A Low-Carbon-Emission Flowsheet for BF-Grade Iron Ore Using Advanced Electric Smelting Furnace

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The transition from integrated steelmaking, the blast furnace (BF)-basic oxygen furnace flowsheet, to alternative flowsheets with lower greenhouse gas emissions is a growing trend for the decarbonization of the iron and steel industry. One such flowsheet is the direct reduced iron (DRI)-electric arc furnace (EAF) route. However, the DRI-EAF route is inefficient when using lower-grade, higher-gangue iron ores traditionally processed in the BF, which is the majority of iron ore supply in the world. The ability to effectively process BF-grade iron ore with a low-emission flowsheet is critical to the decarbonization of the steel industry globally. This study proposes the use of electric smelting furnace to improve the overall process yield and efficiency when using BF-grade iron ore and compares it to the established DRI-EAF process.

Steel is an integral part of global infrastructure and continues to grow as an essential commodity. As a result of this, the emissions from steel are becoming increasingly significant. The iron and steel industry's direct emissions are approximately 2.6 Gt-CO_2 per year, around 7% of the global total.[1] When accounting for indirect emissions, such as the use of offgas, this figure grows to 3.7 Gt-CO_2 per year.[2] The steel industry needs to decarbonize to achieve international emissions goals. The Sustainable Development Scenario (SDS) aims to limit global temperature rise to 1.5°C; to meet this goal, the steel industry would need to decrease its average CO_2 intensity from 1.4 to 0.6 t-CO_2/t crude steel, a 60% decrease.[2]

There are two main process routes in the steel industry: the traditional blast furnace (BF) to basic oxygen furnace (BOF) integrated route and the newer direct reduced iron (DRI) and/or scrap to electric arc furnace (EAF) mini-mill route. Currently, the BF-BOF route is the most popular, accounting for 71% of global production.[1] However, the BF-BOF route is also the most emissions- and energy-intensive route, as shown in Table 1. EAFs are becoming more popular, partially due to the increasing availability of scrap. It is possible to operate EAFs solely on scrap, but higher-quality products often

Table 1

Process Route Scope 1 and 2 Emissions Intensities[2] and Energy Consumptions[4]

Process route	Scope 1+2 emissions [t-CO_2/t-steel]	Energy [GJ/t-steel]
BF-BOF	2.2	21.4-22.7
NG-DRI → EAF	1.4	17.1-21.8
Scrap → EAF	0.3	2.1-5.2

require the addition of virgin iron units (VIU), such as DRI, to dilute the residual elements present in scrap. The carbon present in DRI also offers benefits such as slag foaming in the EAF and chemical energy supply.[3]

BF-BOF producers must focus on reducing their Scope 1 emissions due to their inherent dependence on carbon-based raw materials. There are few opportunities for BF-BOF producers to reduce Scope 2 emissions since they rely so little on grid electricity. Contrarily, EAF steelmakers rely heavily on the grid and should be looking to reduce their Scope 2 emissions. Regions with green power grids present a valuable opportunity for Scope 2 emissions reduction and a potential path for EAF steelmakers to get to net zero.

DRI production has increased globally and is expected to continue doing so. Since 2010, global production has increased from 72 to 114 Mtpa in 2021.[5] Predictions for the future indicate that by 2050, DRI production will reach 272 Mtpa. Over half of that increase could be through a carbon-free, hydrogen-based process route, assuming the cost of green hydrogen decreases.[6] Steelmakers throughout North America and Europe have already announced plans to transition to a DRI-EAF based flowsheet to reduce CO_2 emissions.

DRI-EAF steelmaking is expected to have a prominent place in the future of the iron and steel industry. However, with it come several important constraints to be addressed:

- Limited availability of direct reduction (DR)-grade iron ore pellets. Presently, <10% of global merchant iron ore exports are DR-grade pellets or pellet feed/concentrate (see Fig. 1). The use of lower-quality raw materials, such as BF-grade pellets or lump ore, in the DRI-EAF process causes issues downstream in the EAF such as higher slag volume, higher energy consumption and yield losses.
- Moving to H_2-DRI from natural gas (NG) will pressure conventional EAFs to use low-carbon or carbon-free DRI. This would require significant alteration from established EAF operation, greatly impacting efficiency, availability and quality unless major changes are made.
- The inability of EAFs to produce certain grades of steel products that the BF-BOF route does today, such as low-nitrogen steel for automotive sheets.
- The inability of EAFs to process a significant amount of iron-bearing plant wastes. In a BF-BOF process, steelmaking waste, such as mill scales, slag reverts and dusts, can be recycled in the sinter plant to easily recover the iron units.

Introduction to the Electric Smelting Furnace

The DRI-EAF flowsheet is dependent on DR-grade pellets since its gangue rejection capability is limited compared to the BF-BOF flowsheet. The DR process is unable to remove gangue since there is no phase separation as the oxide pellets are reduced to DRI. Consequently, the gangue needs to be removed in the EAF, which was not designed to handle high levels of gangue since it was optimized for scrap-based steelmaking. Thus, its efficiency, yield and productivity are all negatively impacted by high-gangue DRI.

In comparison, the blast furnace is highly effective at removing gangue from iron ore but requires coke or coal as a reductant and energy source, causing its high CO_2 emissions. Therefore, a process that can effectively remove gangue from DRI is needed to take advantage of its lower emissions and decarbonize the iron and steel industry. For this purpose, the blast furnace process provides some ideas to develop an alternative that can address all these problems.

The shaft-DR process strongly resembles the top half of the blast furnace (above the cohesive zone) in both form and function. In this section of the blast furnace, iron ore (sinter, BF-grade pellets and lump ore) descend downwards and are reduced by hot reducing gases (CO and H_2) rising from the bottom of the furnace. The partially reduced ore continues to descend and is further reduced, melted and carburized by coke around the bottom of the furnace (i.e., hearth area) to produce molten metal and slag. The slag and hot metal (HM) separate

Figure 1

Breakdown of global merchant iron ore export by Fe grade (L) and product grade (R).[7]

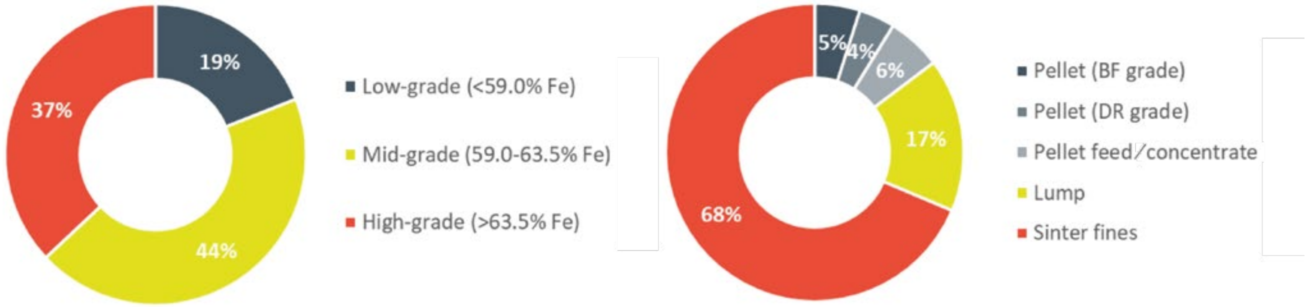
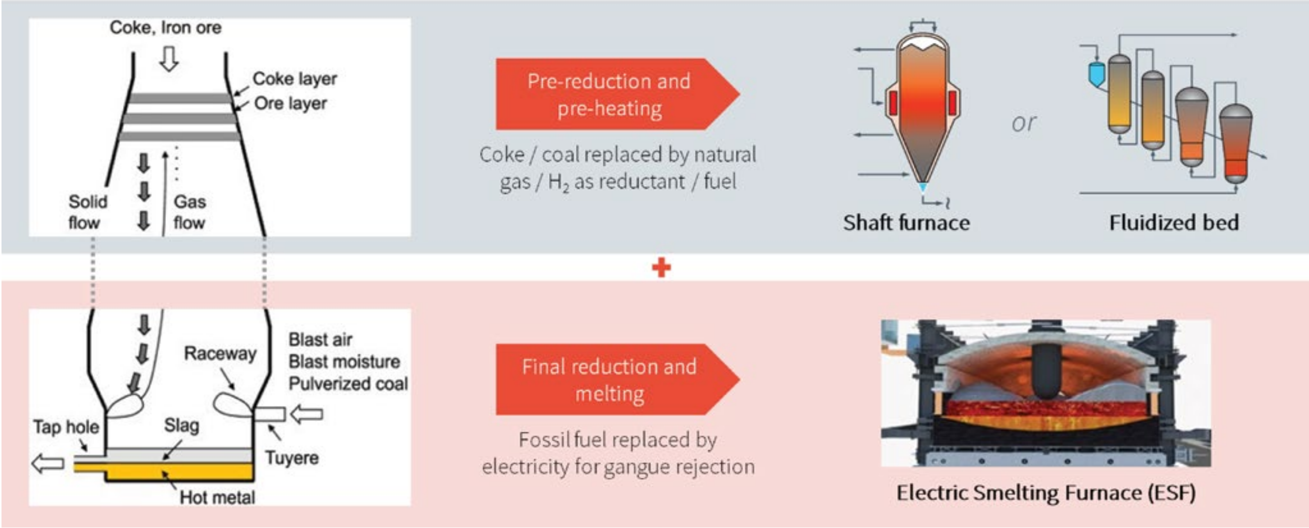


Figure 2

Direct reduction (DR)-electric smelting furnace (ESF) flowsheet concept compared to blast furnace (BF).



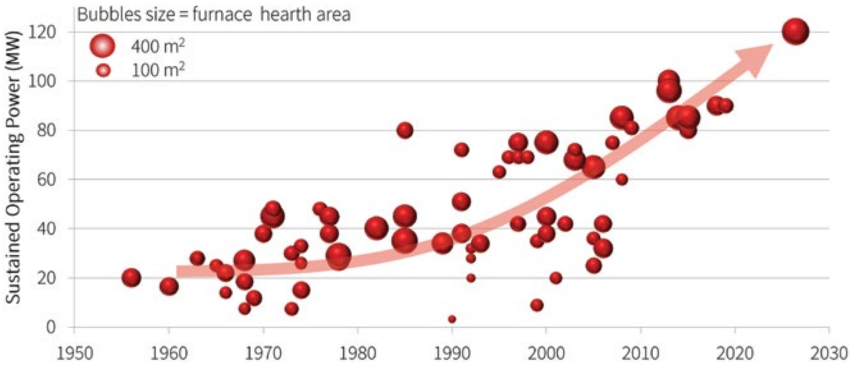
naturally after tapping due to density differences, producing clean, carbon-bearing hot metal for steelmaking. Following these mechanisms, the alternative process requires several key characteristics:

- Does not rely on carbon to provide energy for melting gangue.
- Able to handle large slag volumes (i.e., low Fe yield loss).
- Able to reduce FeO in DRI and minimize FeO content in the slag (i.e., strong reducing atmosphere).
- Pairs well with upstream DR operation (i.e., continuous feeding and tapping).
- Able to produce sufficiently carburized hot metal for BOF steelmaking.
- Maintain high availability with minimal disruption to existing operations.
- Can effectively process fines/wastes/reverts from all areas within the plant.

The electric smelting furnace (ESF), commonly used in non-ferrous, ferroalloy, and ironmaking (from ilmenite/vanadium-titanium magnetite) applications, satisfies the above criteria and is uniquely suitable for this application. Fig. 2 illustrates the concept of combining the DR process and ESF to imitate the blast furnace.

Figure 3

History of ESF development since the 1950s.



The ESF, often mistakenly called submerged arc furnace (SAF) for its commonly known modes of operation, is a large, stationary (non-tilting), continuously operated furnace with Soderberg electrodes, a fixed roof, and permanent refractory linings. ESFs have been used extensively for metallurgical operations for over a century, widely applied for non-ferrous, slag cleaning and certain ferrous processes (vanadium-titanium-magnetite and ilmenite ores) in the 20th century and now. ESF hearth size and operating power progression over the past 70 years is shown in Fig. 3.

Hatch is a pioneer of ESF development for ferrous metallurgy and ironmaking applications. With over 65 years of experience, Hatch has developed ESF technology in several ferrous applications. This includes ilmenite (iron sands) smelting furnaces with operating power up to 80 MW, which can provide useful references to insights on crucible and taphole design. Work has also been done on smelting ferronickel (FeNi), with many of the world's largest references for circular furnaces of 90 MW and rectangular furnaces of up to 100 MW. These furnaces are considered the largest ESFs that share similar feed rates required in iron- and steelmaking, including hot transfer of pre-reduced feeds at >850°C. Furthermore, Hatch has extensive knowledge in the development of new processes and pilot plants with 15+ years of Continuous Reduced Iron Steelmaking Process (CRISP) direct steel development. Some other notable examples involve converting Highveld electric iron furnaces into partially open bath (POB) operations and the development of the shielded arc smelting process for ferronickel.

Around 2010, Hatch successfully developed and piloted the CRISP furnace to produce low-carbon steel directly from DRI in an ESF.

The CRISP process has since evolved into Hatch's CRISP+ technology package, designed to meet the industry's need for an effective DRI melting process to support the decarbonization goals of the iron and steel sector.

Process Advantage of DRI-ESF Process Using CRISP+

The advantages from the DRI-ESF-BOF process using CRISP+ relative to the DRI-EAF route:

- Efficient processing of high-gangue DRI, producing higher yields and enabling use of non-DR-grade pellets/lump iron ore.
- CRISP+ slag comparable to BF slag, meeting specifications for sale to the cement industry.
- CRISP+ ESF can be fed with pellet- and lump-based DRI by operating in POB mode, and can also operate in other modes (e.g., open bath).
- Reverts such as high-FeO slag from the BOF, ladle metallurgy furnace (LMF) or EAF can be fed back into the smelting furnace.
- Continuous and stable operation provides a steady power draw, reducing the strain on the power grid.
- The large surface area of the furnace allows for significant active inventory of hot metal in the furnace, allowing for very high availability of hot metal delivery to the meltshop, even during most unplanned downtimes.
- Long campaign life of 15–20 years, comparable to a blast furnace.
- Stationary, sealed furnace design which minimizes air ingress to provide a CO-rich offgas and reduces nitrogen pickup. This helps to avoid issues with certain grades of steel.
- Capable of effectively processing large quantities of fines charged into the ESF.
- Stable tapping operations including the possibility of continuous tapping.

Advantages of the DRI-ESF process using CRISP+ relative to existing BF-BOF routes:

- Coal-based energy from the blast furnace is replaced with natural gas or hydrogen for the DRI plant, and electrical energy in the CRISP+ furnace, resulting in significant reduction in CO_2 emissions.

Figure 4

Schematic of the Hatch Continuous Reduced Iron Steelmaking Process (CRISP)/CRISP+ Furnace working in tandem with a shaft DR furnace to produce steel/hot metal.

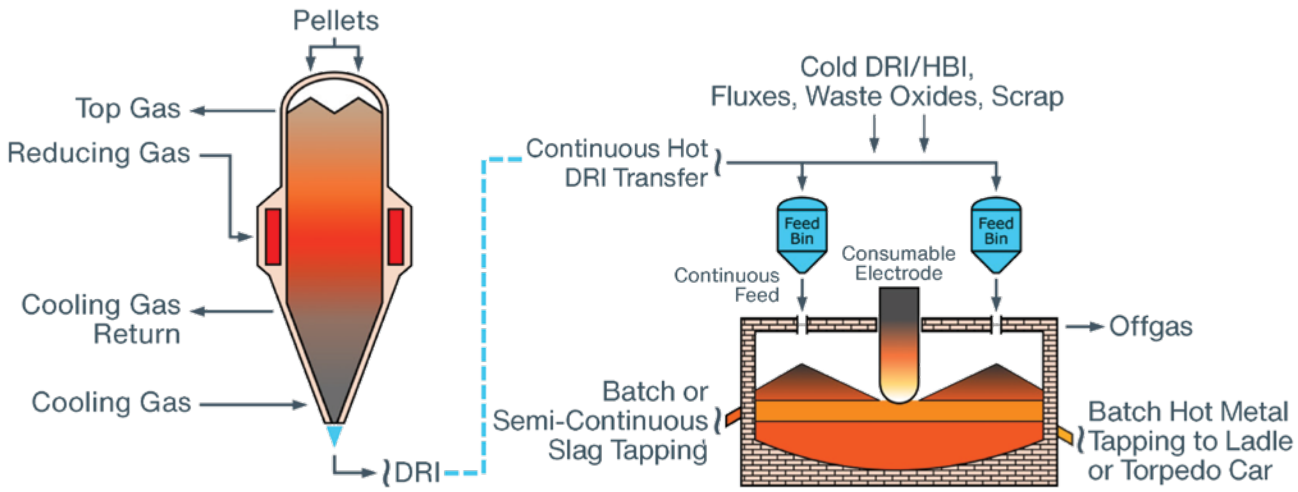


Table 2

Cases for Analysis

Cases	BF control case	NG control case	NG base case	H_2 control case	H_2 base case
Feed	Sinter	BF pellets	BF pellets	BF pellets	BF pellets
Ironmaking	BF	Shaft NG DR	Shaft NG DR + ESF	Shaft H_2 DR	Shaft H_2 DR + ESF
Steelmaking	BOF	EAF	BOF	EAF	BOF

- Higher operational flexibility; productivity of a multi-DRI, multi-ESF complex can be quickly ramped up or down.

This ESF technology has been well proven in equivalent power and size to other metallurgical applications with equipment technically ready for immediate implementation. With the many advantages it can provide, this furnace is a proven solution for the near future as the industry transitions to natural gas–based DRI processes.

Analysis Methodology

Hatch Model Introduction

Evaluating the viability of ESFs on the path to decarbonization requires a comprehensive approach to compare the benefits of gangue rejection upstream at beneficiation to gangue rejection downstream in the smelter as slag. Consequently, Hatch has developed a value-in-use model which integrates the entire iron and steel value chain, from beneficiation up to steelmaking. The value-in-use model consists of several high-level process models to represent each step of the value chain, including shaft (i.e., Midrex and Energiron) DR ironmaking technologies and the ESF smelter.

The primary outputs of the model include the consumption and production of various raw materials, consumables, products and byproducts at each processing step. Prices and CO_2 emission factors are then applied to calculate the operating cost and CO_2 emissions of each step. Analyzing and comparing changes between these three categories of outputs across different flowsheets will help to identify the best path forward to reduce CO_2 emissions of processing high-gangue iron ore.

Hatch has identified five cases to determine the effectiveness of the ESF at processing high-gangue ores (Table 2).

The BF-BOF control case represents the best-case scenario in terms of gangue rejection at the cost of CO_2 emissions, while the shaft-DR-EAF cases represents the worst-case scenario for gangue rejection. Both NG-based and hydrogen-based direct reduction will be considered to demonstrate the impact of low-carbon DRI on ESF performance. For the purposes of this study, the battery limits will be defined as ironmaking, smelter, and steelmaking to produce liquid steel. All processes upstream of ironmaking (i.e., agglomeration, beneficiation and mining) are excluded. However, their CO_2 emissions will be considered as part of Scope 3 emissions associated with the BF ferrous burden.

Key Assumptions

Table 3 summarizes the key parameters used to model each flowsheet included in this study. These parameters were selected to represent the typical operation of each process unit.

Table 4 outlines the assumed cost and emission factors used to calculate the operating cost and CO_2 emissions associated with each flowsheet.

Results and Analysis

The key results from the case studies are summarized in Table 5, focusing on four main metrics to assess the performance of various flowsheets: total slag rate, operating cost, overall Fe yield, and Scope 1 and 2 CO_2 emissions. All metrics are normalized per metric ton of liquid steel to establish a fair basis of comparison for all flowsheets.

Fig. 5 shows the calculated slag rates for the first three cases. As expected, the BF control case shows high slag rates due to the use of high-gangue sinter as the BF ferrous burden. However, the BF is designed to handle these slag volumes effectively with minimal Fe losses since BF slag typically only contains ~1% FeO. Furthermore, BF slag is salable to the cement industry, so high slag rates are not disadvantageous economically. The DR-EAF flowsheet has the highest slag rate out of all three cases, even higher than the BF-BOF flowsheet. Additionally, EAF slag is not salable and has significant impact on the Fe yield of the process because it contains 30% FeO. Clearly, the EAF has significant drawbacks when used to process high-gangue DRI.

In comparison, the ESF is an effective process to remove gangue from high-gangue DRI. Due to its reducing environment, Fe loss and slag rates are minimized because the slag FeO content is controlled to less than 1%. Additionally, ESF slag composition is similar to BF

Table 3

Modeling Parameters of Various Process Units

Operating parameters	Unit	Value	Operating parameters	Unit	Value
BF			BOF		
Hot blast temperature	°C	1,200	BOF charge mix	wt. %	90% HM/10% scrap (BF) 92% HM/8% scrap (ESF)
Oxygen enrichment	vol. %	5	Dust rate of fluxes and scrap	wt. %	1
Pulverized coal injection rate	kg/t_{HM}	200	BOF slag B2	–	3.0–3.8
Ferrous burden	wt. %	100% sinter	BOF slag FeO	wt. %	15–21
Hot metal carbon content	wt. %	4.5	BOF slag MgO	wt. %	6–8
BF slag B2	–	1.2	Liquid steel carbon content	wt. %	0.1
BF slag B4	–	1	Refractory consumption	kg/t_{steel}	1.5
DR			Oxygen consumption	Nm^3/t_{steel}	550
Metallization	%	94	EAF		
DRI carbon content	wt. %	3% (NG) 1.4% (H_2)	Feed mix	wt. %	90% DRI/10% scrap
Electricity demand	kWh/t_{DRI}	140	Slag B3	–	1.7
Process gas heater efficiency	%	80	Slag FeO	wt. %	30% (NG DR) 40% (H_2 DR)
Dust	t/t_{DRI}	0.07 (DR) 0.02 (BF)	Slag MgO	wt. %	10
DRI fines	t/t_{DRI}	0.04	Refractory consumption	kg/t_{steel}	4
Pre-screening losses	t/t_{pellet}	0.03 (DR) 0.05 (BF)	Anthracite	kg/t_{steel}	5

Table 3 (cont'd)

Modeling Parameters of Various Process Units

Operating parameters	Unit	Value
ESF		
Feed mix	wt. %	100% DRI
Ferrous burden to dust	wt. %	0.1
Other to dust	wt. %	0.5
Hot metal carbon content	wt. %	3
Slag B2	—	1.2
Slag B4	—	1
Slag FeO	wt. %	1%
Air ingress	Nm^3/t_{HM}	60
Electrode	kg/t_{HM}	4
Feed material fines	kg/t_{HM}	47

slag, so it can also be sold to the cement industry and continue to provide an additional revenue stream for the steelmaker.

When using hydrogen reduction, the DR-EAF flowsheet continues to be the worst performer, producing a high rate of unsalable, Fe-rich slag. In comparison, the DR-ESF flowsheet produces the lowest slag rate and the ESF slag chemistry can be controlled to match BF slag. The ESF continues to be a viable solution to process high-gangue DRI after the transition to hydrogen.

Comparing these flowsheets from a cost perspective, the BF-BOF leads with the lowest cost since it can process the least expensive, highest-gangue ores. This advantage is reflected by the dominance of the BF-BOF process today. In comparison, switching to DR results in a significant increase in costs due to the higher price of ore caused by operating the pelletizing process. Further, the EAF consumes a large amount of electricity due to the high slag rate, which also increases cost. In contrast, the operating cost of the ESF-BOF flowsheet is lower than the DR-EAF flowsheet since the ESF minimizes feed costs by recovering most of the FeO in the ferrous charge. In summary, the ability to process high-gangue DRI will come at a significant cost compared to the traditional BF-BOF since it was not designed to handle that much gangue.

When evaluating the overall Fe yield of these different flowsheets, the BF-BOF displays its effectiveness at processing high-gangue ores with minimal Fe loss as

Table 4

Assumed Cost and Emission Factors

Cost/emission factors	Unit	Value	Cost/emission factors	Unit	Value
Sinter	\$/t	100	Natural gas	\$/GJ	3.5
Pellet	\$/t	160	Hydrogen	\$/kg	4
Blended scrap	\$/t	239	Oxygen	$\$/Nm^3$	0.08
Coke	\$/t	270	Electricity	\$/kWh	0.07
PCI	\$/t	130	Electrode	\$/kg	1.7 (ESF)/10 (EAF)
Quartz	\$/t	20	Refractory	\$/t	900
Bauxite	\$/t	200	Slag sales (-)/disposal (+)	\$/t	-50 (BF and ESF)/ 5 (BOF and EAF)
Dolime	\$/t	100	Dust disposal	\$/t	5
Lime	\$/t	80	Electricity emission intensity	$g\text{-}CO_2/kWh$	450

Table 5

Key Modeling Results

Cases	BF-BOF	NG DR-EAF	NG DR-ESF-BOF	H_2 DR-EAF	H_2 DR-ESF-BOF
Slag rate [t_{slag}/t_{LS}]	0.40	0.43	0.36	0.55	0.36
OPEX [$/$t_{LS}$]	321	476	413	740	631
Fe yield (%)	90.1	80.9	88.9	75.9	88.9
CO_2 emissions [kg/t_{LS}]	1.53	1.06	1.12	0.87	0.96

shown by Fig. 7. Comparatively, the DR-EAF presents a near 20% drop in Fe yield compared to the BF-BOF since the oxidizing environment in the EAF produces an FeO-rich slag. Additionally, material losses in the DR reactor can be significantly higher compared to the BF and contribute to a lower Fe yield. These changes primarily come from the dust loss in the DR reactor, which can change significantly with ore quality. However, the ESF's reducing environment helps to minimize FeO in the slag and improves Fe yield compared to the EAF. This improvement holds true when processing H_2-DRI as well. Therefore, the DRI-ESF flowsheet is the preferred option for processing high-gangue DRI compared to the DR-EAF flowsheet many steelmakers are interested in today.

Figure 5

Total slag rate of various flowsheets.

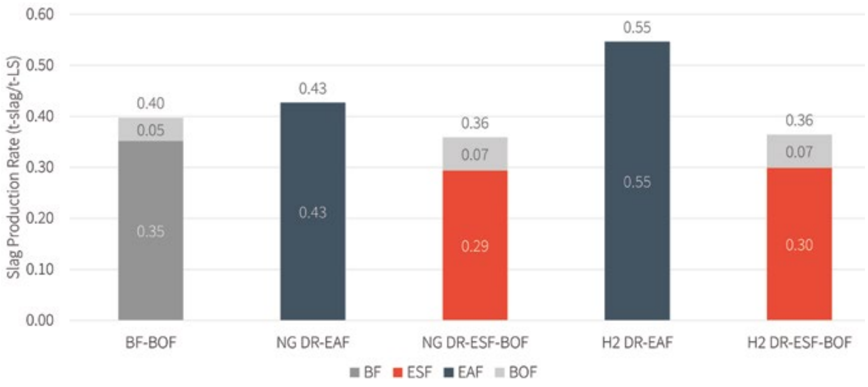


Figure 6

Estimated operating cost of various flowsheets.

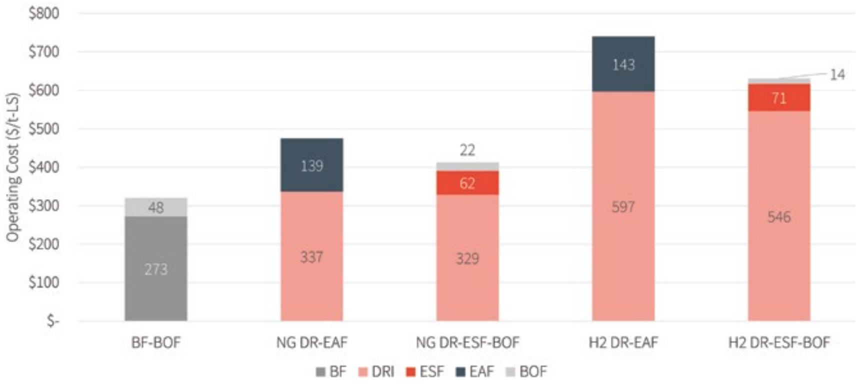


Fig. 8 shows the Scope 1 and 2 emissions of each flowsheet considered in this study. As expected, the BF-BOF flowsheet emits the most CO_2 due to the extensive use of coke and coal in the BF. Switching to natural gas as the reductant and energy source in the DR process allows for ~50% reduction in ironmaking emissions. Additionally, the use of electricity in the EAF allows for further CO_2 emission reduction if the grid emission factor is low. On the other hand, the DRI-ESF flowsheet consumes a similar amount of electricity to the EAF but the addition of anthracite to maintain the reducing environment in the ESF increases total Scope 1 emissions of the DR-ESF-BOF flowsheet compared to the DR-EAF flowsheet. After transitioning to hydrogen reduction, ironmaking emissions decrease even further since CO_2 is no longer a byproduct of reduction. Overall, the DR-ESF flowsheet is an attractive alternative to the BF-BOF flowsheet for processing high-gangue ore, with significant emission reduction potential while minimizing Fe loss and impact on operating cost.

Risks and Opportunities to Commercialization

Although the ESF is a mature technology, its application in the iron and steel industry to replace the BF is new and comes with several risks and opportunities to commercialization, including:

- Controlling hot metal chemistry.
- Controlling slag chemistry.
- Use of reverts and scrap.
- Product flexibility.

Firstly, controlling the carbon content in the hot metal produced by the ESF is crucial to ensure that the BOF downstream can operate normally. The BOF requires chemical energy provided by the oxidation of carbon in the hot metal to ensure the liquid steel and slag remain molten. In the ESF, hot metal carburization is controlled by the addition of a reductant into the furnace. However, reductant addition needs to be controlled to preferentially carburize the hot metal rather than reduce slag components into the metal or reductant combustion in the furnace freeboard. The carburization efficiency of the reductant can be maximized by charging the reductant together with the ferrous burden (DRI + scrap) to ensure it contacts the molten metal and minimizes carbon loss to furnace byproducts. This problem is further amplified when processing hydrogen-reduced DRI, which will be limited to 1.4% carbon compared to its natural gas–reduced equivalent. With such a low carbon content, reductant addition alone will not be enough for carburization. Other carburization methods inside the ESF or post-tapping will need to be developed to maintain normal BOF operation. Similarly, the ESF provides greater control on the concentration of minor elements in the hot metal, such as Si, P and S, compared to the blast furnace. This is achieved by changing the mixture of different feed materials (e.g., scrap, DRI/hot briquetted iron, reverts) to control P, mixture of reductants (e.g., coke, anthracite, biomass) for S, and smelting conditions for Si. Once tapped, ESF hot metal can pass through different processing steps (e.g., de-Si, de-P, de-S and carburization) to further refine the hot metal specification to best meet the needs of steelmaking.

Figure 7

Overall Fe yield of various flowsheets.

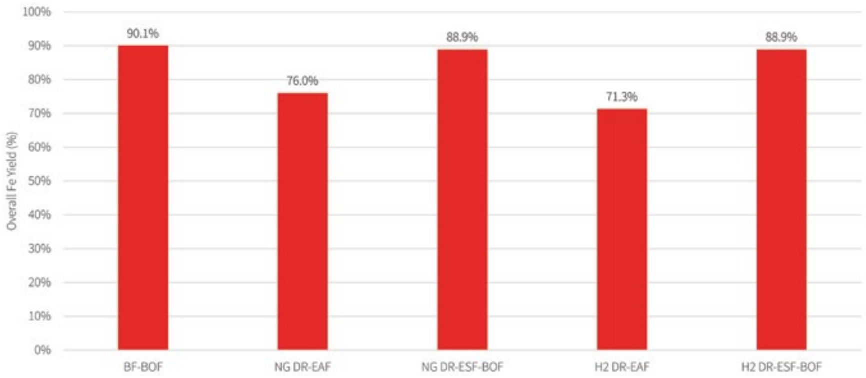
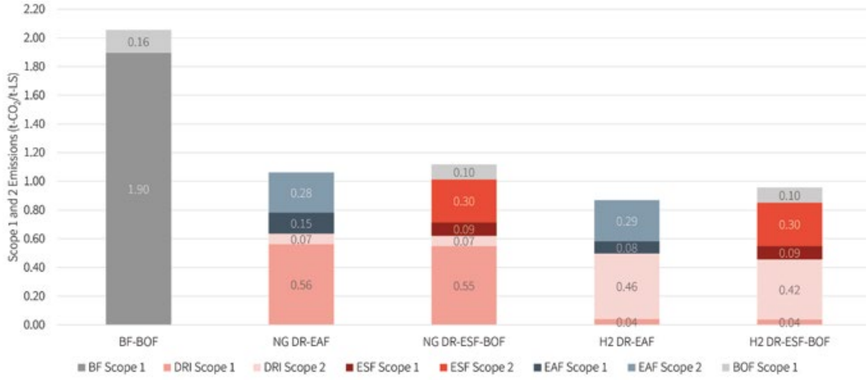


Figure 8

CO_2 emissions of various flowsheets.



Secondly, ESF slag chemistry is more flexible compared to the slag produced by the BF. Currently, the model calculations assume that the ESF slag would be controlled to match typical BF slag composition that can be sold to the cement industry. However, BF slag composition does not represent the ideal composition for the cement industry since it is strongly affected by gangue content in the sinter/pellets. By contrast, ESF allows for greater control of slag chemistry to optimize its physical and/or electrical properties for furnace operation and match the needs of the cement industry, since the formation of feed piles in the ESF using the right particle size allows operators to feed any kind of flux. Additionally, the ESF operates at a higher temperature and uses heat more efficiently, resulting in better melting and dissolution of the fluxes, ensuring more accurate control of the slag chemistry. Furthermore, the use of electricity as the primary energy source in the ESF helps to limit the emissions from an increased slag rate in response to additional fluxes charged in the feed piles. In comparison, performing the same practice in a BF would require additional coke which would increase CO_2 emissions.

Thirdly, the ESF is designed to process reverts from other areas of the steel mill, including pellet fines, mill scale, DRI fines, dust and scrap. This is enabled by the reducing environment of the ESF, which helps to maximize Fe recovery from various Fe-bearing byproducts. This strategy would allow the ESF to further increase its Fe yield advantage over the DR-EAF flowsheet.

Finally, the ESF is designed to produce a variety of products based on different slag and hot metal chemistries. Hot metal, cast or granulated pig iron and semi-steel can all be produced from the ESF. Furthermore, controlling the hot metal chemistry as described allows the ESF to produce different grades to optimize steelmaking. This flexibility is not possible with the BF-BOF and DR-EAF flowsheets, which are limited by the properties of their feed materials and their preferred operating conditions.

Conclusion

In summary, transitioning from the conventional BF-BOF flowsheet to alternative flowsheets using DRI is an important step to decarbonizing the iron and steel industry. The use of natural gas and electricity in the DR-EAF flowsheet would allow steelmakers to reduce their total Scope 1 and 2 CO_2 emissions of ironmaking and steelmaking However, the DR-EAF flowsheet is inefficient when processing BF-grade iron ores that make up much of the available iron ore supply today. On this front, this study has investigated the use of electric smelting furnaces for processing lower-grade iron ores and compared their technoeconomic performance to the DR-EAF flowsheet.

Hatch has developed a high-level, first principles value-in-use model to compare the BF-BOF, DR-EAF and DR-ESF-BOF flowsheets on a per-metric-ton-liquid-steel basis. Key performance indicators for comparison include total Scope 1 and 2 emissions, archetypal total operating cost, total slag rate, and overall Fe yield of each flowsheet. Modeling results indicate that both the DR-EAF and DR-ESF-BOF flowsheets can achieve significant CO_2 emissions reductions compared to the conventional BF-BOF process at 1.06 and 1.10 t-CO_2/t-LS, respectively, with natural gas or 0.85 and 0.94 t-CO_2/t-LS, respectively, with hydrogen. The DR-ESF-BOF flowsheet significantly outperforms the DR-EAF flowsheet in all other areas, with lower total operating cost, lower total slag rate and higher overall Fe yield. Overall, the electric smelting furnace, and its ability to effectively process lower-grade iron ore, is a crucial component in decarbonizing the iron and steel industry globally.

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