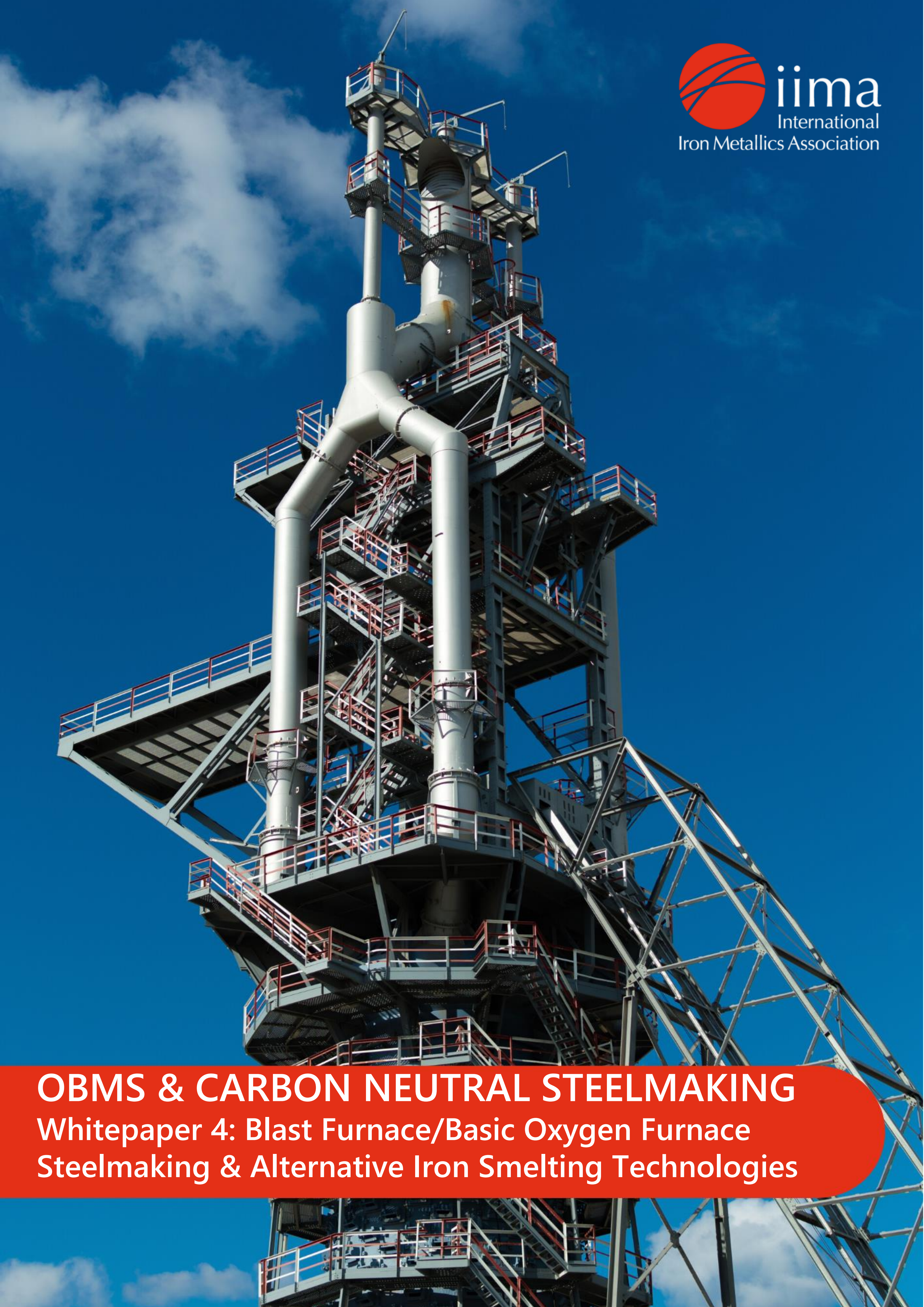

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# OBMS & CARBON NEUTRAL STEELMAKING

## Whitepaper 4: Blast Furnace/Basic Oxygen Furnace Steelmaking & Alternative Iron Smelting Technologies

# OBMs & CARBON NEUTRAL STEELMAKING

## Paper 4 Blast Furnace/Basic Oxygen Furnace Steelmaking & alternative iron smelting technologies

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# Foreword

## Overview

With the recent acceleration in interest, strategic thinking, and commitment towards decarbonization, we as a key component of the steelmaking value chain need to play our part in this endeavour. To be effective in tackling the challenges and opportunities we face, the merchant ore-based metallics sector has begun exploring its role in the pathway to creation of a carbon-neutral steelmaking industry. The current findings are contained in the first edition of a series of whitepapers on this topic.

## Introduction to the Whitepapers

The whitepapers aim to foster discussion and ignite collaboration with stakeholders in the merchant ore-based metallics value chain including academia and public policy makers. We believe that the foundation to successful decarbonization is knowledge sharing and awareness raising on the challenges and opportunities inherent in this process, garnering deeper understanding and fostering potential solutions but most importantly ensuring sustainable outcomes. Many companies in our value chain from iron ore miners to steelmakers have already published their thinking and strategy for decarbonization and there will be more to come. The purpose of our whitepaper is to examine these, identify common elements and issues and to catalyse thinking and advocacy for action. We recognise this is an evolving space and therefore plan to continually monitor and regularly update the whitepaper as a living document.

## IIMA OBM & Carbon Neutral Steelmaking Whitepapers

- **Whitepaper 1** – Ferrous Metallics for Steelmaking
- **Whitepaper 2** – An Assessment of Future Challenges for Electric Arc Furnace Steelmaking
- **Whitepaper 3** – Future DRI Production & Iron Ore Supply
- **Whitepaper 4** – Blast Furnace/Basic Oxygen Furnace Steelmaking and Alternative Iron Smelting Technologies

# Abstract

The scope to reduce $CO_2$ emissions from the BF/BOF steelmaking processes by perhaps 20-50% or more through improved raw materials, charging metallics, alternate injectants, process optimization and flow sheet changes is discussed.

Alternative hot metal processes and new technologies that have reached or nearly reached commercial scale (COREX, FINEX, HIsmelt, HIsarna), although capital intensive, can offer $CO_2$ reduction benefits if sufficient "green" reductants (e.g., biomass, etc.) become available and/or when $CO_2$ capture and sequestration methods become technically feasible and economically viable. Other technologies, such as direct reduction of iron ore followed by melting the DRI to form hot metal have a high probability of success.

The extent to which their full $CO_2$ reduction potential can be realised will depend on regional circumstances and in any case when existing BF/BOF facilities reach the end of their useful and economic lives. The Asia Pacific region, that accounts for greater than 70 % of global steel production, also has the newest BF/BOF production facilities. Early stage novel ironmaking processes, such as molten oxide electrolysis, must advance through the pilot and demonstration plant phases before they can be seriously considered.

# 1 Introduction & scope

## The scope to reduce $CO_2$ emissions from the BF/BOF steelmaking processes

A great deal of what has been written about the roadmap to carbon-neutral steelmaking revolves around the shift from integrated steelmaking via the blast furnace / basic oxygen furnace (BF/BOF) route to the direct reduction / electric arc furnace (DR/EAF) route that is expected to take place over the coming decades. Figure 1 shows the development in ironmaking processes projected by the International Energy Agency (IEA) in the steelmaking chapter of its report "Energy Technology Perspectives 2020." IEA's two scenarios are: STEPS = Stated Policies Scenario (in effect, business as usual); SDS = Sustainable Development Scenario (based on the UN sustainable development goals). Figure 2 is a simplified version of the ironmaking chart in Figure 1.

FIGURE 1: GLOBAL STEEL PRODUCTION BY ROUTE AND IRON PRODUCTION BY TECHNOLOGY IN THE SUSTAINABLE DEVELOPMENT SCENARIO (IEA)

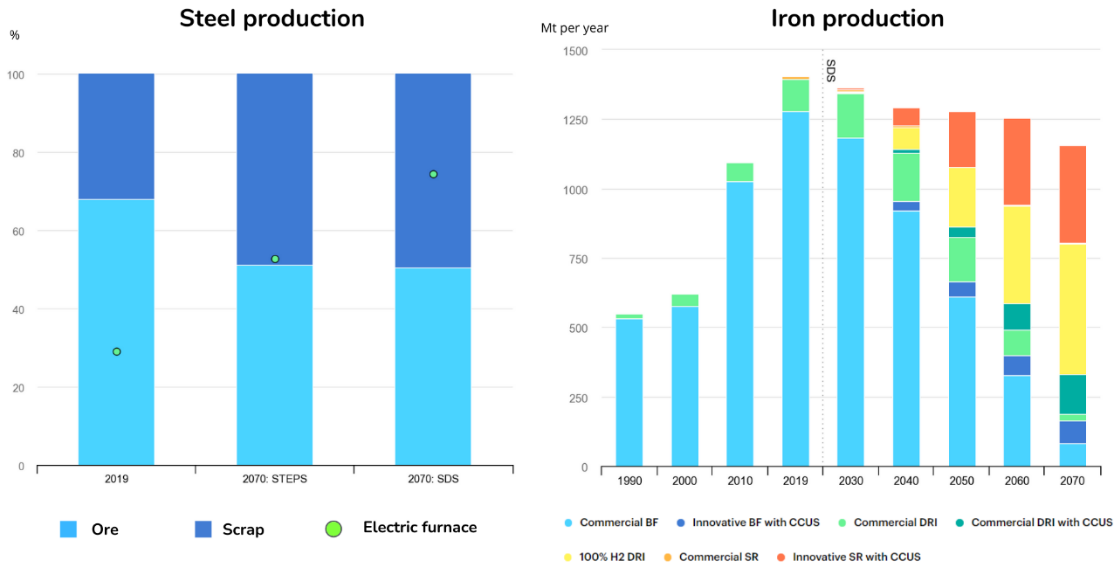
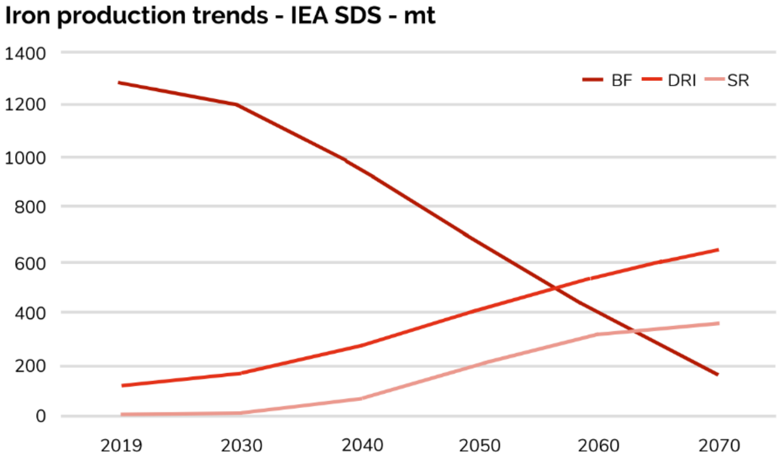


FIGURE 2: SHIFT IN IRONMAKING PROCESS ROUTE PER IEA SDS



This paper will start by examining the basic premise: how far can integrated steel mills progress towards carbon neutrality? It will then consider the different ironmaking strategies in the main steelmaking countries/regions and conclude with an overview of smelting reduction technologies.

# 2 How far can integrated steel mills progress towards carbon neutrality?

This section will cover the following aspects of the BF/BOF process route:

- burden preparation, coke ovens, blast furnace, BOF, etc.
- use of hydrogen, natural gas, biomass/bioenergy, plastics, (incl. coke to gas shift)
- burden materials (higher grade iron ore and more agglomerates, HBI/DRI, scrap)
- energy efficiency: higher blast temperatures (plasma heating)
- top gas recycling (100 % oxygen BF); injection of reducing gases in 2nd bustle above cohesive zone
- best practice technologies (e.g. waste heat recovery, coke dry quenching,)
- Carbon Capture, Utilization and Storage (CCUS)
- HBI/Scrap charging

## 2.1 Burden preparation

**Sintering process** – these efforts include:

- replacing carbon (coke breeze, anthracite) with biomass fuel sources; some of this is already ongoing in Brazil with partial replacement by charcoal and selectively elsewhere with other biomass sources;
- utilize "green" $H_2$ as ignition furnace fuel, switch to electricity generated from renewable sources (so-called "green electricity") for fans, drives, etc.; so far "green" $H_2$, or for that matter, any $H_2$ is currently too costly for sinter plant use. Green electricity should be increasingly available as renewable sources increase their role in overall electrical energy supply.

**Pelletizing process** – these efforts include:

- replacing carbon additions (coke breeze, anthracite, etc.) with biomass fuel sources for hematite ore pelletizing; some experimental work with partial replacement by biomass such as charcoal is already ongoing in Brazil; typical current coal utilization rates are in the range of 10 - 25 kg/ton[1] of pellets;
- due to the exothermic oxidation of magnetite to hematite, use of magnetite ores in pelletizing does not require admix of carbon so, by pelletizing magnetite ore, LKAB in Sweden is already producing "greener" pellets;
- utilize "green" $H_2$ as burner fuel (see comments above for sintering);
- plasma torch-based induration using "green" electricity: a supplier of plasma torches (PyroGenesis) has announced a pilot program with a major pellet producer;
- switch to green electricity for fans, drives, etc, (see comments above for sintering).

As potential alternatives to sinter or pellets, both of which require energy-intensive induration at high temperatures, are briquetting of iron oxides or production of cold bonded pellets. Though successfully applied in some sectors, large scale success in

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[1] In this paper ton refers to metric ton or tonne.

these technologies remains elusive. With much less CAPEX than an induration machine and much lower energy requirements, they are attractive and “greener” alternatives, but sustaining physical and metallurgical product integrity remains a significant challenge, as demonstrated in the case of briquetting of waste materials. For cold bonded pellets the necessity to add a binder may decrease its iron content considerably, making subsequent processing also more energy intense and expensive.

## 2.2 Coke ovens

**Coke ovens** – these efforts include:

- aiming for optimal distribution and utilization of the arising process gases;
- Real “green” opportunities are limited to green electricity for motors, fans, etc. (see comments above for sintering);
- CDQ (coke dry quenching) provides some BF coke rate reduction and therefore some $CO_2$ reduction benefit (due to less moisture);
- Non Recovery Coke ovens technology reduces emissions, but requires large space requirements and CAPEX;
- Biomass addition to coking coal.

When considering the coke oven process, the allocation of $CO_2$ emissions associated with the metallurgical coal feedstock should be taken into account. By contrast iron ore mines exhibit much lower $CO_2$ emissions (kg/ton), mainly associated with electrical power and fuel use in mobile equipment and processing facilities. Detailed information can be found in the sustainability reports of the various coal and iron ore producers, but see Figures 3 and 4 for examples from Teck (coal) and Rio Tinto (iron ore).

FIGURE 3: $CO_2$ FROM COAL PRODUCTION (TECK)

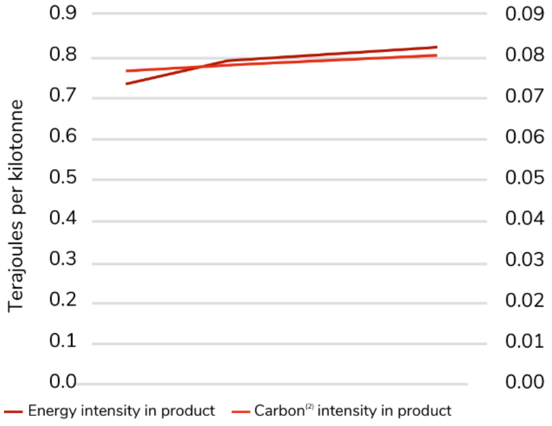
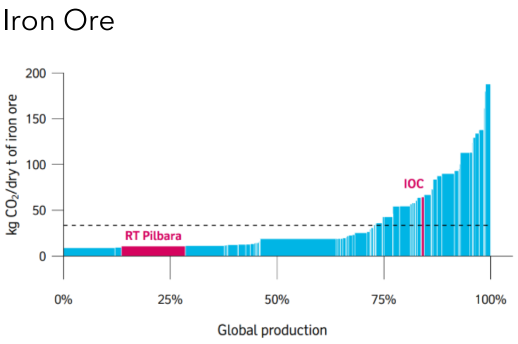


FIGURE 4: $CO_2$ FROM IRON ORE PRODUCTION (RIO TINTO IRON ORE)



## 2.3 Injection of hydrogen, natural gas, biomass/bioenergy, plastics

TABLE 1: CURRENT AND PROJECTED PCI RATES FOR SELECTED COUNTRIES (SOURCE: CRU)

| **Country** | **PCI rate (kg/tHM)** | |  | **PCI rate (kg/tHM)** | |
|---|---|---|---|---|---|
| | **2020 e** | **2025 p** | | **2020 e** | **2025 p** |
| **Austria** | 45 | 50 | **Turkey** | 85 | 100 |
| **Belgium** | 230 | 230 | **Russia** | 25 | 50 |
| **Czech Republic** | 0 | 100 | **Ukraine** | 20 | 35 |
| **Finland** | 0 | 125 | **USA** | 45 | 50 |
| **France** | 175 | 180 | **Canada** | 62 | 70 |
| **Germany** | 170 | 175 | **Mexico** | 80 | 85 |
| **Italy** | 165 | 170 | **Brazil** | 116 | 125 |
| **Netherlands** | 255 | 255 | **South Africa** | 84 | 90 |
| **Poland** | 40 | 75 | **China** | 135 | 145 |
| **Romania** | 0 | 175 | **India** | 108 | 125 |
| **Slovakia** | 158 | 165 | **Japan** | 145 | 150 |
| **Spain** | 187 | 195 | **South Korea** | 150 | 160 |
| **Sweden** | 163 | 170 | **Taiwan** | 150 | 160 |
| **UK** | 173 | 180 | **Australia** | 112 | 125 |

Globally, nearly all blast furnaces outside of North America and the CIS inject pulverised coal at rates of 150-200 kg/ton hot metal (tHM) (so-called pulverised coal injection - PCI); this could eventually be replaced by "green" $H_2$ injection; as an intermediate step, injection of natural gas or "blue" $H_2$ also reduces $CO_2$ emissions. Some steelmakers are conducting trials with $H_2$ injection, e.g. ThyssenKrupp Steel in Germany. A summary of global PCI rates with some projections through 2025 is shown in Table 1. Table 2 shows BF injection practice for USA BFs in 2018.

TABLE 2: INJECTION PRACTICE BY USA BFS IN 2018 (SOURCE: AIST PROCESS BENCHMARKER)

| **Injectant** | **No. of BFs** |
|---|---|
| **Natural gas** | 10 |
| **Coal** | 1 |
| **Natural gas + coal** | 16 |
| **Coke oven gas + natural gas** | 2 |

However, until $H_2$ is available as an injectant in sufficient quantity and at economic cost, some PCI, along with natural gas injection, will still be desirable from the perspective of overall $CO_2$ reduction as coke rates can be minimized with such "co-injection" of natural gas and coal. Note that there is a limit to natural gas injection as the disassociation energy required reduces RAFT (raceway adiabatic flame temperature). By contrast, $H_2$ injection entails no disassociation energy; here the ultimate limitation depends on the extent to which coke rates can be reduced, as limited by the following:

- minimum amount of coke required to support the BF burden and maintain permeability of gases and liquids in the furnace;
- minimum amount of gas flow needed to preheat descending burden materials; especially as the use of oxygen lowers stack gas nitrogen content and total gas volume;
- the top gas temperature should be >100°C in order to avoid condensation of gaseous $H_2O$ in the furnace.

So far, satisfactory BF operation has been maintained with coke rates as low as 250 kg/tHM, suggesting that co-injection (coal, natural gas) rates of 250 kg/tHM or $H_2$ rates of 40 kg/tHM are feasible.

**Injection of biomass and plastics:** depending upon availability and cost, these materials can also replace coal injection. So far the practice of plastics injection is limited to several countries, e.g. Japan and Germany, but more importantly, the economics of plastics injection depend on subsidies from plastics manufacturers and/or governments, reflecting the alternative costs associated with plastics disposal. Whereas biomass can be claimed to fit into a circular economy, plastic injection merely displaces primary carbon usage, similarly to $CO_2$ use for chemical upgrading. Not all plastics are suitable for injection: for example PVC contains high ratios of chlorides which at elevated levels are detrimental for the BF process.

**Injection of Syngas**: various combinations of natural gas, oxygen, steam, H2 and plant recycled gases (BF gas, coke oven gas) can be processed by reforming or partial combustion methods to produce synthetic reducing gases. Such gases may be injected at the stack level or at the tuyere level.

**Co-injection of multiple injectants:** co-injection of coal, gas, biomass, plastics, etc. can maximize coke replacement and yield net reduction in $CO_2$ emissions. Coal and gases such as natural gas and $H_2$ can also be combined with plastics, biomass, etc. In all cases, the injectants other than $H_2$ convert to CO in the raceway. Though carbon exhibits the highest caloric value, gases with hydrogen promote direct reduction and might end up with a good replacement ratio and a thermally more stable process.

### 2.4 Burden materials (higher grade iron ore, more agglomerates, HBI/DRI, scrap)

**Higher grade iron ores:** higher grade ores allow production of agglomerates (sinter, pellets) with higher Fe content, thus lowering required rates of sinter and/or pellet consumption with attendant reduction of $CO_2$ from these agglomeration processes. Agglomerates with higher Fe content also lower blast furnace fluxing requirements (limestone/dolomite) and hence slag rates, with attendant reduction in coke rate and $CO_2$ emissions. Furthermore, higher proportions of agglomerates (i.e., less lump ore) in the BF burden lowers coke rates and therefore $CO_2$ emissions.

However, there has been a long term decline in Direct Shipping Ore (DSO) grades, summarized as the averages for nine of the principal sources of sinter feed fines in Table 3 (from Australia, Brazil, South Africa and Mauritania). Sinter feed is the largest component of global iron ore seaborne trade, comprising perhaps >80%. Over a 20 year period there has a clear decline in the Fe content and an increase in acidic gangue and P levels. The deterioration in Fe, $SiO_2$ and $Al_2O_3$ levels has several implications for conventional BF/BOF steel production:

- necessitates increased sinter production to provide the same Fe units from the sinter plants;
- results in increased BF slag volumes and increased coke rates at lower BF productivity;
- increases BOF flux consumption to maintain P removal.

The decline in DSO grades would also impact upon their use in alternative smelting reduction technologies such as COREX, FINEX, HISMELT, etc. which are designed to utilize the most commonly available iron ores such as DSO.

TABLE 3: DECLINE IN IRON ORE SINTER FEED GRADES (DSO) %

| | **1998** | **2010** | **2019** |
|---|---|---|---|
| **Fe** | 63.9 | 62.9 | 61.9 |
| **$SiO_2$** | 4.11 | 4.10 | 5.16 |
| **$Al_2O_3$** | 1.70 | 1.73 | 1.87 |
| **P** | 0.048 | 0.056 | 0.067 |

Source: Raw Materials & Ironmaking Global Consulting

TABLE 4: CONCENTRATES AND PELLET FEED GRADES %

| | **1998** | **2010** | **2019** |
|---|---|---|---|
| **Fe** | 67.3 | 66.9 | 67.2 |
| **$SiO_2$** | 3.70 | 4.04 | 3.84 |
| **$Al_2O_3$** | 0.26 | 0.36 | 0.32 |
| **P** | 0.017 | 0.021 | 0.016 |

Source: Raw Materials & Ironmaking Global Consulting

However, for iron ore concentrates and pellet feed, the history is somewhat different, due principally to the ability to maintain or improve grade through the use of beneficiation technology. Table 4 shows the same comparisons for 1998, 2010 and 2019 for Fe, $SiO_2$, $Al_2O_3$ and P for five of the leading pellet feed and concentrate products (from Brazil, Canada, Sweden and Mauritania). While not as comprehensive as the DSO compilation in Table 3, it is nevertheless representative of the sector.  Not included in this data set are concentrates from Russia and Ukraine, both significant suppliers, where many of the leading producers have upgraded or are currently upgrading their beneficiation plants in order to increase Fe content and decrease acidic gangue. Table 4 indicates little substantive change in overall quality.

Pellet quality in general reflects the quality of the source pellet feed.  The issue of pellet quality for direct reduction is addressed in the companion paper on DRI production and use.

While the acid gangue content of a pellet can be at a minimum, sinter requires a certain amount of slag formers and although high basicity sinter has been produced with 3.5% silica (Tata Steel IJmuiden) it is difficult to produce good quality sinter with silica below 4%.

It would appear that declining iron ore quality will be less of a quality issue for direct reduction processes utilizing pellets or concentrates. However, there will doubtless be a cost impact for steelmakers with the shift from use of DSO to the higher grade concentrates and pellets and the related CAPEX that will be needed to facilitate the technological shift in steelmaking processes.

## 2.5 Charging metallics (HBI/DRI, scrap)

TABLE 5: BF COST STUDY ON HBI USE

| BF consumption kg/tHM | Base case: no HBI | 50 kg/tHM HBI | 100 kg/tHM HBI |
|---|---|---|---|
| | | | |
| **Charge rate kg/tHM:** | | | |
| **HBI** | 0 | 50 | 100 |
| **Metallic Fe** | 0 | 43 | 86 |
| **Carbon** | 0 | 0.4 | 0.8 |
| | | | |
| **Blast furnace results kg/tHM:** | | | |
| **Coke rate** | 356 | 341 | 320 |
| **Slag volume** | 240 | 230 | 221 |
| **Slag basicity** | 1.08 | 1.08 | 1.09 |
| **Oxide pellet charge** | 683 | 613 | 543 |
| **Sinter charge** | 900 | 900 | 900 |
| **Flux charge** | 78 | 70 | 64 |
| | | | |
| **Hot metal costs $/tHM** | 239 | 242 | 247 |
| | | | |
| **Production tHM/day** | 5,000 | 5,227 | 5,559 |
| **Δ base case** | | +227 | +559 |
| | | | |
| **HBI consumption t/day** | 0 | 261 | 523 |
| | | | |
| **Calculated cost benefit per ton HBI charged** | | | |
| | Base case: no HBI | 50 kg/tHM HBI | 100 kg/tHM HBI |
| | | | |
| **Hot metal cost $/tHM** | 239 | 242 | 247 |
| | | | |
| **Production tHM/day** | 5,000 | 5,227 | 5,559 |
| **Δ base case** | | +227 | +559 |
| **HBI consumption t/day** | 0 | 261 | 523 |
| **Δ gross profit $/day** | 0 | +8,675 | +17,645 |
| **Δ $/t HBI** | 0 | +33 | +34 |

Charging of metallics offers significant benefits in coke rate reduction (0.3 kg coke rate/1.0 kg metallic Fe) and thus reduction in $CO_2$ emissions; metallics can replace 25 - 40 % of charged Fe units but some $CO_2$ credit is needed to overcome the higher initial cost of metallics. The advantages of HBI use in BFs can be summarised as follows: HBI is easier to use than scrap in the BF materials handling and charging systems. The rule of thumb is that each 10% increase in burden metallization gives a production rate increase of 8% and a coke rate decrease of 7%, where the reduction of coke rate results in reduced $CO_2$ emissions (the quantum of which depends on the starting coke rate). The practical limit of HBI use in BFs is about 25 - 40 % of the iron bearing charge as a certain minimum level of coke is necessary to support the descending BF burden and maintain its permeability such as to enable the gas volume necessary to preheat incoming raw materials; thus, the coke rate cannot be reduced too far.

A BF cost study on HBI use (based on cost [$/ton] assumptions: coke, $160; pellets, $80; HBI, $220; incremental steel profit, $100) yielded the results shown in Table 5 above. As can be noted from the results in Table 5, hot metal costs increase when HBI is charged; hence, in the absence of a productivity benefit, a credit for $CO_2$ reduction based on the coke rate reduction is needed to achieve viable economics.  Viable economics may also be achieved when prices for coke and injected coal increase to very high levels.

The benefits to $CO_2$ emissions reduction by charging some HBI have been demonstrated in extended test programs in Austria by Voestalpine Stahl and in Japan by Kobe Steel. At Kobe Steel, a 20 % reduction in $CO_2$ emissions was achieved in a large (4,844 $m^3$) BF operation. In the demonstration test, it was verified that RAR (reducing agent rate) could be stably lowered from 518 kg/ton of hot metal (tHM) to 415 kg/tHM by charging a large amount of hot briquetted iron produced by the MIDREX® Process (described in more detail in the companion paper of DRI production and use).

## 2.6 Energy efficiency from higher blast temperatures (plasma heating) and other measures

Higher blast temperatures achieved by plasma superheating of the hot blast (only if based on "green" electricity) can provide a direct benefit through reduction in the coke rate and thus in $CO_2$ emissions. Some experimental and theoretical studies[2] have demonstrated the following rule of thumb: though every 100°C increase in hot blast temperature can save about 9 kg coke, both flame temperature and top gas temperature should be monitored to ensure stable operation.

Other BF energy efficiency measures include:

- burden and gas distribution control to improve gas utilization: conversion of any remaining two bell top furnaces (with or without movable armour) to bell-less tops can increase gas utilization and thereby reduce coke rates whilst at the same time increasing BF lining availability and life;
- digital process control to optimize hot metal: digitization of the BF process can also lead to reduced coke rates and $CO_2$ emissions through more precise adjustment of blast conditions and burdening.

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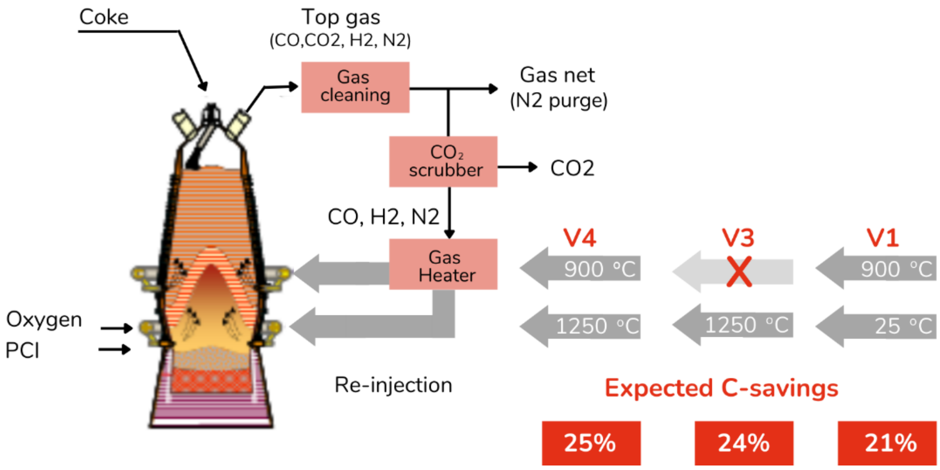
[2] Source: McMaster University Ironmaking Course 2018

## 2.7 Top gas recycling (100 % oxygen BF)

This includes injection of reducing gases in a second bustle pipe above the cohesive zone along with possible injection of additional reducing gases such as CO, $CH_4$ and $H_2$ through the tuyeres. Utilization of $CO_2$ scrubbed from top gas can be considered for other applications, such as chemicals, etc. (refer section 2.9).

The ULCOS top gas recycle BF concepts (see Figure 5) have been well demonstrated at the LKAB experimental blast furnace. Further scale up efforts were planned at operating blast furnaces in France and Germany, but these projects have been derailed by cost reduction mandates over the past ten years.

FIGURE 5: THREE DIFFERENT VERSIONS OF THE ULCOS BLAST FURNACE[3]



## 2.8 Best practice technologies

**Waste heat recovery:** sinter plant waste heat recovery is incorporated into a number of the technologies aimed at sinter plant pollution control.

**Blast furnace top gas pressure recovery turbines** (TRT): such turbines are incorporated into all of the newer, larger blast furnaces operating at high top pressure. For older, smaller blast furnaces the top pressure is not enough to justify them. Low electricity prices, such as in the USA, also limit the return on such investments. Both of these factors have resulted in only one blast furnace in the USA having a top gas pressure recovery turbine. A dry BF top gas de-dusting system will considerably enhance the TRT efficiency.

**Coke dry quenching:** coke dry quenching (CDQ) is extensively used in countries with high energy costs such as Japan, but far less so elsewhere. CDQ coke also

[3] Top gas recycle blast furnace developments for low $CO_2$ ironmaking, van der Stel et al, 2012

has a small coke rate benefit and so could be helpful in reducing $CO_2$ emissions with more widespread application. In addition, other environmental impacts such as waste water treatment are reduced.

**Coal moisture control:** coal moisture control (CMC) is another technique practised extensively in Japan, but less so elsewhere. It also contributes to improved coke quality as well as coke oven yield.

**BOF off gas energy recovery:** this is another technology that has required high energy costs to justify the investment involved, but otherwise has no other potential for process improvement as has been observed for many of the above energy saving techniques.

**Heat recovery from slags:** dry granulation of slags is yet another technique that offers no additional process benefit, so project investment return depends upon energy pricing and the $CO_2$ credit for the electricity that could be produced.

**Utilization of slags:** furthermore, many BFs direct their slag-to-slag granulation facilities, usually joint ventures with cement producers to provide feed material for cement production. This does provide a $CO_2$ reduction benefit for the cement producer as it offsets the production of clinker, normally produced in coal-based, environmentally unfriendly rotary kiln operations. Accordingly, such blast furnace operations feeding slag granulators should seek some $CO_2$ credits. Due to its content of free lime, BOF slag does not offer such co-product possibilities, but much BOF slag finds its way into road aggregate applications. In some parts of the world where low phosphorus iron ores are processed (as in the USA) the majority of BOF slag is actually recycled into the blast furnace, usually by direct charging, but also into the few remaining sinter plants in the USA.

**Power generation from any excess plant gas sources:** many steel plants globally direct excess plant gas into co-generation plants that can generate electricity for plant or external use. However, the priority applications for the major sources of plant gases are within the same or related processes:

- using BF top gas as BF stove fuel or rolling mill reheat furnaces;
- using coke oven gas (COG) or BF gas for coke oven under-firing;
- using COG or BF gas as sinter plant burner fuel.

The possible processing COG to produce $H_2$ gas is a key feature of major $CO_2$ reduction programs, such as the Course50 program in Japan and as reductant for direct reduction.

## 2.9 CCUS, Carbon Capture Utilization & Storage

These technologies are considered here mainly in the context of BF/BOF steelmaking, but it should be noted that they are also relevant to gases generated in smelting reduction processes such as COREX, FINEX, HIsmelt, etc. For the smelting reduction processes the required plant sizes for $CO_2$ capture are by far smaller than those for the BF, due to the absence of nitrogen.

**Flue gas carbon capture (CC) technologies for subsequent CCS and CCU:** flue gases from typical metallurgical ironmaking processes containing from zero to 30% $CO_2$ (except the HIsarna process which contains about 90% $CO_2$) can be captured by cryogenics, (V)PSA, Amine and membrane processes, typically achieving the purity of 90% required for conversion of $CO_2$; the exception is photosynthesis for which regular flue gases are sufficient.

**Carbon Capture and Storage technologies (CCS):** after carbon capture, the $CO_2$ has to be compressed before it can be used or stored.
Carbon Capture and Utilisation (CCU) technologies (see Figures 6, 7 and 8):
Chemical conversion of $CO_2$: reactions include the following:

- Reverse water shift $CO_2 + H_2 \leftrightarrow CO + H_2O$
- Methanation: $CO_2 + 4\ H_2 \leftrightarrow CH_4 + 2\ H_2O$
- Production of urea via the Bosch-Meiser industrial process
- Photosynthesis: algae

**Conversion of CO and $H_2$ to higher value products:** these include the following (gas cleanliness issues include as dust, $H_2S$, COS, $NO_x$, $O_2$ and $SO_2$):

- Water gas shift: $CO + H_2O \leftrightarrow CO_2 + H_2$
- Fischer-Tropsch synthesis: $(2n+1)\ H_2 + nCO \rightarrow CnH2_{n+2} + nH_2O$
- Carbonylation: $CH_3OH + CO \rightarrow C_2H_3COOH$ (Acetic acid)
- Bio fermentation of CO: Ethanol, Butanol

FIGURE 6: USES OF CAPTURED $CO_2$

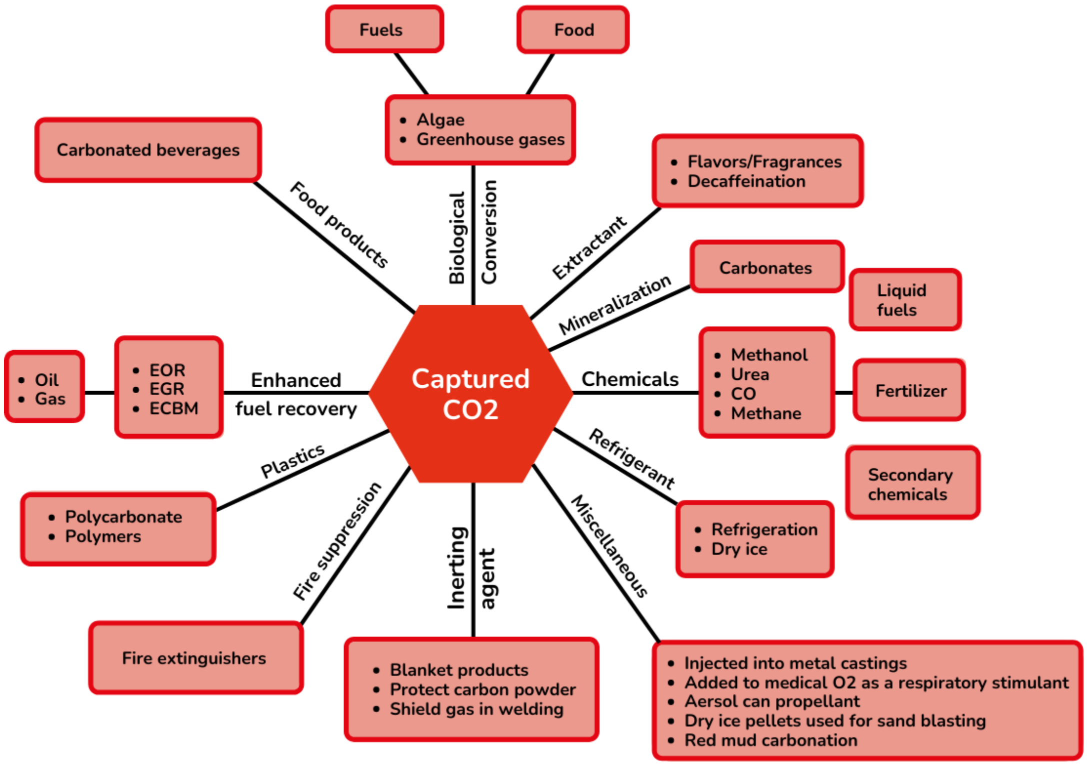


FIGURE 7: CCUS FROM THE PERSPECTIVES OF THE STEEL INDUSTRY

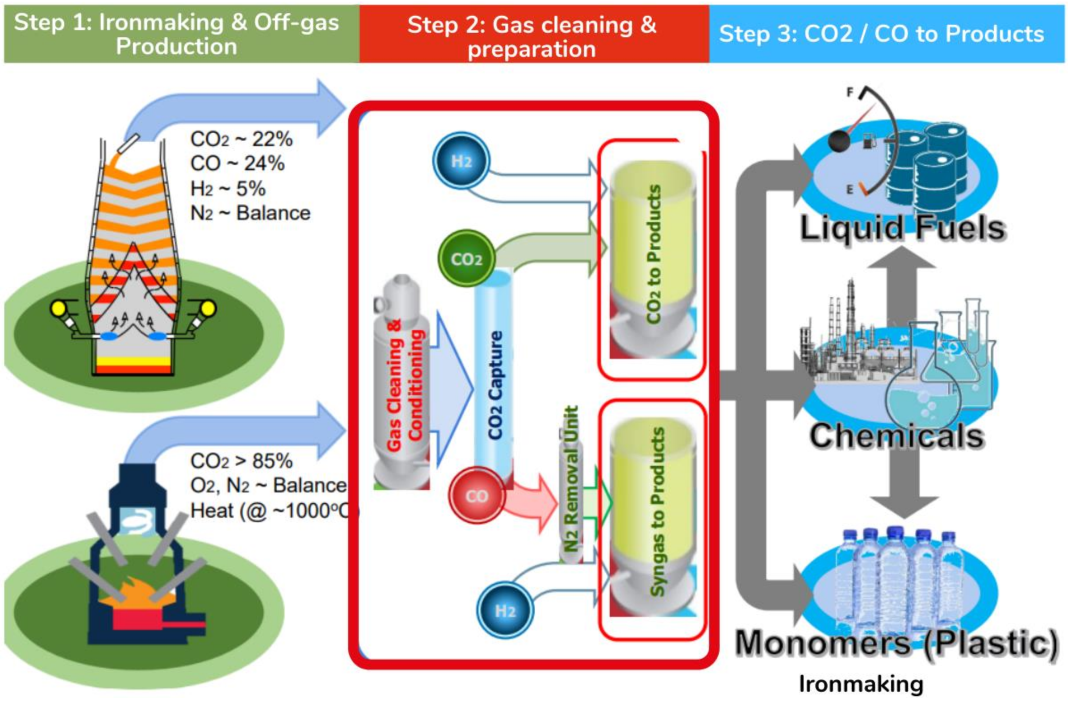
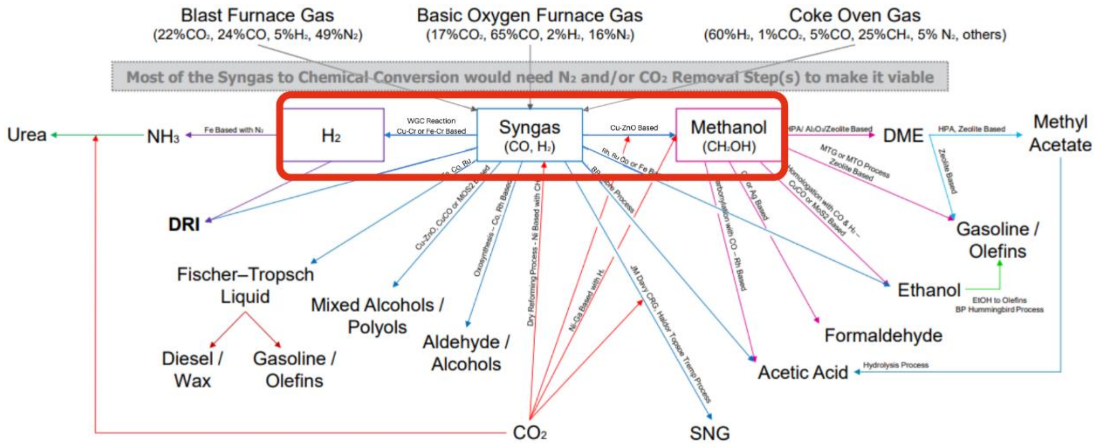


FIGURE 8: CHEMICAL CONVERSION OF WORKS ARISING GASES



Research and development into alternative routes for works arising gases and solutions for $CO_2$ will create multi-disciplinary knowledge of the chemistry and technology for future engineering solutions on Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) - $CO_2$ and/or syngas to chemicals & fuel.

# 3 Differing regional approaches

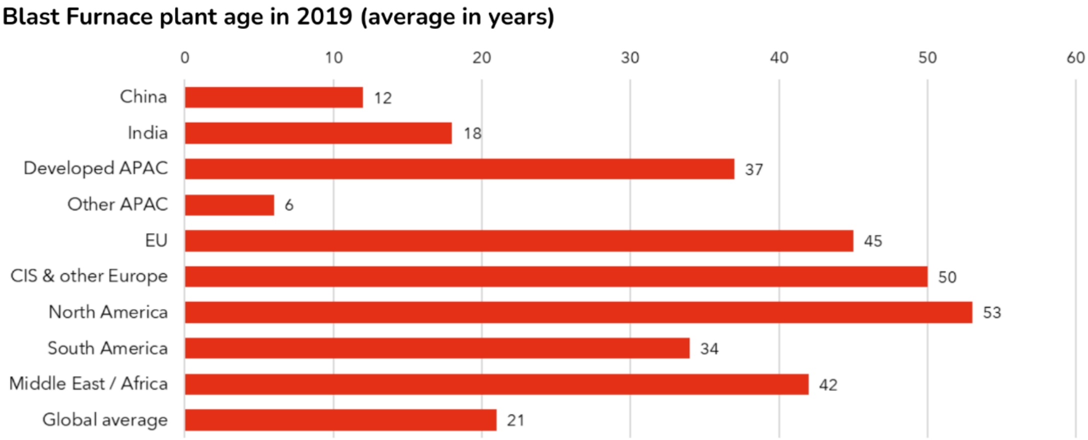
## An overview of the different global approaches as the evolution of the steelmaking process unfolds

## 3.1 China, ASEAN

**Age of plant/equipment** – this is a key factor as China has added >500 million tons of new BF/BOF capacity in the past 15 years and is not likely to abandon it prematurely. Furthermore, developed Asia (Japan, South Korea, Taiwan) and growing Asia (India, ASEAN) have newer BF/BOF capacity. This region is more likely to pursue incremental $CO_2$ reduction via the BF/BOF route with the steps outlined above. Also with respect to the BOF, increasing scrap ratios in the BOF charge can be expected as China's scrap reservoir grows. Essentially, the same level of steel production but with lower hot metal ratio in BOF decreases specific $CO_2$ emissions per ton of steel.

Figure 9, based on data from a recent presentation by BHP illustrates the median age of ironmaking/steelmaking facilities in all regions of the world. It is particularly noteworthy that the facility ages in China, India and other APAC (Asia Pacific: Vietnam, Indonesia, Malaysia, etc) are 12, 18 and only 6 years, respectively. These regions account for over 75 % of global steel production; thus the CAPEX barriers for major process equipment changes are formidable; the OPEX barriers (Australian iron ore not suitable for DRI) are already high. These barriers point in the direction of incremental $CO_2$ reduction within the existing BF/BOF route as exemplified by the Japanese Course50 program outlined below.

FIGURE 9: MEDIAN AGE OF BLAST FURNACE PLANTS IN 2019[4]



## 3.2 Japan: Course50 Program

The Japanese steel industry's Course50 program is fully defined as: $CO_2$ Ultimate Reduction System for Cool Earth 50. The key elements are outlined below.

- $CO_2$ capture and storage from blast furnace gas:

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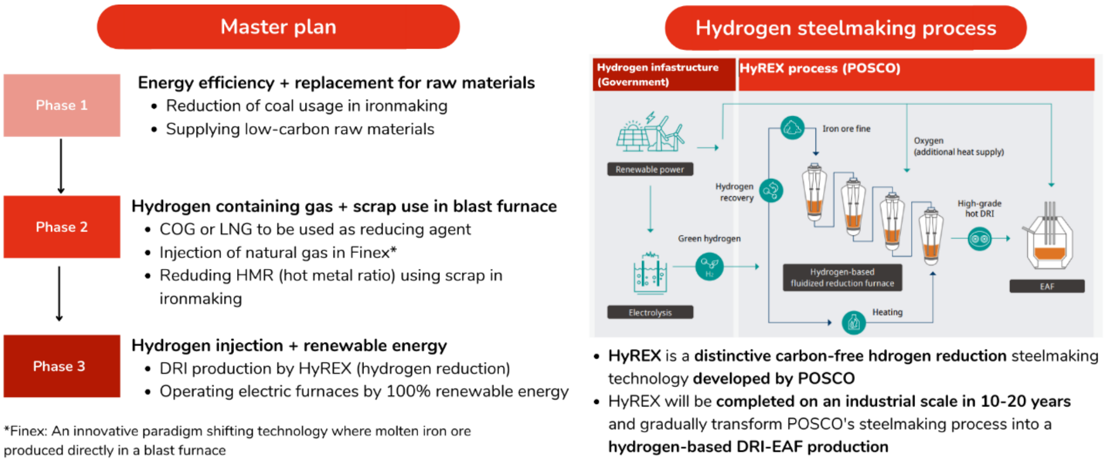
[4] Regional capacity-weighted average age for integrated steel plants – a sample estimate, not a census of all operations

  - direct $CO_2$ capture ($CO_2$ storage is not included in the project);
  - reduction of $CO_2$ capture energy: by using waste heat from steelworks input of external energy is minimized.
- Promotion of carbon-alternative reduction in the BF
  - utilization of $H_2$ in coal as a BF reductant (conventionally used for power generation and heating);
  - development of a future $H_2$ reduction technology.

## 3.3 South Korea

FIGURE 10: POSCO'S CARBON NEUTRAL ROADMAP



**Master plan**

Phase 1 — **Energy efficiency + replacement for raw materials**
- Reduction of coal usage in ironmaking
- Supplying low-carbon raw materials

Phase 2 — **Hydrogen containing gas + scrap use in blast furnace**
- COG or LNG to be used as reducing agent
- Injection of natural gas in Finex*
- Reduding HMR (hot metal ratio) using scrap in ironmaking

Phase 3 — **Hydrogen injection + renewable energy**
- DRI production by HyREX (hydrogen reduction)
- Operating electric furnaces by 100% renewable energy

*Finex: An innovative paradigm shifting technology where molten iron ore produced directly in a blast furnace

**Hydrogen steelmaking process**

- **HyREX** is a **distinctive carbon-free hdrogen reduction** steelmaking technology **developed by POSCO**
- HyREX will be **completed on an industrial scale in 10-20 years** and gradually transform POSCO's steelmaking process into a **hydrogen-based DRI-EAF production**

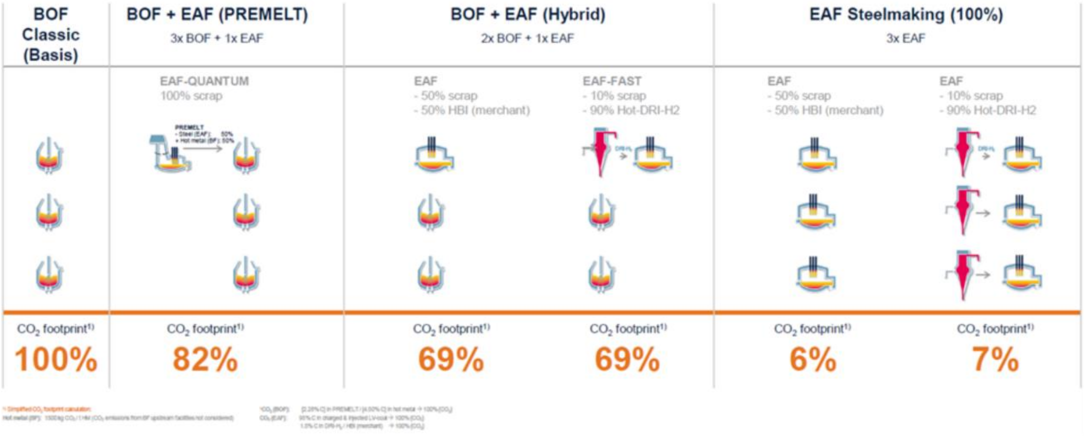
South Korea’s approach is summarized in Figure 10. 100 % reduction in $CO_2$ emissions per Phase III depends on both renewable energy (wind, solar, etc) and $H_2$ based steel production. This builds on POSCO’s success with the COREX and FINEX processes. The FINEX process, based on fluidized bed reduction of iron ore fines, is converted to the HyREX process by adapting to $H_2$ as the reducing gas (produced by electrolysis) and melting the DRI/HBI produced in an EAF.

## 3.4 Europe

Europe is still heavily dependent upon the BF/BOF route. Current EU plans strongly emphasize a transition to the DR/EAF route, so far only at commercial scale at ArcelorMittal Hamburg, dating back to the early 1970s.  AM Hamburg is planning for $H_2$ based DRI production via an $H_2$ electrolysis plant and eventually for conversion of its existing DR plant to $H_2$ use.

The HYBRIT project in Sweden, a joint venture between SSAB (steel producer), LKAB (iron ore pellet producer) and Vattenfall (hydro-electricity producer) is the next project with near term potential. This entails DRI/EAF production via with “green” pellets produced from magnetite ore by LKAB, “green” hydrogen and hydropower. Commercialization is expected before 2030.

FIGURE 11: THE FULL RANGE OF OPTIONS PER PRIMETALS TECHNOLOGIES



There is an increasing number of other direct reduction-based projects in Europe, covered in the companion paper of DRI production and use. These involve direct feeding of DRI/HBI to EAFs, charging HBI to BFs and melting DRI in an electric furnace to produce hot metal. A recent chart from Primetals Technologies shown in Figure 11 illustrates the range of options for integrated steel plants.

## 3.5 Liberty Steel, Australia and EU

FIGURE 12: LIBERTY STEEL'S "GREEN STEEL" APPROACH

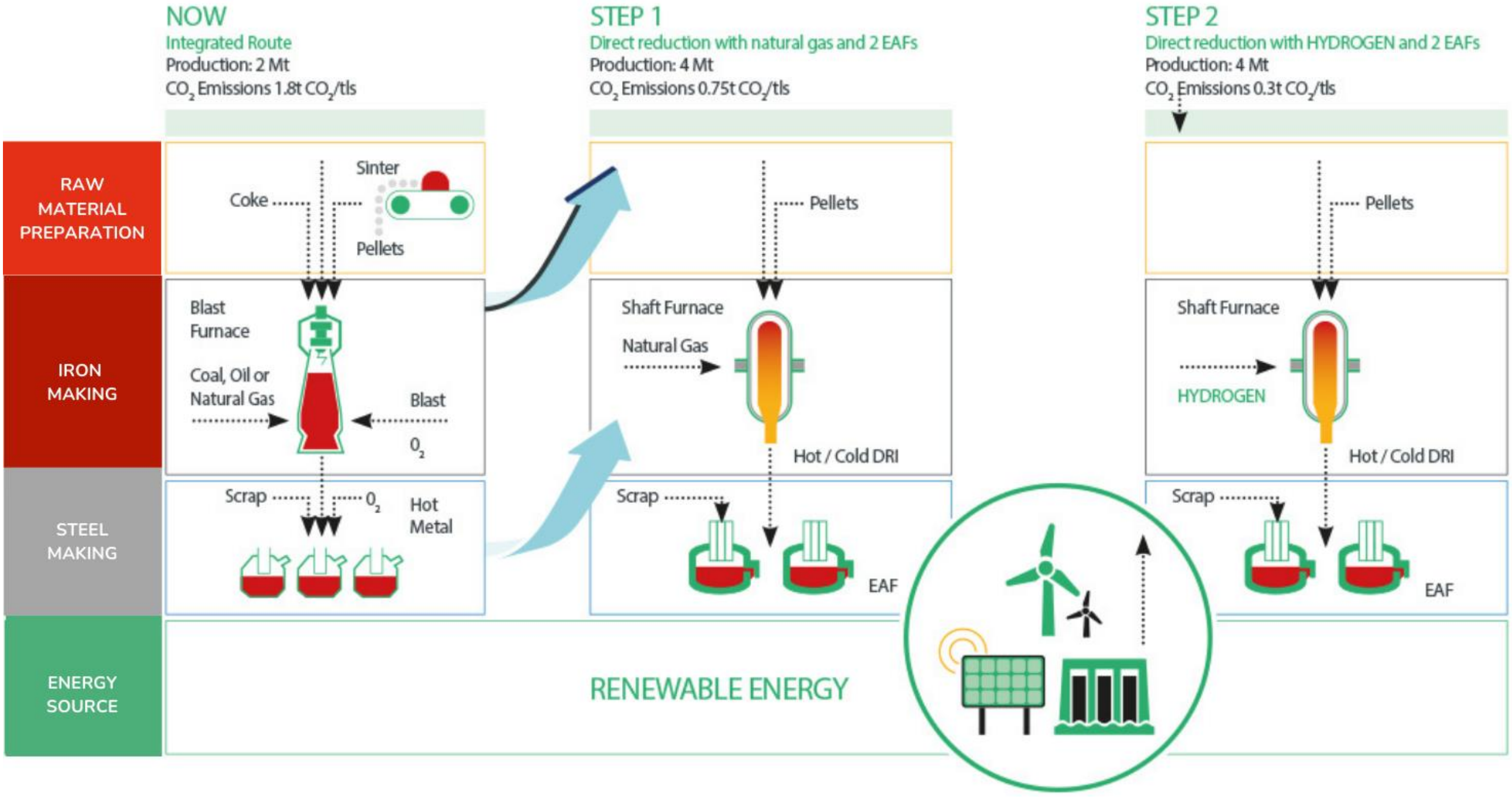
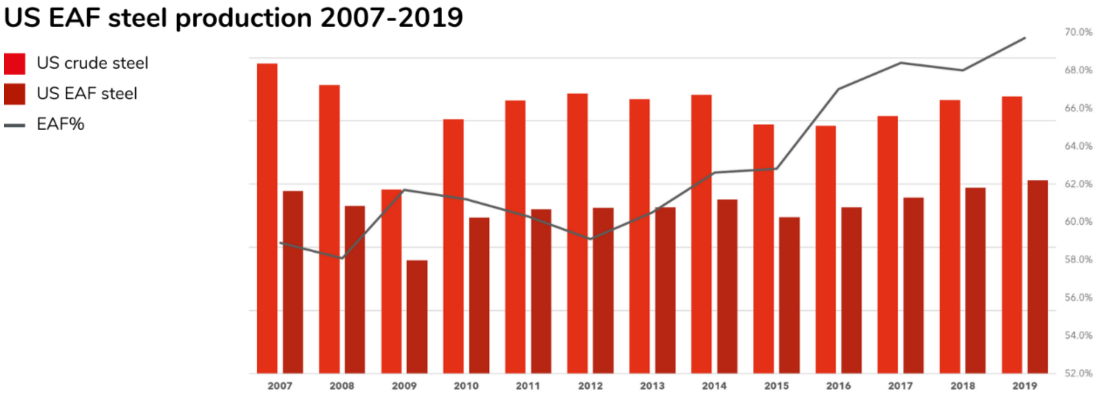


Figure 12 above outlines the approach proposed by the Liberty Steel Group for its integrated steel plants in the EU (Czech Republic and Romania) and Australia.

## 3.6 NAFTA

The DR/EAF route is well established in Mexico (Ternium in Monterrey & Puebla, ArcelorMittal Lazaro Cardenas) and in the USA (in the case of Nucor with captive DRI from its plants in Louisiana and Trinidad and in the case of Cleveland Cliffs with its captive HBI plant in Ohio). Canada has one major DR/EAF plant (ArcelorMittal Contrecoeur, Que); one other BF/BOF plants may pursue incremental $CO_2$ reduction within the BF/BOF framework described above. Two other BF/BOF producers (Algoma, ArcelorMittal Dofasco), have announced conversion to EAF steel production while AM Dofasco has also announced a DRI project, as well. About 12 million tons EAF capacity has been recently commissioned or is under construction in the USA which will significantly increase the EAF share of steel production beyond the 69.7% of 2019 (see Figure 13) and thus demand for scrap and ore-based metallics.

FIGURE 13: USA STEEL PRODUCTION BY PROCESS



| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **US crude steel production (tonnes)** | 98.2 | 91.4 | 58.2 | 80.5 | 86.4 | 88.7 | 86.9 | 88.2 | 78.8 | 78.5 | 81.6 | 86.6 | 87.8 |
| **US EAF steel production (tonnes)** | 57.8 | 53.1 | 35.9 | 49.3 | 52.1 | 52.4 | 52.6 | 55.2 | 49.5 | 52.6 | 55.8 | 58.8 | 61.19 |
| **EAF%** | 58.9% | 58.1% | 61.7% | 61.2% | 60.3% | 59.1% | 60.5% | 62.6% | 62.8% | 67.0% | 68.4% | 68.0% | 69.7% |

## 3.7 Brazil

Brazil already has a well-established charcoal-based, lump ore fed mini-BF sector that is primarily a producer of merchant pig iron for local and export markets as feedstock for EAF steelmaking and metal casting applications. Some charcoal mini blast furnaces also produce hot metal for BOF steelmaking in smaller scale steel plants.

Brazil also has a large coke-based BF/BOF steel production sector that relies on nearly 100 % imported coal for both coking and PCI applications. $CO_2$ reduction efforts are focused on charcoal-based PCI along with natural gas injection as off shore oil and gas production is ramping up in Brazil. The large iron ore pelletizing sector in Brazil, dominated by VALE, is exploring $CO_2$ reduction via biomass replacement of anthracite, plasma indurating burners and other initiatives.

Another development is Vale's plans to commercialize the Tecnored smelting reduction process using briquettes of iron ore fines, waste oxides and/or biomass materials to produce merchant pig iron. Vale has been successfully operating a 50 kt/year demonstration plant in the Sao Paulo area and is planning a 500 kt/year commercial plant in northern Brazil (refer section 4.9 for further information).

### Basic premise: how far can integrated mills progress towards carbon neutrality?

In conclusion of this section on the scope for $CO_2$ footprint reduction of the BF/BOF steelmaking route, this question can be answered as follows: the Course 50 program in Japan is based on maintaining the BF/BOF route, but aiming at 50% reduction in $CO_2$ missions. A study by SMS Paul Wurth[5] indicates potential of up to 44-76% reduction in $CO_2$.

It is beyond the scope of this paper to offer an opinion about the differing pathways to carbon-neutral steelmaking being followed around the world, other than to express the view that the process will be evolutionary rather than revolutionary. What is clear is that there is considerable scope for reduction in $CO_2$ emissions from the integrated steelmaking route, although apparently not to the extent possible for the $H_2$-based DRI/EAF route. Economics, including the reliance on expensive DR grade pellets versus lower cost sinter feed ores and waste oxides, will play an important role in steel company decision-making, as will the attitudes and policies of governments and regulators. Also, additional processes will be needed to utilize waste oxides (a fines based DRI process would be helpful in this respect).

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[5] Presentation at AIST Scrap Supplements and Alternative Iron Seminar, March 2020, Orlando, FL

# 5 Alternative hot metal processes/new technologies

## 5.1 Introduction

The following topics will be addressed in this section:

- hot metal processes: smelting reduction, RHF/IDI, nuggets, cupolas, etc.;
- pig iron/hot metal, based on DRI production followed by electric melting;
- use of redundant/excess BF capacity to produce merchant pig iron to supplement scrap-based EAF steel production;
- alternative hot metal/steel processes in early stage research.

Alternative smelting reduction processes have been under development since the 1970s, driven on the one hand by operating cost reduction, and on the other by elimination of the coke making step by using cheaper non-coking coals. In addition, some processes have eliminated the iron ore agglomeration steps and use fine coal and fine iron ore.

In general, while hot metal quality is similar to that produced via the BF, coke production is eliminated and energy consumption is thus lower compared to the BF route. Most of the smelting reduction processes consist of a smelting stage after a pre-reduction stage. The sensible heat and chemical energy of the reducing gas leaving the smelting stage are used in the pre-reduction step to pre-reduce and preheat the iron ore.

## 5.2 Hot metal processes: smelting reduction, RHF/IDI, nuggets, cupolas, etc

TABLE 6: HOT METAL PRODUCTION PROCESSES

| **Hot Metal Process** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Reductant** | **coke** | **coke** | **coal based (with biomass possibilities)** | | | | **none** |
| | | | | | | | |
| **Process vessel** | blast furnace | cupola | smelting reduction | smelting reduction | rotary hearth / submerged arc furnace | rotary hearth furnace | electrolytic cell |
| | | | | | | | |
| **Iron bearing material** | sinter, pellets, lump | scrap, waste oxides, iron ore fines | iron ore fines | pellets, lump | iron ore fines, waste oxides | iron ore fines | iron ore fines |
| | | | | | | | |
| **Process** | blast furnace | OxyCup | FINEX | COREX | Iron Dynamics | ITmk3 | molten oxide electrolysis (MOE, Boston Metal) |
| | mini blast furnace* | Tecnored* | HIsmelt | | Fastmelt | | Siderwin (ArcelorMittal) |
| | | | HIsarna | | Redsmelt | | |
| | | | AISI | | Primus (multiple hearth | | |
| | | | DIOS | | | | |
| | | | Circosmelt | | | | |
| | *charcoal/biomass option | | blue font indicates process not commercialized | | | | |

An overview of hot metal processes shown in the Table 6. These processes are classified by reductant type (coal, coke), vessel type (BF, smelting-reduction, RHF [rotary hearth furnace] / SAF [submerged arc furnace], electrolysis vessel), and by iron-bearing materials (pellets, lump ore, sinter, ore fines). Commercial processes are shown in white, while those still under development or abandoned are shown in blue.

The BF is the dominant hot metal producer worldwide while the mini-blast furnace (MBF) plays a role both in small scale steelmaking (EAF or BOF) and in production of merchant pig iron, mainly as EAF feedstock. One type of MBF, mainly in Brazil, uses charcoal as reductant and thus generates lower $CO_2$ emissions. The cupola is used mainly on a smaller scale as a melter of already reduced materials such as scrap, but some current applications (OxyCup Process) are aimed at processing self-reducing agglomerates of waste oxides.

Other large scale processes such as AISI and DIOS are dormant, but some of their features have found their way into other processes.  The smaller-scale processes (Romelt, Circosmelt and Tecnored) have not yet reached commercial status, although Tecnored (refer sections 3.7 and 4.9) is planning for a 500 Kt/yr commercial plant.

The RHF and multiple hearth processes (Primus) mainly process waste oxides on a small scale basis. The RHF processes generally exhibit low productivity when chasing high degrees of reduction and when used without a pre-reduction step. Another RHF process, ITmk3, designed to produce pig iron nuggets, has failed so far. The Induction Heater (not shown in Table 6) and MOE processes are in very early stage development, as is Flash Smelting (of iron ore fines), also not shown in Table 6.

## 5.3 HIsarna process

The HIsarna version of the HIsmelt process is advancing through the process demonstration phase at the Tata Steel Ijmuiden plant in the Netherlands.  It is composed of the former CCF (Cyclone Converter Furnace) process as the pre-reduction phase coupled to the HIsmelt bath smelter. It is fed with iron ore and coal fines (although biomass could be substituted for coal).  The progress and achievements with the HIsarna program is outlined in Table 7.  The HIsarna concept is shown in Figure 14 and a cross- section of the furnace together with the benefits of the process is shown in Figure 15.

FIGURE 14: HISARNA PROCESS CONCEPT

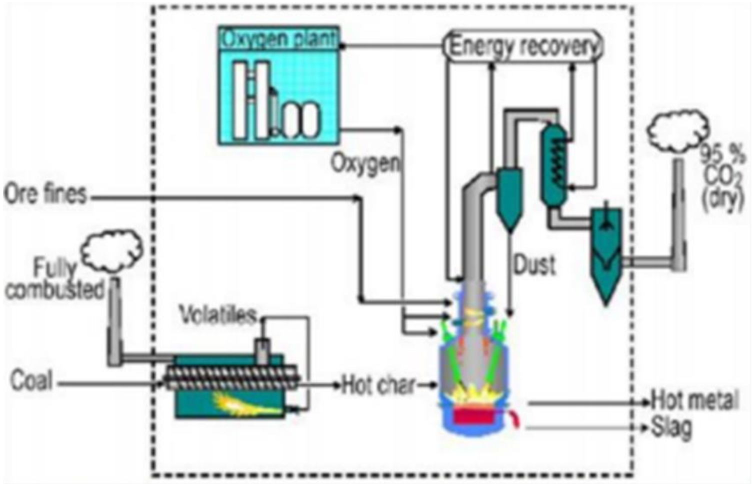
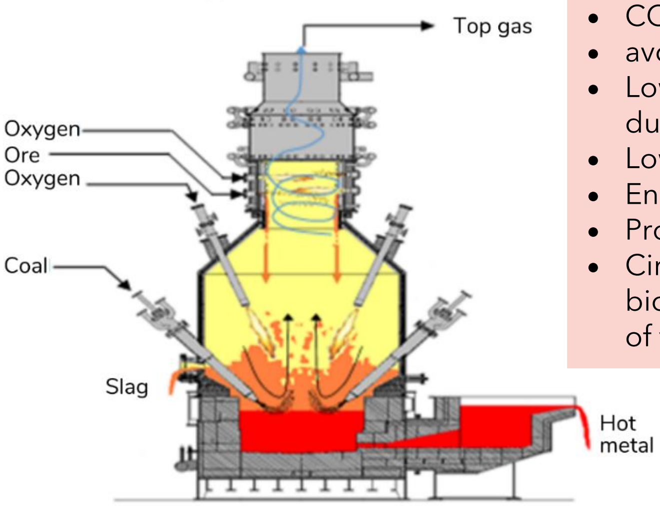


TABLE 7: PROGRESS WITH HISARNA PROCESS

| | | |
|---|---|---|
| **2011** | | - First hot metal tap (May 2011) |
| **2012** | CAMPAIGN B | - First long operating period achieved |
| | | - Use standard raw materials |
| | | - 80% productivity target reached |
| **2013** | CAMPAIGN C | - Use of steam coal (23%VM) |
| | | - Use of low grade ore (< 30% Fe) |
| | | - First hot metal delivered to the BOF plant |
| | | - Achieve good plant availability |
| | | - Productivity target reached |
| **2014** | CAMPAIGN D | - 30% of hot metal produced made into steel |
| | | - Use of high volatile steam coal (39% VM) |
| | | - Use of high Zn waste oxides |
| | | - Use of scrap and ore concurrently |
| | | - Target coal consumption achieved |
| **2015-2017** | | - Major plant upgrade (€25 million investment) |
| **2017** | CAMPAIGN E | - Start of the endurance test (Sept. 2017) |
| **2018-2019** | | HIsarna process incorporated into IJmuiden flowsheet |

FIGURE 15: HISARNA FURNACE CROSS SECTION AND PROCESS BENEFITS

**Hisarna technology benefits**



- $CO_2$ capture ready
- avoid $N_2$, use $CO_2$ recycle
- Lower emissions of $NO_x$, $SO_x$, dust
- Lower grade raw materials
- Energy efficiency
- Process flexibility
- Circularity: use of scrap, biomass, waste oxides, recovery of valuable elements

## 5.4 HIsmelt process

The original HIsmelt version of the process is already at the commercial stage, but now in China. The plant that was originally built in Kwinana, Western Australia was relocated to China under the ownership of Molong Steel. The Molong Steel plant is producing 600 KT/year processing sinter feed fines or concentrates, using a rotary kiln for pre-reduction. Molong is also running trials to process VTM (vanadium titano magnetite) ores. Scale up from 6.0 to 8.5 metre hearth diameter for the smelting vessel is planned; this could increase production from 0.6 to 2 million tons per year.

The HIsmelt process can smelt a broad range of low-cost ferrous bearing materials that cannot be economically used in BFs or DR plants, for example:

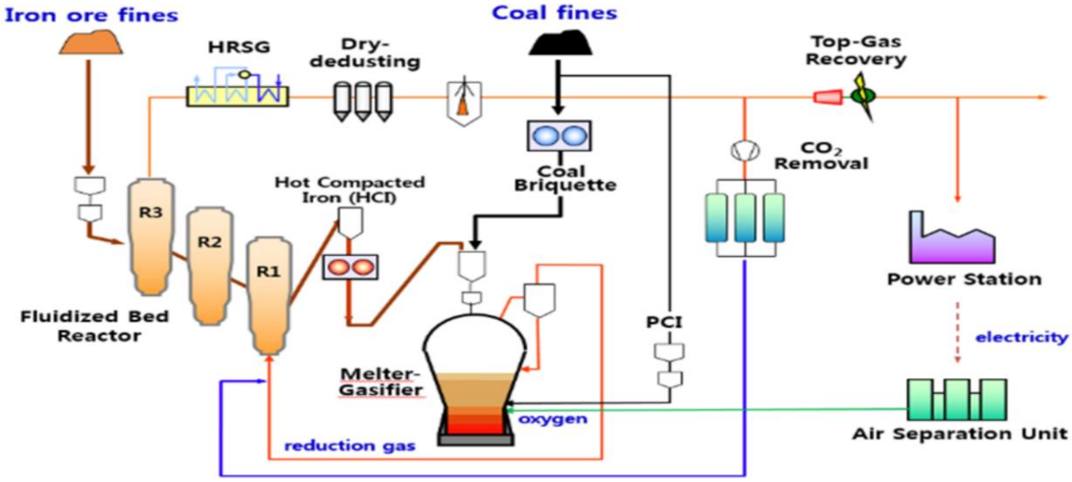
- steel plant wastes – mill scale, BF/DRI/BOF/EAF dusts and sludges, BOF/EAF slags
- contaminated ores high in phosphorus, alkalis or titania
- tailings from production of phosphates, nickel, etc.

HIsmelt hot metal has low levels of phosphorous, manganese and silicon and HIsmelt pig iron is sold as High Purity Pig Iron, at a 20% premium over basic pig iron.

## 5.5 COREX/FINEX process

These processes have two distinct stages where the hot, solid pre-reduced ore needs to be transported physically between the two stages. The Corex process requires pellets/lump as a ferrous burden, while the FINEX version of the COREX process, shown in Figure 16, uses fine iron ore. A major issue is high CAPEX as FINEX is composed of two high CAPEX processes, COREX and FINMET, also with the addition of in-between briquetting and other steps. The FINEX process is also sensitive to the granulometry of the fines that are processed in the multiple fluid beds.

FIGURE 16: FINEX PROCESS FLOWSHEET



These processes are commercially proven, for COREX up to 3,000 t/day using a high percentage of pellets while FINEX is producing 4,000 tons/day using ore fines. Both reportedly also use a small amount of coke. The absence of post-combustion in COREX implies that much of the chemical energy is lost in the off gas and coal consumption exceeds that of any other ironmaking process. Therefore, direct $CO_2$ emissions of the COREX process are 2,300 kg/tHM while the BF stands at 1,700 kg/tHM. Because pure oxygen is used in COREX, its caloric value is much higher and thus deserves higher credits for subsequent power generation.

Although these processes have been criticized for the above limitations and high capital cost, it must be recognized that the process is less than three decades old and that there is much time available for evolutionary improvement. The BF process has been evolving over hundreds of years, by comparison.

Note that the above leading alternatives (HIsarna, HIsmelt, COREX and FINEX) are carbon-based and offer little scope for $CO_2$ reduction - however, all have potential for $CO_2$ reduction by replacement of carbon by alternative reductants and are ready for CCS/CCU ($CO_2$ scrubbing is part of the process scheme).

## 5.6 Iron Dynamics (IDI) hot metal process

The first and only North American stand-alone hot metal plant dedicated to the EAF application is the IDI Plant at the Steel Dynamics Plant in Butler, IN. The IDI plant has been re-configured following its 1999 start-up and subsequent problematical operation. The IDI process concept originally combined the rotary hearth furnace (RHF), direct reduction of a composite iron ore/coal green ball, followed by melting of this DRI in a submerged arc furnace (SAF). The IDI plant uses iron ore concentrate, mill scale and other recycled materials as iron sources together with low volatile coal.  The IDI process has been reconfigured with briquetting replacing green balling as the RHF feed preparation step. The briquetting step facilitates the use of waste oxides, including dusts and sludges; this reduces input iron and carbon unit costs.  The plant produces about 250 KT/year of hot metal.  Replacement of coal by biomass would improve the carbon footprint of this process. Its economics depend on the availability of waste oxides; this and the limited production scale have discouraged any additional projects based on this process concept.

### 5.7 Proposed similar RHF/SAF-type processes

These are the Fastmelt, Sidcon and Redsmelt processes, along with the multiple hearth furnace Primus process. Midrex has commercialized the RHF portions of its process (Fastmet) via waste oxide plants in Japan. A demonstration Redsmelt plant has been operated at the Piombino plant in Italy.  Commercial scale Primus plants have been built in Luxembourg (to process EAF plant waste oxides) and in Taiwan.

### 5.8 ITMk3 (Iron Nugget) process

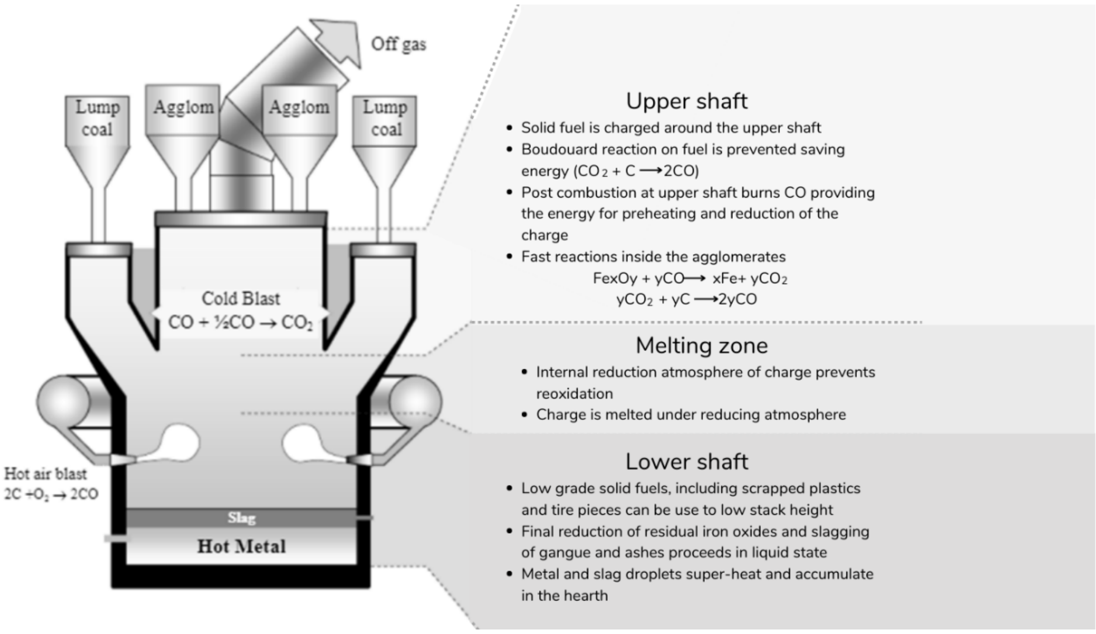
Another development is the ITMk3 rotary hearth process producing iron nuggets (in effect pig iron) as EAF feedstock. A demonstration plant, the Mesabi Nugget project, had operated successfully at the site of the Cliffs Northshore pellet plant. This process involves the green balling of iron ore and coal fines, followed by reduction of these green balls in a rotary hearth furnace where temperatures are high enough to effect melting and slag separation into pig iron and gangue; subsequent magnetic screening steps ensure production of an iron nugget suitable for use in an EAF. The first commercial Mesabi Nugget plant started up in Minnesota, but is now shut down pending further evaluation of this project. Other iron nugget-type processes have been studied at the pilot scale, including the PSH (Paired Straight Hearth) and the E-Nugget Process, developed by Carbontec. Some work on the PSH may be ongoing in China.

### 5.9 Tecnored process

Tecnored produces blast-furnace type carbureted molten iron at a fraction of the capital and operational cost of conventional methods, besides with a much better environmental performance since it uses no coke or indurate burden. The process is based on the use of self-reducing agglomerates as the primary feedstock. The agglomerates contain iron ore fines (low grade ores and/or carbon bearing revert material can be used) and sufficient flux and fines of carbon bearing materials to be totally self-reducing. Additional fuel is used directly in the furnace only to provide the required heat to drive the chemical reactions.

The Tecnored Process is shown in Figure 17. Whereas the iron ore agglomerates in a BF are reduced by CO gas, the iron ore in a Tecnored furnace is reduced within a “self-reducing” briquette, composed of iron oxide fines and carbon (coal or bio-char) reductant.  By combining fine particles of iron oxide and the reductant within the briquette, with the surface area of the oxide in direct contact with the reductant, the reaction kinetics are increased dramatically. The self-reducing briquettes are designed to contain sufficient reductant to allow full reduction of the iron-bearing feed, together with fluxes to provide the required slag chemistry. The briquettes are cured at low temperatures prior to feeding to the furnace. With utilization of biomass as the reductant this process offers low or no $CO_2$ emissions.

FIGURE 17: TECNORED FURNACE, CROSS SECTION



Upper shaft

- Solid fuel is charged around the upper shaft
- Boudouard reaction on fuel is prevented saving energy ($CO_2 + C \longrightarrow 2CO$)
- Post combustion at upper shaft burns CO providing the energy for preheating and reduction of the charge
- Fast reactions inside the agglomerates

$$FexOy + yCO \longrightarrow xFe + yCO_2$$
$$yCO_2 + yC \longrightarrow 2yCO$$

Melting zone

- Internal reduction atmosphere of charge prevents reoxidation
- Charge is melted under reducing atmosphere

Lower shaft

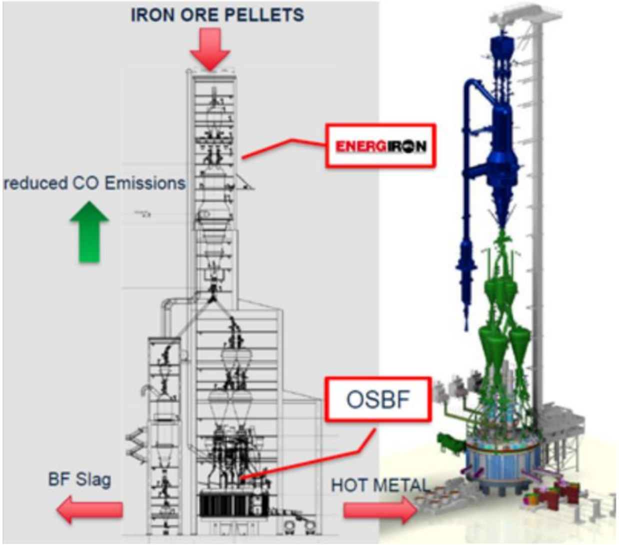
- Low grade solid fuels, including scrapped plastics and tire pieces can be use to low stack height
- Final reduction of residual iron oxides and slagging of gangue and ashes proceeds in liquid state
- Metal and slag droplets super-heat and accumulate in the hearth

The reactor geometry was designed and has been modified to have ample flexibility in the use of raw materials and many have been tested, such as standard iron ore pellet feeds, mill scale, nickel ores as well as dust and sludges generated in the steelmaking process. The principal restriction of the source of iron units is the granulometry required to produce high quality briquettes. In general, the materials are fine with more than 50% passing 0.1 mm. Several standard iron ores have been used without process limitations.

## 5.10 Pig iron based on direct reduction followed by electric melting

This concept is one that all major metallurgical plant builders are marketing. For example, Tenova HyL is marketing a process whereby a DR shaft furnace is combined with an open slag bath furnace (OSBF) to produce liquid hot metal (see Figure 18).

FIGURE 18: TENOVA DR/OSBF PROCESS SCHEME



**Inputs**

- Low grade iron ore pellets (BF quality)

**Outputs**

- Hot metal compatible with BF product (e.g. c 4%, Si 0.2-0.4%)
- Slag with BF slag composition, fully compatible with cement industry requirements
- High reduction of CO2 emissions (down to almost zero_

**Key technological advantages**

- Same possibility as BF to run long continuous campaigns (OSBF refractory: 5 to 10 years)
- Higher flexibility (vs BF): possibility to switch on and off
- Low impact on power grid
- Use of 100% hydrogen as reducing gas is proven
  Pilot DRI plant in Hybrit (Sweden) being commissioned

Two projects using this technology are under study: (a) by Black Rock Metals which plans to pelletize concentrate from a titanomagnetite ore body in Quebec as feedstock for a plant in Saguenay, Quebec and (b) by Petmin USA using commercially sourced iron oxide pellets as feedstock for its permitted plant in Ashtabula, OH (according to the company's website, construction is due to start in 2021). Both companies plan to produce nodular pig iron (feedstock for production of ductile iron castings)

## 5.11 Air Products

Air Products, an industrial gas supplier, has also proposed two concepts:

- a natural gas fired melter to produce pig iron from DRI;
- a DRI preheater to enable charging of hot DRI to an EAF.

## 5.12 Redundant BF capacity used to produce merchant pig iron

In 2020 Stelco installed a 1 million ton capacity pig caster as part of its recent BF upgrade at Lake Erie works in Ontario, Canada, providing it with the ability to supply the merchant market in competition with imported pig iron (currently it is utilizing all its BF capacity for more profitable steel production). Most recently, US Steel announced a pig caster project (500 KT/year) at their Gary Plant, mainly to utilize BF production capacity at their 4 blast furnaces that would otherwise be idled by downstream facility delays and outages. Such pig iron would likely be shipped to their Big River Steel EAF plant. The USA has currently idle BF capacity exceeding 5 MTPY. US Steel (now owner of Big River Steel) and Cleveland Cliffs (now owner of the former AK Steel and the integrated steelmaking assets of ArcelorMittal USA) both have excess BF capacity, current and potential, as well as iron ore pellet and coke oven assets, and could potentially install pig casters and supply the merchant market. There is less potential elsewhere globally for this concept for a variety of reasons: cost, availability of pellets, coke; limited high-end EAF markets; limited idle BF capacity, etc.

## 5.13 Global merchant pig iron production

So far, this chapter has focused on blast furnace production with respect to its role in global steel production as a liquid hot metal feed to oxygen steelmaking (BOF, KOBM, LD, etc) vessels. However, a portion of global pig iron production produces merchant pig iron as a feed to EAF's or to foundries.

Many EAF operators prefer merchant pig iron to HBI or DRI, given its advantages (see Table 7 below) with respect to Fe, metallization, carbon and gangue levels.

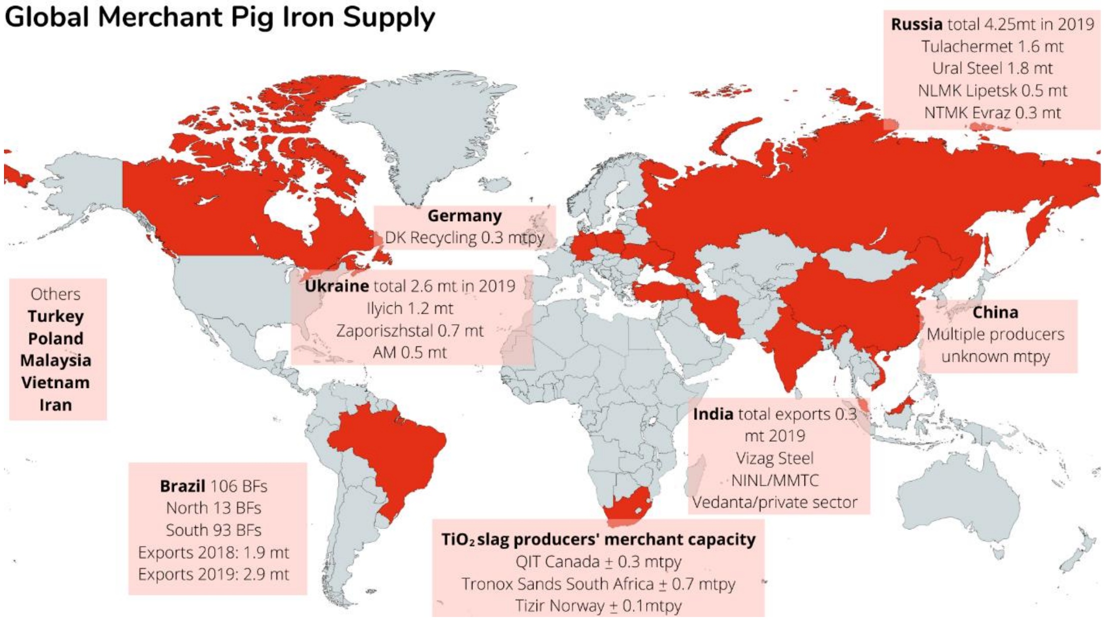
TABLE 8: CHEMISTRY OF METALLIC FEED MATERIALS

| | **Prompt scrap** | **Pig iron/ hot metal** | **DRI/HBI** |
|---|---|---|---|
| **Fe** | 98.0 | 94.5 | 93.0 |
| **Metallisation** | 100 | 100 | 95 |
| **Metallics Fe** | 98.0 | 94.5 | 88.6 |
| **FeO** | 0 | 0 | 6.6 |
| **Carbon** | 0 | 4.5 | 1.5 |
| **Acid gangue** | 1.0 | 1.0 | 2.2 |
| **Basic gangue** | 1.0 | 0 | 1.1 |

Indeed, the IIMA has a significant portion of its membership dedicated to merchant pig iron as an important OBM (ore-based metallic), used as EAF feedstock and in production of ferrous castings. The volume of cross-border trade in merchant pig iron was 14.5-15 mt in 2020.

Figure 19 portrays global merchant pig producers. Most are blast furnace producers but some operations produce pig iron as a co-product of TiO2 slag production via electric smelting furnaces. Another special situation is in Brazil where all merchant pig iron production is produced in mini blast furnaces that use charcoal rather than coke as a reductant and energy source. The main iron bearing material is small sized lump ore, so the sintering process is not necessary except for several sinter recycling operations. The overall system of forestation, charcoal production and mini-BF production has a very low $CO_2$ footprint and should continue into the far future, The remaining producers using conventional coke blast furnaces, especially those in Russia, Ukraine and China, can be expected to utilize many, if not most, of the techniques outlined earlier in this section to reduce the $CO_2$ footprint in the context of existing coke oven/sinter plant/blast furnace operations. Nevertheless, some of the novel smelting reduction techniques outlined earlier may also be deployed in merchant pig iron production; one example is the Tecnored Process where the first commercial plant will produce merchant pig iron.

FIGURE 19: GLOBAL MERCHANT PIG IRON SUPPLY

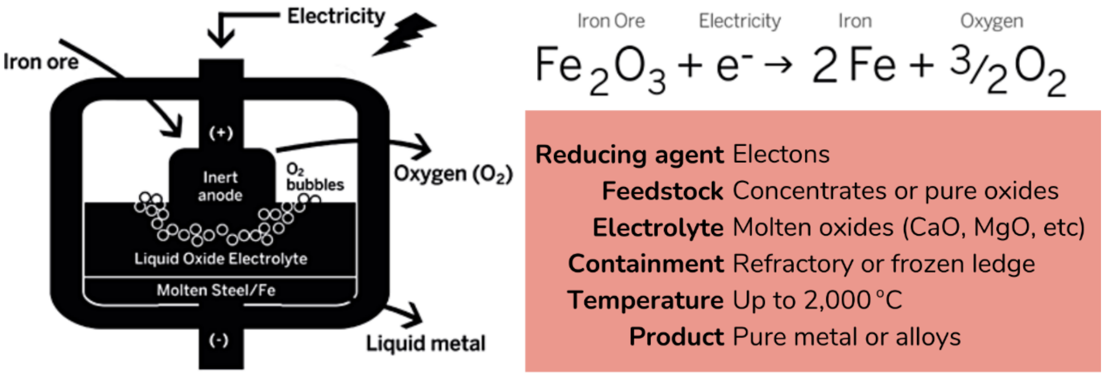


## 5.14 Alternative hot metal/steel processes in early stage research (MOE and flash smelting)

**Molten oxide electrolysis (MOE)** is an electrolytic process (similar to aluminium production) and a platform technology applicable to a wide variety of metals, developed at MIT.[6] MOE technology uses a reaction vessel containing a molten electrolyte which dissolves the metal oxide (see Figure 20). The molten oxide solution is then electrolyzed by passing an electric current from an anode suspended in the solution from the top of the vessel to a cathode located at the base of the vessel. No chlorine or fluorine is used, only other oxides are used in the electrolyte. MOE has a much higher temperature capability: it can process high temperature metals as liquids (i.e. Fe, Ti, etc.). There is the prospect of modular production with low capital cost and ability to up-scale.

[6] Massachusetts Institute of Technology, Cambridge MA

FIGURE 20: MOE REACTION VESSEL (SOURCE: BOSTON METAL)



$$Fe_2O_3 + e^- \rightarrow 2\,Fe + {}^3\!/_2O_2$$

| | |
|---|---|
| **Reducing agent** | Electons |
| **Feedstock** | Concentrates or pure oxides |
| **Electrolyte** | Molten oxides (CaO, MgO, etc) |
| **Containment** | Refractory or frozen ledge |
| **Temperature** | Up to 2,000 °C |
| **Product** | Pure metal or alloys |

In terms of steel production**,** Boston Metal in Woburn, MA is attempting to commercialize MOE with the objective of reducing metal oxides (including iron ores) into high purity metals via electrolysis, without the need for reductant fossil fuels. MOE has the potential to produce "green" steel if "green" electricity is consumed in the process.

MOE consists of the following steps:
1. feedstock (iron ore) is fed into the cell in a solid (ground to fine size) form;
2. iron ore is mixed with more stable oxides to form a molten electrolyte tailored for that iron ore;
3. electricity is passed through the cell to melt and reduce the iron ore;
4. iron collects at the bottom of the cell on the cathode where it may be alloyed with other metals before being tapped from the cell;
5. the oxygen removed from the iron ore is emitted from the cell.

The ArcelorMittal Siderwin process is another variant of a molten oxide electrolysis process that is under laboratory-scale development.

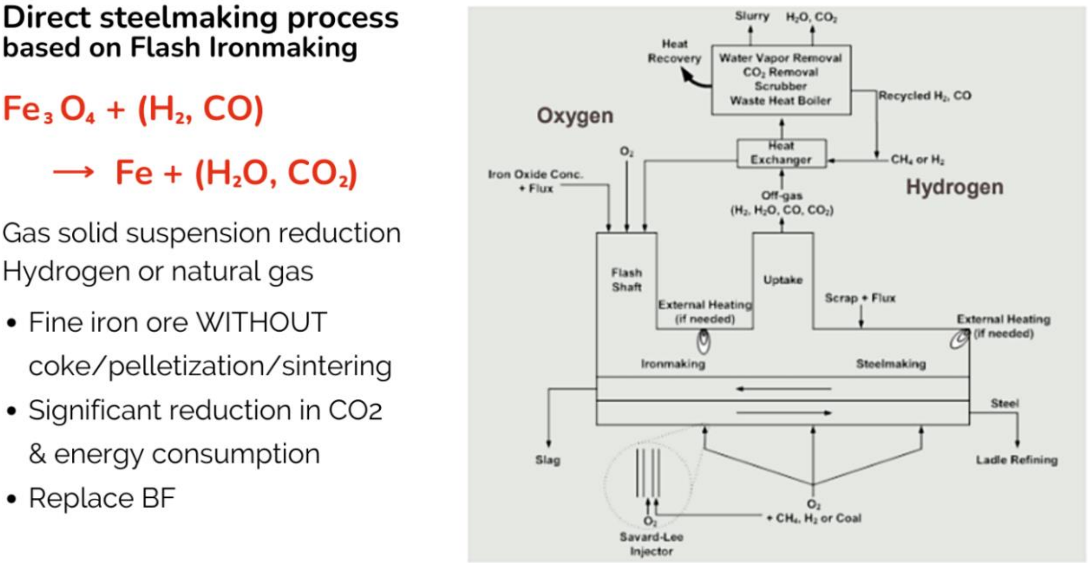
### Flash smelting of iron ore concentrates

This process was adapted from copper flash smelting technology and developed at University of Utah with AISI support (see Figure 21). The process was developed using taconite concentrates from Minnesota and other concentrates with natural gas and/or $H_2$ as reducing gas. As the flash smelting uses concentrates directly, agglomeration is not required. Without particle sticking or fusion, high temperatures can be used supporting a very rapid reaction rate (seconds). Kinetic feasibility, proof of concept at laboratory scale, and process validation and scale-up have been completed, but the next step of construction of an industrial pilot plant is awaiting funding.

The process is characterised/promoted as follows:

- low $CO_2$ emissions: 2.5% of BF ironmaking (w/ H2);
- energy saving: 3.0 GJ/ton Fe (55%) cf. BF (w/ H2);
- eliminate cokemaking and pelletising/sintering & associated pollution;
- 90-99% reduction in 2-7 seconds at 1200-1500oC;
- enormous hydrogen utilization potential.

FIGURE 21: FLASH SMELTING OF IRON ORE (SOURCE UNIVERSITY OF UTAH)



**Direct steelmaking process**
**based on Flash Ironmaking**

$$Fe_3O_4 + (H_2, CO) \longrightarrow Fe + (H_2O, CO_2)$$

Gas solid suspension reduction
Hydrogen or natural gas

- Fine iron ore WITHOUT coke/pelletization/sintering
- Significant reduction in CO2 & energy consumption
- Replace BF

### Use of biomass and microwave technology

Other new early stage laboratory research includes a joint effort by Rio Tinto and the University of Nottingham to process iron ore fines and biomass via microwave technology to produce iron.

## 5.15 Summary - alternative hot metal processes/new technologies

Section 5 on alternative hot metal processes and new technologies has covered the following technologies that have reached or nearly reached commercial scale: COREX, FINEX, HIsmelt, HIsarna, IDI; however all are highly capital intensive and only offer $CO_2$ reduction benefits if sufficient “green” reductants (e.g. biomass, etc.) become available and/or when $CO_2$ capture and sequestration methods become technically feasible and economically viable.

Other technologies, such as direct reduction of iron ore followed by melting the DRI to form hot metal, while not yet fully commercially demonstrated, have a high probability of success. These technologies also face CAPEX barriers and some OPEX hurdles, notably the need for iron oxide pellet feedstock. The extent to which their full $CO_2$ reduction potential can be realised will depend on regional circumstances and in any case when existing BF/BOF facilities reach the end of their useful and economic lives.

Section 5 also has covered early-stage research and development into molten iron electrolysis and flash smelting of iron ore concentrates. These processes must advance through the pilot and demonstration plant phases before they can be seriously considered as realistic propositions for the iron and steel industry.

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