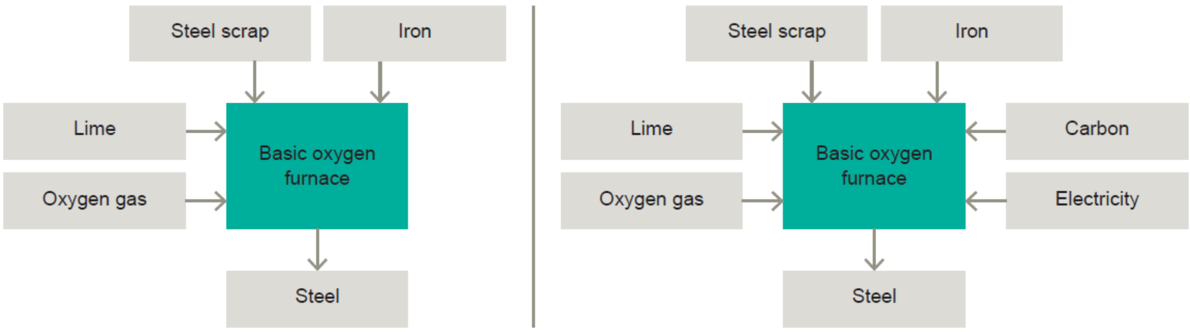


**Figure 9. Current technology pathways for steelmaking**. The basic oxygen furnace and electric arc furnace are currently the 2 major processes used for ironmaking. The basic oxygen furnace is typically coupled with the blast furnace process and the electric arc furnace is typically coupled with the DRI process.

The BOF process for steelmaking is typically coupled with the BF process of ironmaking and similarly, the EAF process for steelmaking is typically coupled with the DRI process of ironmaking.

## 3.1 Basic Oxygen Furnace

The Basic Oxygen Furnace (BOF) is a steelmaking process in which oxygen is blown into furnace containing molten iron. The oxygen initiates the oxidation of such impurities as carbon, silicon, phosphorus, and manganese leading to the production of steel.[107] A diagram of a the BOF has been provided in **Figure 10**.

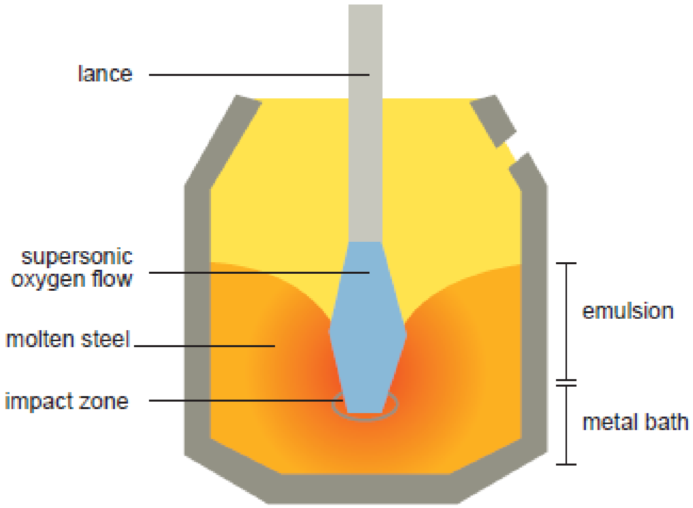


**Figure 10. Diagram of a basic oxygen furnace**. Image adapted from.[108] Iron, oxygen and flux (sometimes including steel scrap) are introduced into the furnace to allow for the production of steel.

First applications of the BOF date back to the 19th century, with the development of the Bessemer process.[109] However, due to its reliance on ambient air containing a significant amount of nitrogen, the Bessemer process is incapable of converting iron with >1.5% Si in one step.[27] In the 1950s, the Linz-Donawitz (LD) process, utilising oxygen-rich blast air and a modern basic oxygen furnace, was introduced.[110] This innovation reduced the steelmaking process from 8 hours to 45 minutes and continues to be used today.[109]

The basic oxygen furnace represents the most developed method for producing steel from iron.[111] Globally, there are an estimated 405 BOF plants (397 of which existing as integrated BF-BOF plants).[112] These produce an estimated 1397 million tonnes (62%) of the world's current crude steel production.[113] BOF vessel capacities can range from 70 to 300 tonnes.[114]

Molten iron and flux are added to the BOF where oxygen is then blasted into the mixture through a nozzle from the top of the vessel to enable the following two reaction steps; primary oxidation and secondary oxidation.[27] During primary oxidation, carbon and iron are oxidised, reducing their concentration in the molten iron.[27,115]

$$C_{(s)} + {}^1\!/_2\, O_{2(g)} \rightarrow CO_{(g)} \qquad \textbf{Eq 12}$$

$$CO_{(g)} + {}^1\!/_2\, O_{2(g)} \rightarrow CO_{2(g)} \qquad \textbf{Eq 13}$$

$$Fe_{(s)} + {}^1\!/_2\, O_{2(g)} \rightarrow FeO_{(l)} \qquad \textbf{Eq 14}$$

During secondary oxidation, the impurities are oxidised to form slag.[27,115,116] The formation of wustite ($FeO$) aids with the dissociation of lime ($CaO$) (used as flux) allowing the formation of calcium-ferrite which reacts with impurities allowing aiding in their removal from the steel.

$$C_{(s)} + FeO_{(l)} \rightarrow CO_{(g)} + Fe_{(s)} \qquad \textbf{Eq 15}$$

$$Si_{(s)} + 2FeO_{(l)} \rightarrow SiO_{2\,(l)} + 2Fe_{(s)} \qquad \textbf{Eq 16}$$

$$2FeO_{(l)} + SiO_{2\,(l)} \rightarrow 2FeO \cdot SiO_{2\,(l)} \qquad \textbf{Eq 17}$$

$$Mn_{(s)} + FeO_{(l)} \rightarrow MnO_{(l)} + Fe_{(s)} \qquad \textbf{Eq 18}$$

$$MnO_{(l)} + SiO_{2\,(l)} \rightarrow MnO \cdot SiO_{2\,(l)} \qquad \textbf{Eq 19}$$

$$2P_{(s)} + 5FeO_{(l)} \rightarrow P_2O_{5\,(l)} + 5Fe_{(s)} \qquad \textbf{Eq 20}$$

$$P_2O_{5\,(l)} + 4CaO_{(l)} \rightarrow 4CaO \cdot P_2O_{5\,(l)} \qquad \textbf{Eq 21}$$

$$FeS_{(l)} + CaO_{(l)} \rightarrow CaS_{(l)} + FeO_{(l)} \qquad \textbf{Eq 22}$$

The oxidation of the impurities is highly exothermic, providing excess heat than what is required by the process. For instances where the process is overheated, steel scrap or hematite can be added to cooldown the process.[116,117]

The following **Figure 11** and **Table 7** outline the major process inputs and waste products for the typical Basic Oxygen Furnace process.

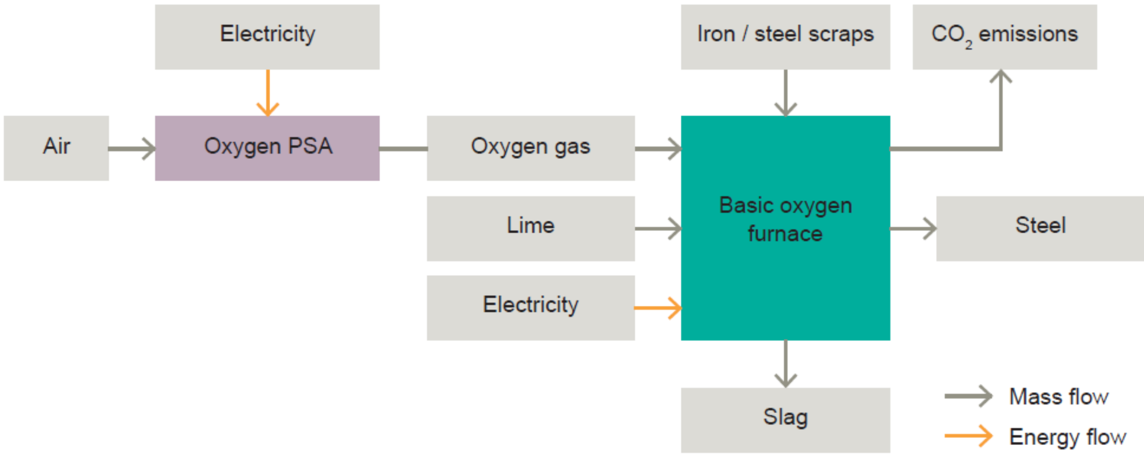


**Figure 11. Schematic of a basic oxygen furnace process**. Iron (sometimes including steel scrap), oxygen and lime (flux) are introduced into the furnace for the production of steel, and slag.

**Table 7. Major process inputs and outputs from a typical basic oxygen furnace process.**

| Stream | Description | Rate |
|---|---|---|
| Iron / Steel Scraps | Pig Iron, typically consisting of 4-5%C.[28] Steel scrap can also be added (up to 25-30% of the total weight).[27,118] | 1.1 $t/t_{Steel}$[3] |
| Lime | Lime is the most common flux material used for steelmaking. Flux is used to react with and remove impurities form the iron ore (in the form of slag).[47] | 35-43 $kg/t_{Steel}$[3,119] |
| Oxygen Gas | Oxygen gas is used as an oxidant to convert the impurities into oxides which can then be removed as slag.[27] | 79-83 $kg/t_{Steel}$[7,119] |
| Electricity | Electricity is used to power ancillary equipment and electrical systems. | 0.02 $MWh/t_{Steel}$[7,8] |
| | Electricity used to power the air separation unit (for oxygen gas production) | 0.39 $MWh/t_{Oxygen}$[8] |
| Slag | Slag is produced as a waste product from the basic oxygen furnace, resulting from the impurities present in the iron.[47] | 56-120 $kg/t_{Steel}$[12,52,120] |
| $CO_2$ Emissions | Direct CO2 emissions from primary reactor. Omits indirect emissions including electricity generation and raw material preparation. | 193 $kg_{CO2}/t_{Steel}$[1] |

To withstand the high temperatures of the reaction conditions of the BOF, each furnace is equipped with refractory lining. Wear of the BOF refractory lining results from a combination of factors such as process heat, corrosion from chemical attack from slag composition, erosion during oxygen blowing and tilting, and impact and abrasion from charging of scrap metal and iron.[121] The campaign life of the BOF refractory lining thus depends on the process operating regime and the chemical composition of the steel and steel slag, lasting from **2,500-5,000 heat cycles** (for 24-36 heat cycles per day) and up to **20,000-35,000 heat cycles** (for 18-26 heat cycles per day).[114,120] Outside of refractory lining, BOF routine maintenance requirements include the following key aspects:[122]

- **Skull Removal**: The buildup of slag deposit (referred to as skull) can lead to mechanical wear or vessel damage and needs to be removed in between heat cycles.
- **Slag Shields**: Slag shields are to be inspected for warpage due to heat. If this warpage is excessive and the shield sections should be replaced.
- **Tapping Nozzles**: Tapping nozzles are to be inspected after each campaign for cracked welds and for burn-throughs.
- **Suspension system**: Each BOF is furnished with a suspension system to support the vessel in the trunnion ring. After each campaign the vessel suspension system components are to be inspected.

The following **Table 9** summarises some of the major global suppliers of BOF and related products.

**Table 8. Major suppliers of basic oxygen furnaces and related equipment**

| Supplier | Location |
|---|---|
| Nippon Steel & Sumikin Engineering[123] | Japan |
| McKeown International[124] | USA |
| AMETEK Land[125] | UK |
| Magnezit Group[65] | Russia |
| Air Products[126] | USA |
| Autotherm[127] | India |

## 3.2 Electric Arc Furnace

The Electric Arc Furnace (EAF) is a steelmaking process which heats material by means of an electric arc. There are currently two types of electric arc furnaces, ones which operate on Alternating Current (AC) and ones which operate on Direct Current (DC). The first EAF appeared in the 19$^{th}$ century for experimental use.[128] However, it wasn't until 1888 that the early design of the modern EAF using AC current was developed, eventually leading to industrial-scale production by 1907.[128] The use of DC current EAFs saw later development, reaching industrial application in the early 1980's.[129] In 2022, approximately 29% (665 million tonnes) of global steel production could be attributed to electric arc furnaces, most of which integrated with DRI processes. Worldwide, there are approximately 554 electric arc furnace plants with the capacity to produce 665 million tonnes of steel currently.[113]

EAFs operate in batch and use graphite electrodes and electricity to generate an electric arc to melt the contents of the furnace.[130] In the charging phase, the raw materials including steel scraps, lime (flux) and iron are loaded into the furnace in layers. A diagram of an EAF if provided in **Figure 12**.

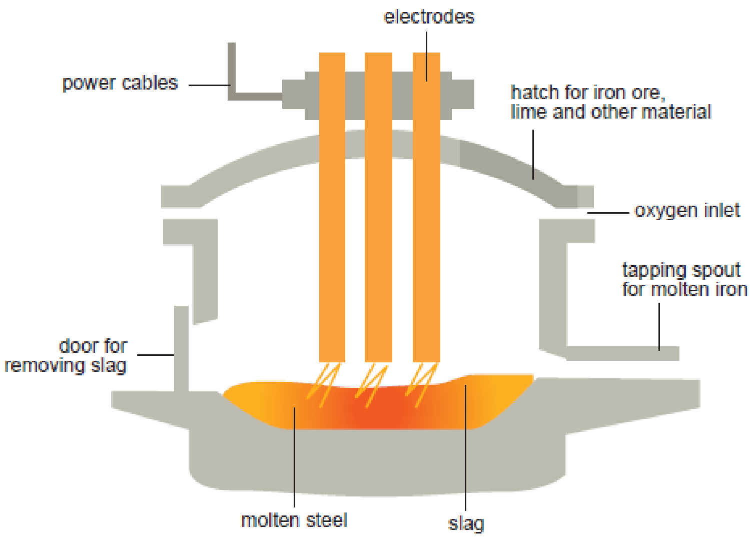


**Figure 12. Diagram of an electric arc furnace**. Image adapted from.[131] Iron (including steel scraps), carbon, oxygen and flux are introduced into a furnace where graphite electrodes provide electrical energy allowing for the production of steel.

For instances where the EAF is coupled with a DRI process, the steel scraps are preheated by the heat exchange with the DRI process.[132,133] Electrical resistance from the electric arc formation generates heat to melt the steel scraps, lime and iron in the furnace.[134] Oxygen is also introduced so that it can oxidised the impurities and form slag.[133] Slag is discharged from the top of the furnace and molten steel is received from the base.[133] The chemical reactions within the EAF process are similar to that of the BOF (**Eq 12** to **Eq 22**, **Section 3.1**).

The following **Figure 13** and **Table 9** outline the major process inputs and waste products for the typical EAF process.

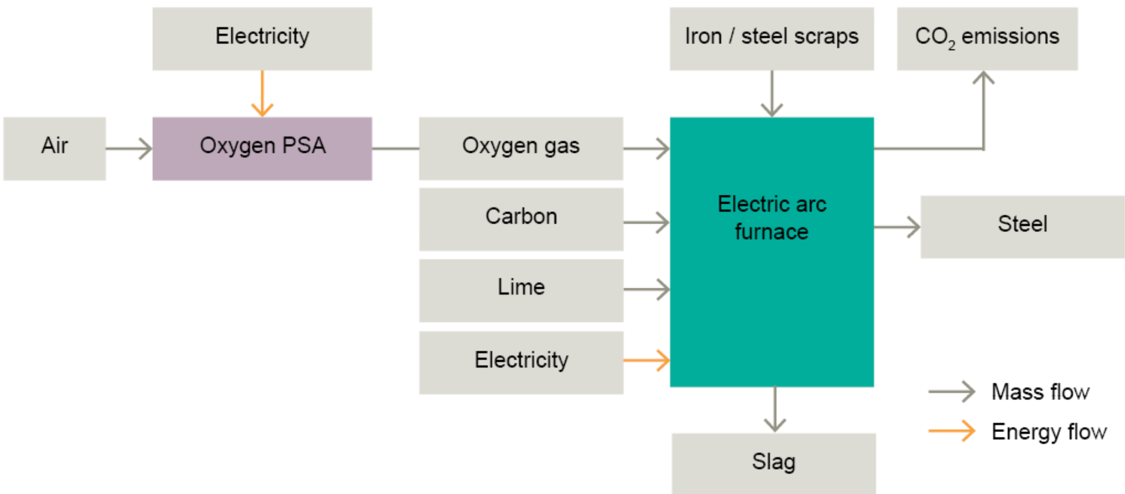


**Figure 13. Schematic of electric arc furnace process.** Iron (including steel scraps), carbon, oxygen and lime are introduced into the electric arc furnace where electrical energy is used to produce steel and slag.

**Table 9. Major process inputs and outputs from a typical electric arc furnace process.**

| Stream | Description | Rate |
|---|---|---|
| Iron / Steel Scraps | A typical EAF process operates on a mixture of direct reduced iron and steel scraps, with 40-50% of the total weight as steel scraps.[130] | 1.2 $t/t_{Steel}$[9] |
| Lime | Lime is the most common flux material used for steelmaking. Flux is used to react with and remove impurities form the iron ore in the form of slag.[47] | 40-50 $kg/t_{Steel}$[8,9] |
| Carbon | Carbon is added to the EAF to raise the carbon content of the steel to the desired level.[8] | 12-27 $kg/t_{Steel}$[9,19] |
| EAF Electrode | The EAF electrode are consumed by the process, requiring replacement.[135] | 1-2 $kg/t_{Steel}$[19,135] |
| Oxygen Gas | Oxygen gas is used as an oxidant to convert the impurities into oxides which can then be removed as slag.[27] | 54 $kg/t_{Steel}$[9] |
| Electricity | Electricity is used for EAF operation. Hot linking refers to the process where DRI is added directly to the EAF, allowing for thermal energy of the DRI to be used in the EAF process.[9] | Hot Linked:[a] 0.36-0.38 $MWh/t_{Steel}$[8,9]<br>Not Hot Linked: 0.45 $MWh/t_{Steel}$[9] |
| | Electricity used to power the air separation unit (for oxygen gas production) | 0.39 $MWh/t_{Oxygen}$[8] |
| Slag | Slag is produced as a waste product from the blast furnace, resulting from the impurities present in the iron ore.[47] | 70-150 $kg/t_{Steel}$[9,53] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor. Omits indirect emissions including electricity generation and raw material preparation. | 50[b] $kg_{CO2}/t_{Steel}$[2,19] |

a. Hot linking involves directly adding hot direct-reduced iron (DRI) from the DRI process to the electric arc furnace (EAF) to recover residual heat. Hot linking can only be implemented in an integrated DRI + EAF process.

b. Based on the injection of carbon and consumption of graphite electrodes in the EAF process.[2,19]

EAF vessels have a refractory lining designed to withstand the high temperatures of the process. Maintenance stops are required every 2 weeks, with each stop lasting 45-55 minutes for repair or relining, typically occurring after 100-120 heat cycles.[136] Repairs are conducted using gunned refractories or mud slingers. In most modern furnaces, the use of water-cooled panels has significantly reduced the need for patching or "fettling" between heats.[137] In addition to the refractory lining, EAF processes require the following maintenance:

- **Hearth**: The hearth of on EAF typically withstands a two-year campaign (more than 4,000 heat cycles) before being completely replaced during each major overhaul.[138]
- **Graphite Electrodes**: Graphite electrodes are a crucial and costly consumable in EAF steel production,[139] typically consumed every 8 to 10 hours.[140] Their purchase alone constitutes 3 to 5% of steel manufacturing costs.[140]
- **Oxy-fuel Burner System**: Oxy-fuel burners are standard on large, high-powered

furnaces, ensuring rapid scrap melting in short tap-to-tap times. Maintenance involves preventing metal or slag plugging, and frequent inspection.[137]

- **Vacuum Switch**: The vacuum switch is an electrical switch which allows for the secondary electrical circuit to be broken either under load or without load. Most vacuum switches are rated for 40,000 operations or four years. In practice, it is not unusual for such switches to achieve 200,000 operations without maintenance.[137]
- **Tap Changer**: The purpose of a tap changer is to allow a choice of different combinations of volts and amps for different stages of a heat through the EAF heat cycle. These contacts are subject to heavy erosion due to arcing and therefore require frequent inspection and maintenance as necessary.[137]
- **Bus Bar / Current Conducting Arm**: The bus bar and current conducting arm provides the electrical connection between the power cables and the electrode holder. These are susceptible to mechanical wear, requiring frequent inspection and maintenance as necessary.[137]
- **Electrode Heads /Contact Pads**: The Electrode heads and contact pads provide the final connection between the power supply and the graphite electrode. They are exposed to extreme mechanical conditions (vibration, torsion etc.) and thermal cycling. Additionally, any dirt build-up in this area will result in resistance to current flow and will cause over-heating and damage to the electrode holder/contact pad, hence frequent inspection and maintenance of the electrode heads and contact pads are required.[137]

The following **Table 10** summarises some of the major global suppliers of EAFs and related products.

**Table 10. Major suppliers of electric arc furnaces and related equipment**

| Supplier | Location |
|---|---|
| Danieli[141] | Italy |
| Primetals Technologies[61] | UK |
| AMETEK Land[125] | UK |
| Magnezit Group[65] | Russia |
| SMS Group[142] | Germany |
| Tenova[143] | Italy |
| Electrotherm[144] | India |
| IHI Corporation[66] | Japan |
| Nippon Steel & Sumikin Engineering[123] | Japan |
| Steel Plantech[145] | Japan |
| Doshi Technologies[146] | India |
| Sermak Metal[147] | Turkiye |
| Siemens[148] | Germany |

# 4 Technology Options for Green Ironmaking

**Various technology pathways exist for the production of green iron, ranging from processes based on conventional ironmaking processes to entirely new methods, each are at different stages of development and with different carbon abatement potentials.**

## 4.1 Blast Furnace

There are currently several proposed pathways for the decarbonisation of the BF process. The major process options that are currently being explored include the use of biomass, coke oven gas (COG)[4], syngas, hydrogen or carbon capture and utilisation (CCUS). Biomass can partially replace coal/coke in the BF process, while Coke Oven Gas (COG), syngas, pure hydrogen, or biomass can partially or completely substitute tuyere fuel injection.[14,149] Global commercial trials, using COG, syngas,[2] and a first phase Thyssenkrupp trial with pure hydrogen,[150] show promising results in energy efficiency, emissions reduction, and enhanced product quality.[28,108] The following **Table 11** outlines the fossil fuel substitution options for the Blast Furnace process, including the substitution rates for each option.

**Table 11. Fossil fuel substitution options for the blast furnace process**

| Stream | Substitution Fuel | Substitution Rate |
|---|---|---|
| Coke | Biomass | 2-10%[14] |
| Pulverised Coal (Tuyere Injection) | Biomass | up to 100%[14] |
| | Coke Oven Gas (COG) | up to 100%[149] |
| | Syngas | up to 100%[14,151] |
| | Hydrogen Gas | up to 100%[152] |

The following **Figure 14** and **Table 12** show the indicative process requirements for a BF process operating with fossil fuel substitution. Any changes in process requirements compared to the base technology (as outlined in **Section 2.1**) have been highlighted.

[4] The use of coke oven gas (COG) for tuyere injection is a form of energy recovery from the coke-making process. Although COG is derived from fossil fuels, its use contributes to energy savings and carbon emission reductions in the overall blast furnace process.

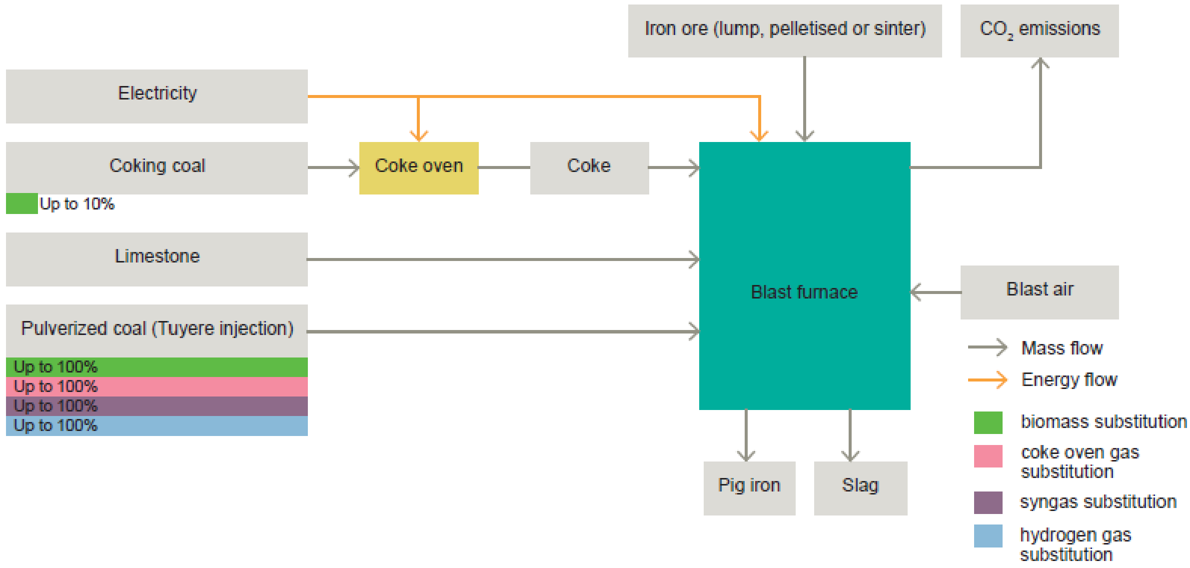


**Figure 14. Schematic of blast furnace process operating with biomass**. Up to 10% of the coke addition can be substituted by biomass and up to 100% of the pulverised coal addition can be substituted with either biomass, coke oven gas, syngas or hydrogen gas.

**Table 12. Major process inputs and outputs from a blast furnace process operating with biomass**.

| **Stream** | **Description** | **Rate** |
|---|---|---|
| Iron Ore | The iron ore used for the BF process is typically a mixture of pellet (62-66%Fe), sinter (55-58%Fe), and direct shipping ore (>60%Fe).[27,47,49] | 1.4-1.5[a] $t/t_{Iron}$ |
| Limestone | Limestone is the most common flux material used for ironmaking. Flux is used to react with and remove impurities form the iron ore (in the form of slag).[47] | 41-44 $kg/t_{Iron}$[3,12] |
| Coking Coal | Coking coal is used to produce coke in the coke oven. | 1.4[b]$t/t_{Coke}$ |
| Coke | Coke requirements if substituting 10% with biomass. | 0.25-0.32[c] $t/t_{Iron}$ |
| | Biomass requirements if substitution of 10% of coke requirements (**Table 11**). | 0.025-0.036 $kg/t_{Iron}$[14] |
| Tuyere Injection | Biomass requirements if substituting 100% of tuyere fuel (**Table 11**). | 180-220 $kg/t_{Iron}$[14] |
| | Coke oven gas (COG) requirements if substituting 100% of tuyere fuel (**Table 11**). | 76[d] $kg/t_{Iron}$[149] |
| | Syngas requirements if substituting 100% of tuyere fuel (**Table 11**). | 47.5-95[e] $kg/t_{Iron}$[14,151] |
| | Hydrogen gas requirements if substituting 100% of tuyere fuel (**Table 11**). | 24-32 $kg/t_{Iron}$[152] |

| | | |
|---|---|---|
| Electricity | Electricity is used to power blast furnace and ancillary equipment. | 0.10 $MWh/t_{Iron}$[8] |
| | Electricity is used to power coke oven and ancillary equipment. | 0.04 $MWh/t_{Coke}$[8] |
| Slag | Slag is produced as a waste product from the blast furnace, resulting from the impurities present in the iron ore.[47] | 0.21-0.28 $t/t_{Iron}$[52,53] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from blast furnace primary reactor. Omits indirect emissions including electricity generation and raw material preparation (including omittance of the 97 $kg_{CO2}/t_{Iron}$[1] generated by the coke oven.) | Refer to **Table 18** |

a. Calculated based on an iron ore grade of 60-65% Fe(w/w) and a pig iron metallic iron content of 92% Fe (w/w).[28]

b. Assuming a coke oven yield of 70%.[54]

c. Determined based on a coke consumption rate of 0.28-0.36 $t/t_{Iron}$[12-14] and a replacement of 10%.

d. Assuming COG has a specific gravity of 0.589.[153]

e. Assuming syngas has a density of 0.95 $kg/Nm^3$.[154]

Although the use of biomass offers many benefits compared to the other decarbonisation options, such as being able to directly replace fossil fuel in the BF process, there are many uncertainties and drawbacks which include the sustainable sourcing of biomass material,[155] direct and indirect land use,[156] cost,[2] as well as technical challenges to product quality when introducing large amounts of biomass into the ironmaking process.[14]

Carbon capture, utilisation, and storage (CCUS) is widely regarded as an effective means of reducing carbon emissions from the BF process.[12,157] This is exemplified by initiatives such as the Carbon2Chem project, a joint venture between German industry and research institutions aimed at converting industrial $CO_2$ emissions and other gases into chemical products.[158,159] Additionally, programs like the European Ultra Low $CO_2$ Steelmaking (ULCOS) and Course50 projects are exploring the use of CCUS to reduce emissions from ironmaking and steelmaking, alongside the development of new low-carbon processes.[157]

The captured carbon from these processes can then be used to produce value-added products via chemical or biological transformation.[17] Chemical transformation involves the use mineral carbonation, such as the Slag2PCC[160] process and the work being undertaken by the Australian-based company MCi Carbon[161] for the production of materials such as magnesium carbonate, calcium carbonate and amorphous silica which have applications in construction and other industries. Biological transformation involves the use of microbial processes to convert captured gases into carbon-based fuels and chemicals. In 2018, LanzaTech implemented its first commercial scale facility for producing ethanol from blast furnace off-gases at the Shougang facility in China.[162] In 2023, LanzaTech expanded its bio-based technology to a pilot study at an ArcelorMittal blast furnace facility in Ghent, Belgium, for the production of ethanol.[163,164] This is coupled with the development of a pilot carbon capture unit by ArcelorMittal and partners Mitsubishi Heavy Industries Ltd, BHP, along with Mitsubishi Development Pty Ltd, with future to plans feed into multiple $CO_2$ transport and storage projects under development in the North Sea region if successful.[165]

## 4.2 Direct Reduced Iron

Recently, the Direct Reduced Iron (DRI) process has received considerable attention as a means for decarbonising primary iron production. This is due to its ability to operate economically with substantially lower greenhouse emissions compared to other technology options.[166,167] Currently, three main pathways are being considered for decarbonising the DRI process. The first is Carbon Capture Utilisation and Storage (CCUS), the second pathway involves using solid biomass or syngas derived from biomass,[168-170] and the third relies on pure hydrogen as the reductant.[2] Additionally, there are emerging DRI technologies that use laser light[171] and ammonia gas[172,173] as reducing agents. However, these options are at much earlier stages of development compared to the aforementioned DRI pathways.

As with the implementation of CCUS for the BF process, CCUS is also seeing adoption as a means to abate carbon emissions for DRI processes. There are currently demonstration plants in operation in Abu Dhabi, Mexico and Venezuela for gas-based DRI processes coupled with CCUS.[11,174] The Al Reyadah facility in the United Arab Emirates (UAE) is the first commercial-scale CCUS plant for DRI production and has a nominal capacity to capture 0.8Mt of $CO_2$ annually. This facility is a joint venture between the Abu Dhabi National Oil Company (ADNOC) and the clean energy company Masdar. The captured $CO_2$ is utilised in ADNOC's onshore oilfields to enhance oil production.[175] Carbon dioxide from the DRI facility in Mexico is captured for downstream use whereas the $CO_2$ emissions captured at the Venezuela are currently vented to the atmosphere.[174]

Predominantly, biomass can be used to produce syngas, which can then operate a traditional gas-based DRI process.[168-170] However, the use of biomass for ironmaking is also being adopted in innovative processes such as the BioIron process, developed by the Australian iron ore mining company Rio Tinto.[176] The BioIron process uses a combination of solid biomass, syngas, and microwaves to produce DRI, requiring a different configuration than traditional gas-based DRI processes. However, similar to the use of biomass in the blast furnace process, the use of biomass for DRI presents several uncertainties and drawbacks, including sustainable sourcing of biomass material,[155] direct and indirect land use impacts, and associated costs.[2,156]

Access to affordable renewable hydrogen will enable many countries to adopt the hydrogen-based Direct Reduced Iron (H2-DRI) process. **Estimates indicate that by 2050, 46% of total iron production will follow the DRI pathway, utilising 100% hydrogen**.[177] Various technology options are in development for the direct reduction of iron using hydrogen gas, these include the MIDREX H2,[178] hydrogen-based HYL/Energiron,[95] HYBRIT,[179] tkH2Steel[180] and ZESTY[181] systems which utilise a shaft furnace similar to conventional gas based DRI processes, as well as the Circored[182] and HyREX[183] processes which employ a fluidised bed system. The first commercial H2-DRI plant was launched in Trinidad in 1998 with the Circored process.[2] It had a design capacity of 500,000 tonnes per annum[184] and exhibited a metallisation rate of 95%.[185] However, this plant was closed down in 2016 due to the process not being commercially viable.[184] Despite these set-backs, recent construction of Europe's first commercial green steelmaking industry (based on the H2-DRI process) has commenced in northern Sweden.[186] The plant is based on the HYBRIT system (using a shaft furnace, similar to the conventional gas-based DRI processes).[2] The plant is due to start production in 2025 with aims to produce 5 million tonnes of green steel per year by 2050.[186]

The reduction reactions in an H2-DRI process thus occurs according to the following reaction:[2]

$$3Fe_2O_{3(s)} + H_{2(g)} \rightarrow 2Fe_3O_{4(s)} + H_2O_{(g)} \qquad \textbf{Eq 23}$$

$$Fe_3O_{4(s)} + H_{2(g)} \rightarrow 3FeO_{(s)} + H_2O_{(g)} \qquad \textbf{Eq 24}$$

$$FeO_{(s)} + H_{2(g)} \rightarrow Fe_{(s)} + H_2O_{(g)} \qquad \textbf{Eq 25}$$

Hydrogen offers advantages over carbon monoxide (forming part of the syngas used in traditional DRI processes) due to its smaller size, facilitating deeper penetration into iron ore and accelerating the reaction rate.[187] If green hydrogen is utilised, the H2-DRI process can potentially achieve zero carbon emissions, assuming the furnace and other electrical equipment are powered by renewable energy.

A significant distinction between the conventional Direct Reduced Iron (DRI) process using syngas and one utilising pure hydrogen is that the H2-DRI reaction is endothermic.[2] This poses a challenge for maintaining correct temperature distribution within the reaction vessel, as regions with higher concentrations of hydrogen can become low temperature zones. This effect can be minimised through the pre-heating of the influent hydrogen gas (as shown in **Figure 15**); however, this results in additional energy input.[9,70,188] As the iron produced in the H2-DRI process lacks carbon, carbon needs to be added during the steelmaking process (in the form of natural gas or pure carbon) to increase the carbon content to the desired level. Furthermore, as the DRI produced in the H2-DRI process has a higher melting point than traditional DRI. This can lead to an increase in power consumption as well as the presence of un-melted iron (ferrobags) in the steelmaking process.[70,188]

The following **Figure 15** and **Table 13** show the indicative process requirements for a DRI process operating with pure hydrogen gas as the reducing agent. Any changes in process requirements compared to the base technology (as outlined in **Section 2.2**) have been highlighted in green.

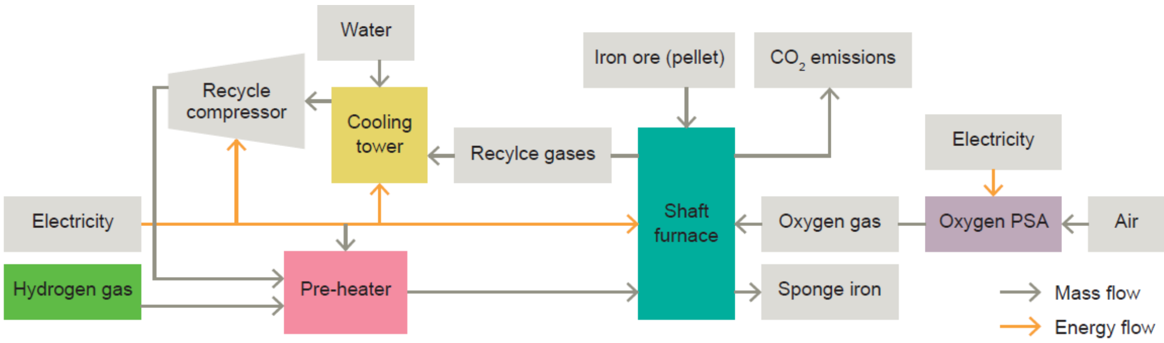


**Figure 15. Schematic of DRI process operating with hydrogen and a shaft furnace**. Hydrogen gas can be used as a reducing agent for the direct reduction of iron ore. As the reaction between hydrogen and iron ore is endothermic, these processes require the use of a hydrogen pre-heater (which replaces the steam reformer in a typical gas-based DRI process).

**Table 13. Major process inputs and outputs from a DRI process operating with hydrogen**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | The DRI process required high grade ore (64-66%Fe, >67%Fe preferred) and containing low levels of impurities (<4% $SiO_2$+$Al_2O_3$, 0.008% S, <0.05% P and <0.15% $TiO_2$, <1% moisture).[27,71] Gas based DRI processes typically use pelletised iron ore.[76,93] | 1.38-1.60[a] $t/t_{Iron}$[4,78] |
| Hydrogen Gas | Hydrogen gas is used as the reducing agent for hydrogen gas based DRI processes | 65 $kg/t_{Iron}$[9] |
| Oxygen Gas | Oxygen is injected into the furnace (or upstream of the shaft furnace) to raise the operating temperature of the shaft furnace, which improves reaction kinetics.[9] | 55 $kg/t_{Iron}$[9] |
| Water | Water for cooling tower operation. Amount of water depends on on-site water recovery.[78] | 1.0-1.3 $m^3/t_{Iron}$[9,78] |
| Electricity | Electricity is used to power the DRI process and ancillary equipment. | 0.07-0.09 $MWh/t_{Iron}$[8,78] |
| | Electricity is used to power the pressure swing adsorption unit for oxygen generation. | 0.39 $MWh/t_{Oxygen}$[8] |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor, for natural gas based DRI process. Omits indirect emissions including electricity generation and raw material preparation. | 0[b] $kg_{CO2}/t_{Iron}$ |

a. The exact amount depends on the iron content and level of impurities of the iron ore.

b. Although this process is reported as having direct carbon emissions of 25 $kg_{CO2}/t_{Iron}$,[2] this is due to carbon addition in the EAF process (if considering the use of H2-DRI coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[2]

## 4.3 Electric Smelting Furnace

The Electric Smelting Furnace (ESF) process is gaining attention due to its capability to integrate with a Direct Reduced Iron (DRI) process to produce pig iron. As discussed in **Section 2.2**, one of the key issues surrounding the use of DRI processes for iron and steelmaking is the presence of gangue material which needs to either be removed through the upgrading of lower grade ore (beneficiation) or removed downstream in the steelmaking process. Although the ESF cannot create iron from iron ore on its own, it can be integrated with DRI processes to remove gangue material before the steelmaking process, enabling the use of DRI on lower grade ores. A diagram of a typical Electric Smelting Furnace is provided in **Figure 16**.

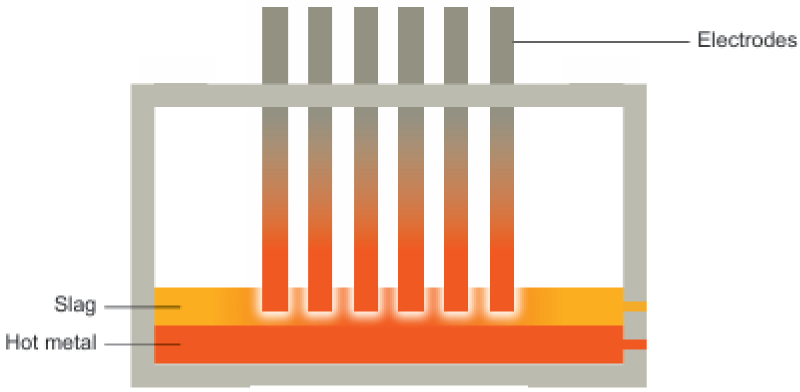


**Figure 16. Diagram of an electric smelting furnace.** Image adapted from.[130] Iron is smelted using electricity allowing for gangue and other impurities to be removed ahead of downstream processes.

Currently, New Zealand Steel is one of the few steelmakers globally operating an ESF process.[17] However, the ESF process is gaining attention from other major iron and steelmakers, such as POSCO and ThyssenKrupp, with the development of the HyREX and tkH2Steel projects, respectively.[180,183] Additionally, Australian iron ore producer BHP recently announced a collaboration with the engineering firm Hatch to design an ESF pilot plant using iron ore from their Western Australian mining operations.[130]

The ESF operates on the principle of resistance heating via electrodes, which either approach or are submerged in the slag melt to provide the energy needed for melting and reactions. The furnace shell is refractory-lined and may also be water-cooled, depending on the configuration and operation. The ESF allows for the continuous addition of carbon and flux to the metallic charge, which can be Direct Reduced Iron (DRI) in the form of sponge iron (if integrated with the DRI process), or hot-briquetted iron (HBI).[17] The process flow diagram and estimated process requirements have been provided in **Figure 17** and **Table 14** based on current available data.

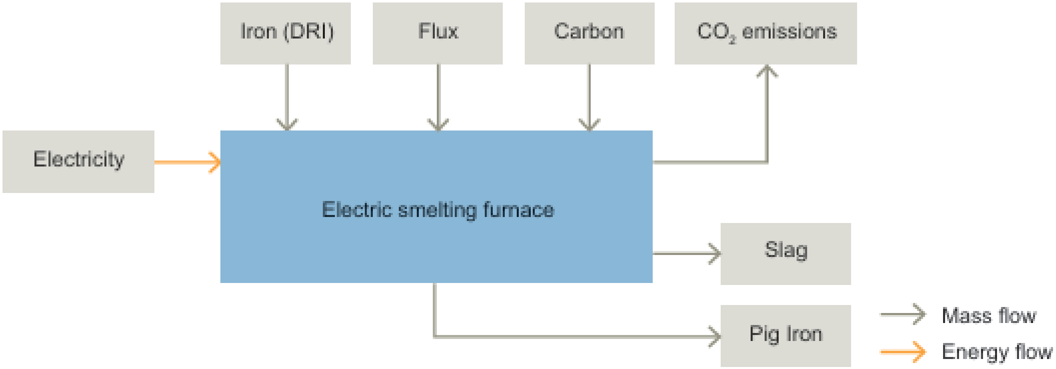


**Figure 17. Schematic of electric smelting furnace process.**[130]

**Table 14. Indicative process inputs and outputs for an electric smelting furnace process**

| Stream | Description | Rate |
| --- | --- | --- |
| Iron (DRI) | The metallic charge of an ESF is typically Direct Reduced Iron (DRI) in the form of sponge iron (if integrated with the DRI process), or hot-briquetted iron (HBI).[17] | 1.05-1.15[a] $t/t_{Iron}$ |
| Electricity | Electricity is used to power the ESF and provide heat energy to melt the iron | Data Unavailable |
| Flux | Flux is used to react with and remove impurities form the inlet iron in the form of slag.[47] | 0.1[b] $t/t_{InletIron}$ |
| Carbon | Carbon can also be added in the ESF to adjust the carbon content of the inlet iron to the desired level | 0.05[b] $t/t_{InletIron}$ |
| $CO_2$ Emissions | Direct $CO_2$ emissions from the ESF. Omits indirect emissions including electricity generation and raw material preparation. | 0[c] $kg_{CO2}/t_{Iron}$ |

a. Based on a DRI metallic Fe content of 81-88%Fe (w/w)[189] and an outlet iron metallic Fe content of 92% Fe (w/w).[28]

b. Based on an inlet feed ratio of 87% inlet iron, 9% flux and 4% carbon.[130]

c. The carbon emissions from the ESF process are assumed to be negligible. However, it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

## 4.4 Emerging Technology

As the iron and steelmaking industry seeks to reduce its carbon footprint, existing decarbonisation efforts primarily focus on optimising and improving current technologies. However, alongside these more established pathways, emerging technologies are introducing entirely new methods for ironmaking. These new approaches promise to further enhance efficiency and sustainability in achieving deep decarbonisation of this sector.

### 4.4.1 Alkaline Iron Electrolysis

Unlike decarbonisation routes for Blast Furnace and DRI (which are based on existing processes), Alkaline Iron Electrolysis offers a new process for the decarbonisation of ironmaking.[2,190] Alkaline Iron Electrolysis (AIE) is a low-temperature process for directly reducing iron ore.[191,192] Iron ore is finely ground before entering a leaching bath. The leached iron ore is transferred to the electrolyser to extract the iron.[2] The reduction efficiency using AIE depends on various factors, including impurities of iron ore, current density, types of electrolytes and their concentration.[193] The reaction takes place under ambient conditions (25°C and 1 atm) as follows:

$$ {}^{1}\!/_{2}\, Fe_2O_{3\,(s)} \rightarrow Fe_{(s)} + {}^{3}\!/_{4}\, O_{2\,(g)} \qquad \textbf{Eq 26} $$

The AIE process, currently under development by the Australian iron ore mining company Fortescue,[194] is still in its early stages. The process flow diagram and estimated process requirements have been provided in **Figure 18** and **Table 15** based on current available data.

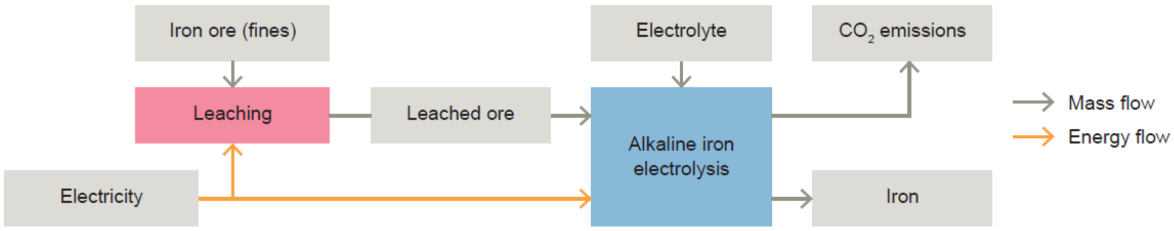


**Figure 18. Schematic of alkaline iron electrolysis process.**[2,191] Iron ore fines are leached prior to being entered into a alkaline iron electrolyser. Electrical energy is then used to convert the leached ore to iron.

**Table 15. Indicative process inputs and outputs for an alkaline iron electrolysis process**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | Iron ore is finely ground to a particle size of approximately 10 μm before being entered into the leaching bath. The leached iron ore is then transferred to the electrolyser where it can be reduced to iron ore.[2] | 1.4-1.5[a] $t/t_{Iron}$ |
| Electricity | Electricity is used to power the Leaching and Alkaline Iron Electrolysis unit processes. | 2.75[b] $MWh/t_{Iron}$ |
| Electrolyte | An electrolyte solution of 50% NaOH is used within the electrolysis reactor.[2] | Data Unavailable |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor, for alkaline iron electrolysis process. Omits indirect emissions including electricity generation and raw material preparation. | 0[c] $kg_{CO2}/t_{Iron}$ |

a. Calculated based on an iron ore grade of 60-65% Fe(w/w) and an outlet iron metallic iron content of 92% Fe (w/w).[28]

b. Estimated based on a process energy consumption rate of $9.9 GJ/t_{Iron}$[2]

c. Although this process is reported as having direct carbon emissions of 180 $kg_{CO2}/t_{Iron}$,[2] this is due to the use of coal as an aggregate in the EAF process (if considering the use of AIE coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[18]

# 5 Technology Options for Green Steelmaking

**Much like the production of green iron, various technology pathways exist for the production of green steel, ranging from processes based on conventional steelmaking to entirely new methods. With some pathways enabling the direct production of steel from iron ore.**

## 5.1 Basic Oxygen Furnace

When examining primary steel production, the BOF is commonly paired with a BF.[11] In the BF-BOF process, the BOF contributes around 10% of the total carbon emissions, with the majority (68%) originating from the BF unit process.[1] Therefore, efforts to decarbonise this steel production route have typically centred on the BF.[2] For this reason, there are currently limited efforts to decarbonise the BOF process, however, strategies are being put in place to reduce the environmental impact of the BOF process, which include the repurposing steel slag waste for alternate applications.[195] Additionally, the BOF process has been enhanced through heat recovery from off-gases, resulting in a potential energy consumption saving of up to 4%.[195] Further improvements, particularly in the oxygen system, have been implemented to save up to 1.5% of the electricity used in oxygen production.[195]

## 5.2 Electric Arc Furnace

The carbon emissions in the EAF process are contingent on the source of electricity since the EAF relies on electric power for operation.[2] The primary contributors to the direct carbon footprint in the EAF are graphite electrodes and the minimal amount of pure carbon added, resulting in an estimated 50 kg$CO_2$ per tonne of steel.[2] Replacing the electricity operation of the EAF with renewable electricity will have result in an estimated 81% in total carbon emissions from the EAF process[5]. Similar to the BOF, strategies are being put in place to reduce the environmental impact of the EAF process, where slag waste generated from the EAF is being repurposed as road base or for use in concrete.[196]

[5] Based on direct and indirect carbon emissions of the EAF process for an electricity consumption of 0.45MWh/$ton_{Steel}$,[9] carbon intensity of grid electricity of 460kg$CO_2$/MWh[1] and a direct carbon emission of 50kgCO2/$ton_{Steel.}$[2]

**The Importance of Steel Scrap**

Steel scrap, derived from sources like old car bodies, shipping containers, and demolished buildings, are a vital component in the steel industry, supporting the production of new steel products.[197] Currently, primary steel production accommodates 15-25% steel scrap with the addition of this scrap metal into the BOF or EAF process, depending on the production route.[11]

The importance of scrap in green steel production is emphasised by the International Energy Agency (IEA), which stipulates that at least 30% scrap steel must be used for steel production to qualify as green steel.[34,35] Further details can be found in **Report 1**.

However, steel scraps contain elements that cannot be easily removed by current smelting processes, such as chromium, tin, copper, nickel, and molybdenum.[198] These are referred to as "tramp" elements. Steel scrap is categorised based on the level of tramp elements it contains, ranging from Q1 to Q4. Q1 scraps contain less than 0.18% tramp elements, Q2 contains 0.18-0.25%, Q3 contains 0.25-0.35%, and Q4 contains more than 0.35%. Currently, Q3 scraps account for 40-60% of the steel scrap market.[198] As steelmaking processes adopt higher levels of scrap use, effective management of tramp materials will become increasingly important for maintaining quality control in the manufacturing of low-carbon steel products.

## 5.3 Emerging Technology

Existing technology options for steelmaking typically involve two production steps: converting iron ore to iron, and then converting iron to steel. However, newer innovative steelmaking processes offer the ability to convert iron ore directly to crude steel in a single reaction step. These new approaches promise to enhance process efficiency and reduce the overall capital intensity of the steelmaking process.

### 5.3.1 Hydrogen Plasma Smelting Reduction

Hydrogen Plasma Smelting Reduction (HPSR) process offers higher integration and superior metal quality compared to processes operating with H2-DRI.[199] Additionally, this process offers the advantage of producing crude steel directly from iron ore.[2,191] This process operated by creating a hydrogen plasma arc by passing electricity through hydrogen gas, generating the required heat to melt the iron, as the hydrogen can reduce the iron ore. The unutilised hydrogen is recycled within the process.

The HPSR technology is in its early developmental stages and has seen successful lab-scale testing.[188] **Figure 19** and **Table 16** outline the process arrangement based on the current limited publicly available data.

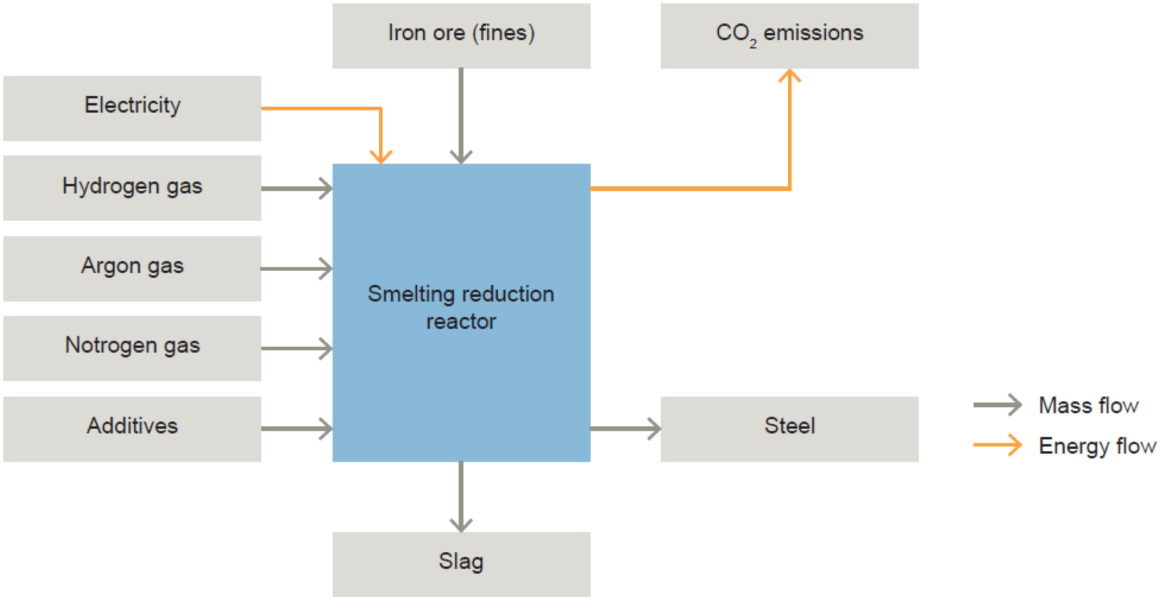


**Figure 19. Schematic of a hydrogen plasma smelting reduction process.**[2,191] Iron ore, hydrogen, argon, nitrogen and additives are introduced into a reactor where electrical energy is used to generate hydrogen plasma enabling the production of steel directly from iron ore.

**Table 16. Indicative process inputs and outputs for a hydrogen plasma smelting reduction reactor**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | Iron ore is finely ground before being entered into the Smelting Reduction Reactor.[191] | 1.5-1.6[a] $t/t_{Steel}$ |
| Hydrogen Gas | Hydrogen gas requirement to generate the plasma arc. | 57-69[b] $kg/t_{Steel}$[20] |
| Electricity | Electricity is used to produce the hydrogen plasma arc. | Data Unavailable [c] |
| Argon Gas | Argon is used to aid with hydrogen plasma formation. A 2:1 Ar:H2 ratio has been used at the laboratory scale.[20] | Recirculated |
| Nitrogen Gas | Nitrogen gas is used to aid with the reaction.[20] | Recirculated |
| Additives | Additives are incorporated to aid with the formation of slag. It is expected that carbon will need to be included to increase the product carbon content if this process is used for steelmaking. | Data Unavailable |
| Slag | Slag is produced as a waste product from the reactor, resulting from the impurities present in the iron ore. | 0.5-0.6[a] $t/t_{Steel}$ |
| $CO_2$ Emissions | Direct CO2 emissions from primary reactor, for the hydrogen plasma smelting reduction reactor. Omits indirect emissions including electricity generation and raw material | 93 $kg_{CO2}/t_{Steel}$[2] |

preparation.

a. Estimated based on an iron ore grade of 60-65% Fe(w/w) and an assumed outlet steel metallic iron content of 98% Fe (w/w). Slag production is assumed to the be the remaining mass fraction on the inlet iron ore and does not account for the mass flow of the slag additives.
b. Estimated based on reported 1.05-1.28x requirement of stoichiometric reaction between hydrogen and hematite ($Fe_2O_3$), based on a bench-scale demonstration for a 1kg same of iron ore.[20]
c. Large-scale or pilot-scale data unavailable. Energy requirements of a bench-scale demonstration for a 1kg sample of iron ore indicate a power consumption of 22-40kWh/$kg_{IronOre}$.[20]

### 5.3.2 Molten Oxide Electrolysis

The Molten Oxide Electrolysis (MOE) process, an electrometallurgical technique, which can directly produce liquid iron from iron ore, presenting a promising avenue for decarbonising iron and steelmaking.[2,200] The carbon emissions in the molten oxide electrolysis (MOE) process are contingent on the source of electricity since the MOE relies on electric power for operation.[10] The basic reaction involved in the MOE is as follows: [10]

$$Fe_2O_{3(s)} \xrightarrow{298K} 2Fe^{3+}{}_{(aq)} + 3O^{2-}{}_{(aq)} \qquad \textbf{Eq 27}$$

$$2Fe^{3+}{}_{(aq)} + 3O^{2-}{}_{(aq)} \xrightarrow{electrolysis} 2Fe_{(l)} + {}^{3}/_{2}\, O_{2\,(g)} \qquad \textbf{Eq 28}$$

The MOE process, currently under development by American-based company Boston Metal[201] is still in its early stages. The process requirements and consumption rates, based on limited public data, are provided in **Figure 20** and **Table 17**.

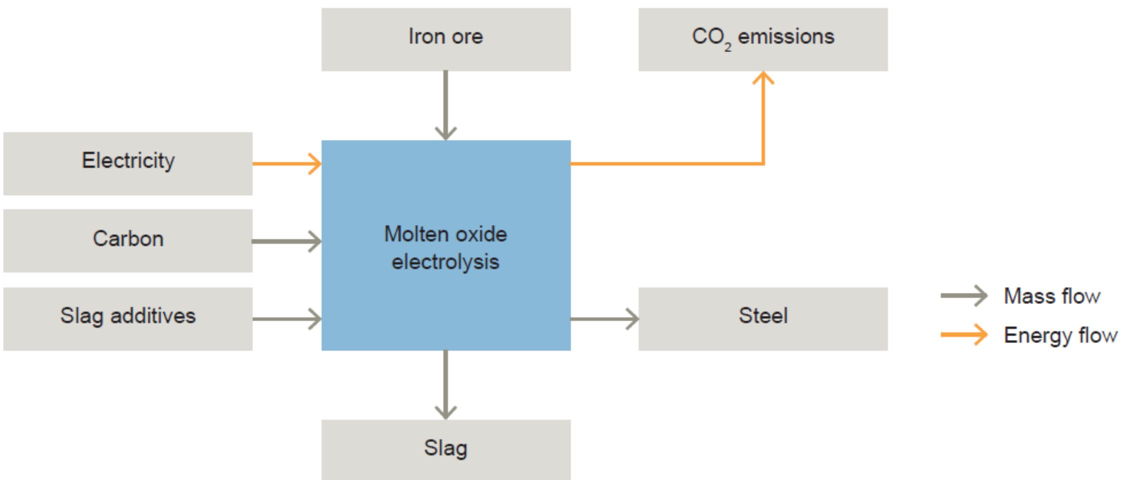


**Figure 20. Schematic of a molten oxide electrolysis process.**[2,191] Iron ore, carbon and slag additives are introduced into a reactor where electrical energy is used to produce of steel directly from iron ore.

**Table 17. Indicative process inputs and outputs for a molten oxide electrolysis process**

| Stream | Description | Rate |
|---|---|---|
| Iron Ore | Iron ore is ground before being entered into the Molten Oxide Electrolysis reactor | 1.5-1.6[a] $t/t_{Steel}$ |
| Electricity | Electricity is used to power the Molten Oxide Electrolysis reactor. | 4.10[b] $MWh/t_{Steel}$ |
| Carbon | Carbon is added to the Molten Oxide Electrolysis reactor to raise the carbon content of the steel to the desired level | Data Unavailable |
| Slag Additives | Slag additives are added to aid with the formation and removal of iron ore impurities through the formation of slag | Data Unavailable |
| Slag | Slag is produced as a waste product from the reactor, resulting from the impurities present in the iron ore. | 0.5-0.6[a] $t/t_{Steel}$ |
| $CO_2$ Emissions | Direct $CO_2$ emissions from primary reactor, for the molten oxide electrolyser. Omits indirect emissions including electricity generation and raw material preparation. | 0[c] $kg_{CO2}/t_{Iron}$[10] |

a. Estimated based on an iron ore grade of 60-65% Fe(w/w) and an assumed outlet steel metallic iron content of 98% Fe (w/w). Slag production is assumed to the be the remaining mass fraction on the inlet iron ore and does not account for the mass flow of the slag additives.

b. Estimated based on a process energy consumption rate of 14.75GJ/$t_{Iron}$[2]

c. Although the reported direct $CO_2$ emissions from this process are 0 $kg_{CO2}/t_{Steel}$ it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

# 6 Comparison of Technological Pathways

**Multiple pathways exist for producing green iron and steel, each at different stages of technological development and offering varying levels of $CO_2$ emission reduction potential. Currently, the most carbon-intensive technology pathways are those involved in converting iron ore to iron.**

There are several technological pathways for the decarbonisation of the Iron and Steel industry, each at differing levels of development. Understanding the level of decarbonisation each pathway can provide, as well as the current Technology Readiness Level (TRL) of each pathway are important factors in assessing the short-term and long-term viability of each process option. Currently, the most energy and carbon-intensive processes involve the conversion of iron ore to iron. A summary of energy requirements, specific capital costs, technology readiness level and direct $CO_2$ emissions for each of the technology pathways considered in this report has been detailed in **Table 18**.

The use of Carbon Capture, Utilisation, and Storage (CCUS) presents significant carbon abatement potential, only requiring capital expenditure for the integration of $CO_2$ capture and storage into existing processes. However, a major drawback of these pathways is their continued reliance on fossil fuels despite offering rapid deployment with minimal disruption to existing supply chains.

Apart from CCUS, carbon emissions can be decreased by incorporating alternative fuels into current processes. Examples include utilising biomass in blast furnace ironmaking or employing bio-syngas or pure hydrogen in the DRI process. These options not only reduce $CO_2$ emissions but also lessen our dependence on fossil fuels. In the gas-based DRI process, up to 100% of fossil fuel input can be substituted with net-zero fuels, leading to significantly higher $CO_2$ reduction potential compared to the blast furnace process route with fossil fuel replacement.

Signification reductions in direct $CO_2$ emissions can be achieved by adopting new alternative process routes independent of existing methods (such as the Alkaline Iron Electrolysis, Hydrogen Plasma Smelting Reduction and Molten Oxide Electrolysis). However, since these processes are currently at low TRLs, substantial investment and development are necessary to reach commercial maturity.

**Table 18. Comparison of the different iron and steel technology pathways.**

| Product Conversion | Base Technology | Energy Consumption[a] (GJ/t) | CAPEX[a] (AUD/t) | Decarbonisation Route | Current Technology Readiness Level[b] (TRL) | Net Direct $CO_2$ Emissions[c] ($kg_{CO2}/t$) |
|---|---|---|---|---|---|---|
| Iron Ore to Iron | Blast Furnace | 15.28[2] | 228[3] | Base Technology | 11 | 1450[d] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 145[e] |
| | | | | Partially Replace Coke with Biomass | 7-10 | 1357[c,f] |
| | | | | Tuyere Injection Fuel Replacement | 7 | 926[c,f] |
| | Coal-Based Direct Reduced Iron | 21.9[4] 20[5] | 250[6] | Base Technology | 11 | 1048[1] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 105[e] |
| | Gas-Based Direct Reduced Iron | 12.16-13.0[2] | 310[2] 280-286[7] | Base Technology | 11 | 522[1] |
| | | | | Fossil Fuel use with CCUS | 7-8 | 52[e] |
| | | | | Syngas Derived from Biomass | 7-8 | 0[c] |
| | | | | Electrolytic Hydrogen | 5-6 | 0[g] |
| | Electric Smelting Furnace | Data Unavailable | Data Unavailable | Base Technology | 9[h] | 0[i] |
| | Alkaline Iron Electrolysis | 9.9[2] | 755-970[2] | Direct Electrification | 4 | 0[j] |
| Iron to Steel | Basic Oxygen Furnace | 4.72-14.72[2] | 152[3] | Base Technology | 11 | 193[1] |
| | Electric Arc Furnace | 1.3-1.6[8,9] | 159[7] 172[3] | Base Technology | 11 | 50[k] [2] |
| Iron Ore to Steel | Hydrogen Plasma Smelting Reduction | Data Unavailable [l] | Data Unavailable | Hydrogen Plasma Reduction | 4 | 93[2] |
| | Molten Oxide Electrolysis | 14.76[2] | 1100-1150[2] | Direct Electrification | 4 | 0[m] [10] |

a. Energy consumption and CAPEX estimates refer to the base technology and do not account for any additional CAPEX or energy requirements where decarbonisation is performed through modification of the base technology. Any currency conversions were assumed at 0.7EUR:AUD and 0.7USD:AUD.

b. As determined by this report, according to Technology Readiness Scale (TRL) defined by the International Energy Agency (IEA).[11]

c. Net Direct $CO_2$ emissions only consider emissions arising from the process, this omits indirect emissions arising from electricity generation & raw material preparation. In cases where biomass is used, these fuels are assumed to have net-zero emissions and are hence deducted from the net direct CO2 emissions for that pathway.

d. Estimated based on a coke consumption rate of 0.32 $t/t_{Iron}$[12-14] and a pulverised coal (tuyere injection) consumption rate of 0.20 $t/t_{Iron}$[14] for a coke emission factor of 2895 $kg_{CO2}/t$[15] and anthracite emissions factor of 2617 $kg_{CO2}/t$[15]. Estimate aligns with literature reported value of 1476 $kg_{CO2}/t_{Iron}$.[1]

e. Assuming a $CO_2$ capture efficiency of 90%.[16]

f. Based on a coke replacement rate of 10% and a pulverised coal (tuyere injection) replacement rate of 100% (refer to **Section 4.1** for details), for a coke emissions factor of 2895 $kg_{CO2}/t$[15] and anthracite emissions factor of 2617 $kg_{CO2}/t$[15]. In both cases the replacement fuel is assumed to net-zero $CO_2$ emissions.

g. Although this process is reported as having direct carbon emissions of 25 $kg_{CO2}/t_{Iron,}$[2] this is due to carbon addition in the EAF process (if considering the use of H2-DRI coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[2]

h. Although the electric smelting furnace is currently under commercial operation in limited applications, further development is needed for the application of ESFs with DRI processes and on different ore types.[17]

i. The carbon emissions from the ESF process are assumed to be negligible. However, it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

j. Although this process is reported as having direct carbon emissions of 180 $kg_{CO2}/t_{Iron,}$[2] this is due to carbon addition in the EAF process (if considering the use of AIE coupled with EAF for steelmaking). Otherwise, this process exhibits negligible $CO_2$ emissions.[18]

k. Due to the injection of carbon in the EAF process and consumption of graphite electrodes.[2,19]

l. Large-scale or pilot-scale data unavailable. Energy requirements of a bench-scale demonstration for a 1kg sample of iron ore indicate a power consumption of 22-40kWh/$kg_{IronOre}$.[20]

m. Although the reported direct $CO_2$ emissions from this process are 0 $kg_{CO2}/t_{Steel}$ it should be acknowledged that there may be some direct $CO_2$ emissions related to the addition of carbon in the process, similar to that of the EAF process.

# 7 Opportunities for Australia and Germany

As detailed in **Section 6**, regardless of which technological pathway is used, large amounts of renewable energy and iron ore are necessary to produce green iron and steel. The symbiotic relationship detailed in **Report 1** where the synergy of abundant renewable energy, iron ore resources and strong international relationships has the potential to establish a value-added supply chain between Australia, Germany, and Europe, fostering the production and export of green iron, steel, and related products. This suggests three possible roles that Australia could provide in the advancement of green steel production in Germany:

i) Export iron ore and renewable hydrogen (and derivatives) to enable the integrated production of green iron and green steel in Germany,
ii) Produce green iron locally in Australia and export green iron and renewable hydrogen (and derivatives) to support the production of green steel in Germany,
iii) Produce both green iron and green steel locally in Australia for export to Germany. The steel would still generally require further processing into the specialty steels used in German and European steel markets.

At present, we acknowledge that the first two options are likely the better fits for current industry arrangements in both Australia and Europe.

# 8 Conclusions and Next Steps

Current steelmaking pathways rely heavily on fossil fuels to provide both energy and to act as a reducing agent[6], with the most carbon-intensive stage being the conversion of iron ore to iron which accounts for over 88%[7] of direct $CO_2$ emissions. Several decarbonisation pathways are under development, each with varying levels of maturity and carbon reduction potential. Carbon Capture, Utilisation, and Storage (CCUS) offers the advantage of providing minimal disruption to existing supply chains but continues to depend on fossil fuels. Incorporating low-carbon fuels, such as biomass or hydrogen, into current ironmaking processes can significantly reduce $CO_2$ emissions. Additionally, alternative process routes like Alkaline Iron Electrolysis and Molten Oxide Electrolysis present promising opportunities for deep decarbonisation through direct electrification, though require further development to reach commercial viability.

This report assesses the different technology pathways available for green iron and steel production and forms the second part of a series of three reports. The first report delves into the potential opportunities and synergies between Australia and Germany in establishing a green metal supply chain that can be used for ironmaking and steelmaking in Germany, and the third report performs a techno economic assessment of a potential green iron and steel value chain between Australia and Germany.

[6] In ironmaking, a reducing agent is a material that removes oxygen from iron ore, converting it to iron.
[7] Based on a blast furnace-basic oxygen furnace (BF-BOF) route and emissions intensity of 1476 and 193 $kg_{CO2}$/t for a blast furnace and basic oxygen furnace respectively.[1]

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