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OBMS & CARBON NEUTRAL STEELMAKING

Whitepaper 3: Future DRI Production & Iron Ore Supply

OBMs & CARBON NEUTRAL STEELMAKING

Paper 3 Future DRI Production and Iron Ore Supply

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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

This paper has been prepared against the background of the goal of a reduction of 80-95% in CO_2 emissions by the steel industry by 2050, a key component of this carbon-neutral roadmap being a progressive, but not necessarily total shift from the integrated blast furnace / basic oxygen furnace (BF/BOF) steelmaking route to the direct reduction / electric arc furnace route (DR/EAF). This is evidenced by the growing number of DR projects announced or under consideration in Europe, the CIS, the Middle East North Africa (MENA) region, China and elsewhere. As reference points and context, the report uses data from the steel chapter of the International Energy Agency's (IEA) report "Energy Technology Perspectives 2020" as well as some other sources.

The longer-term implications for iron ore supply are profound, in terms of both quantity and quality. This paper discusses two principal issues relating to medium- and longer-term production of DRI:

- production of Direct Reduced Iron (DRI) against the background of iron ore demand in excess of 400 mt and as much as 600 mt by 2050, most importantly the issue of the adequacy and quality of iron ore feedstocks;
- the value-in-use aspects (a) of DRI made with lower grade iron ore than currently demanded by DR plants and (b) of hydrogen-based DRI.

There is a short section on the importance of maritime regulation in the context of the impact of likely changes to the characteristics of hot-briquetted iron due to future changes in iron and carbon contents and thus density and reactivity.

The paper concludes with the key message that there must be collaboration along the steel value chain where DRI is concerned, especially between the iron ore and steel industries, to ensure that the former can meet the longer-term goals of the latter where carbon-neutral steelmaking is concerned.

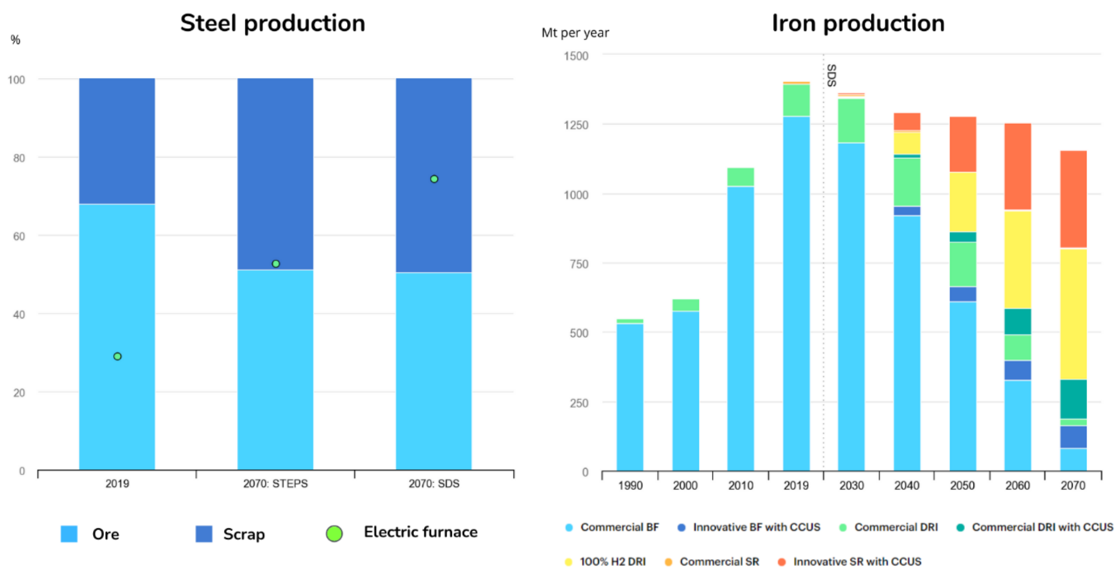
1 Introduction & Scope

DRI, coupled with the Electric Arc Furnace is a key component of the roadmap towards carbon neutral steelmaking, with increasing use of hydrogen

1.1 Introduction

Against the background of an 80-95% reduction of CO_2 emissions by 2050 by the steel industry[1], a key component of the roadmap towards carbon neutral steelmaking is the Direct Reduction of Iron, coupled with the Electric Arc Furnace steelmaking process route, with increasing use of hydrogen as reductant in the direct reduction (DR) process. This is evidenced by the high level of interest in hydrogen-based direct reduced iron (DRI) in Europe, with several projects announced or under consideration. These projects are listed in Appendix 1.

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



Work by the International Energy Agency (IEA) provides useful context for this paper. Its publication "Energy Technology Perspectives 2020" includes the chart in Figure 1 in its chapter on steel. IEA's two scenarios are: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.[2]

[1] Relative to 1990 levels (Eurofer Low Carbon Roadmap, November 2019)
[2] IEA report downloadable here. Also recommended IEA reading here and here.

FIGURE 2: IRON PRODUCTION BY TECHNOLOGY IN THE SUSTAINABLE DEVELOPMENT SCENARIO (MT)

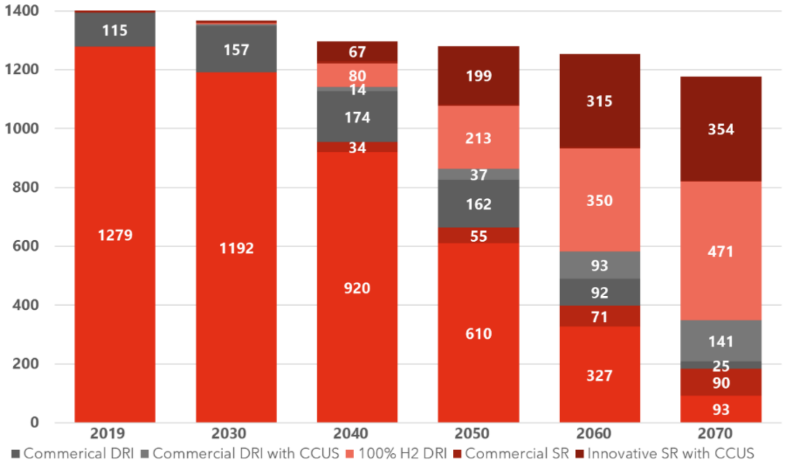
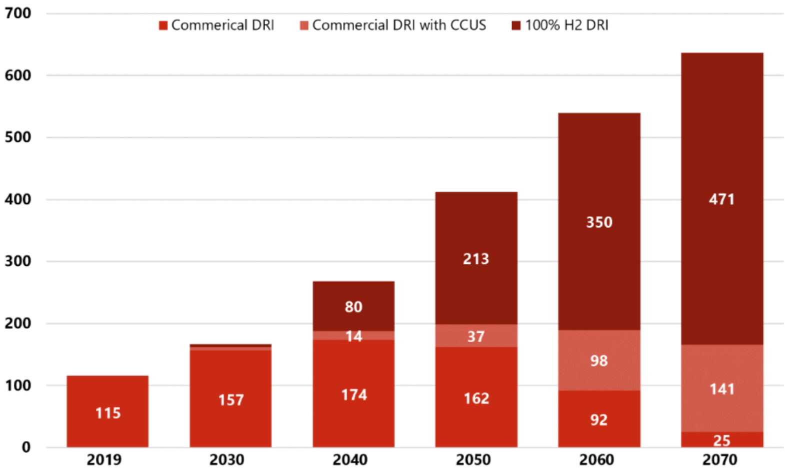


FIGURE 3: DRI PRODUCTION BY TECHNOLOGY IN THE SUSTAINABLE DEVELOPMENT SCENARIO (MT)

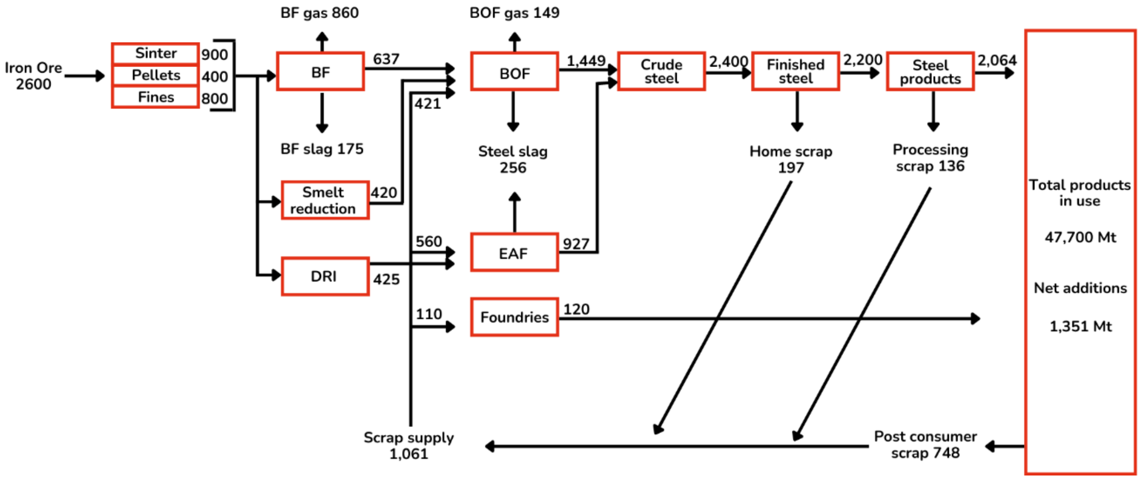


A representation of the iron production chart in Figure 1 is shown in Figure 2[3] with further breakdown for DRI only in Figure 3. As shown in Figure 3, per IEA's SDS, production of commercial or conventional DRI maintains positive growth out to 2040, but then starts to fall away with the growth of hydrogen-based DRI and conventional DRI coupled with Carbon Capture, Utilisation and Storage (CCUS). The total of 411 mt predicted for 2050 compares with the 108 mt produced in 2019, an increase of 280%.

In terms of DRI production, IEA's SDS is fairly close to that of Gielen et al, based on IRENA's[4] renewal energy roadmap (REmap) which suggests that renewables can make up 60% or more of many countries' total final energy consumption. Per this scenario, DRI production in 2050 is 425 mt, as shown in Figure 4.

[3] Data kindly provided by IEA
[4] International Renewable Energy Agency

FIGURE 4: MATERIAL FLOWS IN THE GLOBAL IRON AND STEEL SECTOR BASED ON THE REMAP SCENARIO IN 2050 (MT)



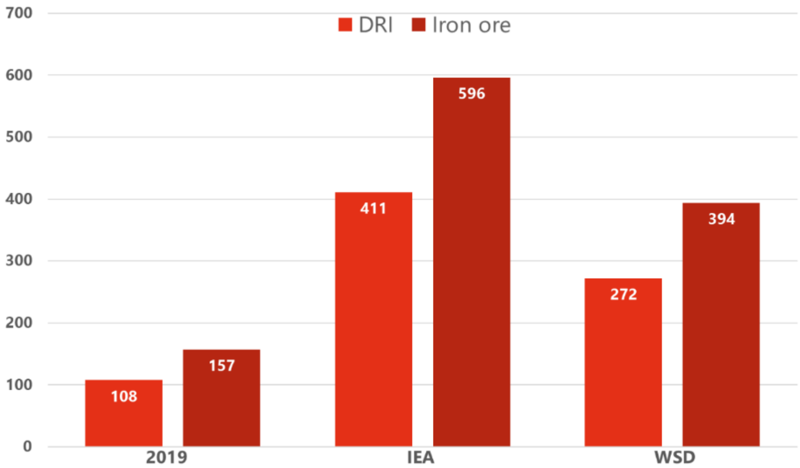
In order to provide some balance to these very high "forecasts" for DRI production, it is appropriate to refer to some more conservative scenarios from industry analysts. One such is from World Steel Dynamics (WSD) which published its "Global steel production outlook to 2050" in October 2020. This was accompanied by the following "health" warning: "Any forecast of steel production by country in 2050, including figures for BOF and EAF steel production and DRI output, is subject to substantial error. Nevertheless, the working out of different scenarios provides a deeper insight into the possible evolution of the steel industry."

In WSD's scenario global steel production in 2050 is forecast to be 1.854 billion tonnes, or within 19 mt of the 1.873 billion tonnes produced in 2019. By comparison, the IEA's STEPS scenario foresees global end-use steel demand in 2050 at 2.1 billion tonnes (up 40% on 2019) and 20% lower in its SDS scenario. WSD's scenario foresees global BOF steel production in 2050 at 1.101 billion tonnes, down 18.9% from 1.357 billion tonnes in 2019, and EAF steel production in 2050 at 753 mt, up 40.7% from 535 mt.

WSD suggests that global DRI production in 2050 may amount to about 272 mt versus 108 mt in 2019. The rise of 164 mt consisted of 100 mt in China, 32 mt in the Advanced Economies and 32 mt in the Rest of the Developing World. WSD's publication does not include a breakdown of DRI production process route, but it notes: "Our DRI forecast for 2050 assumes that hydrogen is available for DRI units at a price of about $2 per kilogram – which, of course, is not assured. We assume that about 45-60 kg of hydrogen is needed per tonne of hydrogen-based DRI."

Figure 5 compares iron ore demand from DRI production in 2019 with the IEA SDS and WSD scenarios (1 tonne DRI requires approximately 1.45 tonnes iron ore).

FIGURE 5: DRI PRODUCTION IN 2050 – SCENARIO COMPARISON (MT)



In both 2050 scenarios the implications for iron ore supply are profound, in terms of both quantity and quality.

The companion IIMA paper "An Assessment of Future Challenges for the EAF Process Resulting from Efforts to Reduce the Carbon Footprint of EAF Steelmaking" considers the impact on EAF steelmaking of DRI produced with hydrogen rather than natural gas as energy source and reductant. The carbon contained in ore-based metallics, including DRI and HBI, is an important contributor of "chemical energy" to current EAF steelmaking practice; DRI/HBI produced with hydrogen will contain little or no carbon and will necessitate changes in EAF design and practice.

1.2 Scope

This paper will cover two principal issues relating to hydrogen-based DRI:

- production of DRI against the background of iron ore demand in excess of 400 mt and as much as 600 mt by 2050, most importantly the issue of the adequacy and quality of iron ore feedstocks;
- the value-in-use aspects of DRI made with lower grade iron ore than currently demanded by DR plants as well as of hydrogen-based DRI.

Three basic assumptions are made:

- that there will be adequate supply of both electrical power and green hydrogen[5] at economic cost to meet the demand for hydrogen-based DRI production
- that there will be no insurmountable process technology barriers, and

[5] Grey hydrogen = produced mainly from natural gas with consequent emissions of CO_2
Blue hydrogen = produced from natural gas, where the CO_2 emissions are captured and stored, or reused
Green hydrogen = generated by renewable energy sources without producing CO_2 emissions in the first place

- that Carbon Capture Utilization and Storage will become a viable solution for more DR plants.

The issue of availability and cost of green hydrogen is beyond the scope of this paper, hence this assumption. There is certainly a great deal of activity in the hydrogen space and there appears to be a consensus that economically-priced green hydrogen will become available by the mid-2030s, as implied in Figures 2 and 3. In the meantime, there will undoubtedly be an element of transition along the way, starting with an increased proportion of hydrogen in the reducing gas and intermediate use of grey or blue hydrogen[5].

Where technology is concerned the principal processes, Midrex and Energiron, both have developed flowsheets for 100% hydrogen-based production. With the existing typical flowsheets based on natural gas, Midrex's reducing gas contains about 55% H_2 and Energiron's about 70% H_2. The Circored and the HYFOR processes are based on 100% H_2, whereas FINORED (formerly FINMET), based on natural gas, has about 70% H_2 in the reducing gas.

CCUS technology is already available to the direct reduction industry and is actually in use in some plants using the Energiron process, in Mexico and the UAE, whereby approximately 250 kg CO_2/tonne DRI (about 62% of total emissions) can be sequestrated and/or sold as a by-product, end-use applications including food and beverage (e.g. carbonation of water and soft drinks), production of dry ice and enhanced oil recovery (EOR). The Midrex process also has a CCUS option available, so far not taken up. Whether or not to bolt on CCUS is in the end an economic consideration, but as the industry advances along the pathway to carbon neutrality, the economics of coupling CCUS with direct reduction should become increasingly attractive.

2 Iron Ore Quality

The implications for iron ore and iron ore supply are significant in quality and quantity

2.1 Quality requirements

In the production of DRI, what is fed to the process (iron ore, i.e. iron oxide) is discharged at the end of the process minus its oxygen content (i.e. metallic iron), but including its impurities, principally gangue materials (SiO_2, Al_2O_3, CaO, MgO), and also phosphorus and metallic impurities, as well as some unreduced iron oxide. The DR process itself is more impacted by the physical and metallurgical properties of the iron ore feedstock, for example particle size distribution, mechanical strength, resistance to abrasion (tumble strength), bulk density, reducibility, etc. than by its chemical composition.

FIGURE 6: SHARE OF DR PRODUCTION PROCESSES IN 2019

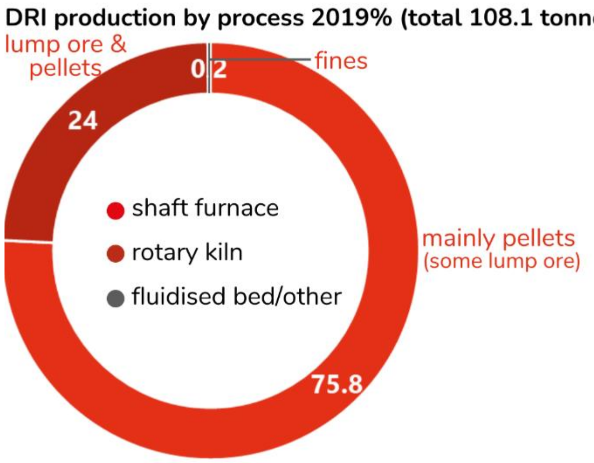


Figure 6 shows the share of DR production by process in 2019 from which it is clear that shaft furnace processes are by far the most significant.

From the perspective of the chemical analysis of iron ore, the main driver of acceptability is the requirements of the steelmaking process step. In the EAF, excess unreduced iron oxide and gangue will impact yield, power consumption, slag volume, etc. Phosphorus and metallic impurities will report to the liquid steel and potentially limit its use for production of higher specification finished steel products.

The BF is a much more tolerant consumer of DRI/HBI with its greater slag volume, etc., but has the same phosphorus constraint as the EAF.

As the EAF is the principal consumer of DRI, its quality requirements indirectly tend to dictate iron ore specifications, in essence:

- Fe content as high as possible, minimum 66%, ideally ≥67%
- Acid gangue content (SiO_2 + Al_2O_3) as low as possible, maximum 3.5%, ideally maximum 2% (also TiO_2 <0.2-0.35%, ideally <0.15% - depending on process)
- CaO up to 2.5%
- MgO up to 1%

- Phosphorus (as P_2O_5) as low as possible, ideally ≤0.015%, but maximum up to 0.08%, depending on the final steel product
- Sulfur as low as possible, maximum 0.025%, ideally maximum 0.015%
- Na_2O + K_2O 0.2% max.
- Metallic impurities such as Cu, Cr, Ni, V, as low as possible

The tolerance of any EAF steel producer to metallic impurities in DRI depends on the specification of the final steel product being made as well as the level of metallic impurities present in other charge materials, particularly scrap.

With respect to particle size distribution, in shaft furnaces using mainly iron ore pellets, typically 8-18 mm in diameter, it is essential to minimise the proportion of fines in the charge – the proportion of fines <6.3 mm should be 1.5-2% or lower. Physical and metallurgical properties will impact plant productivity, yield, gas consumption, etc.

For fines-based processes iron ore feedstock is typically sized as follows:

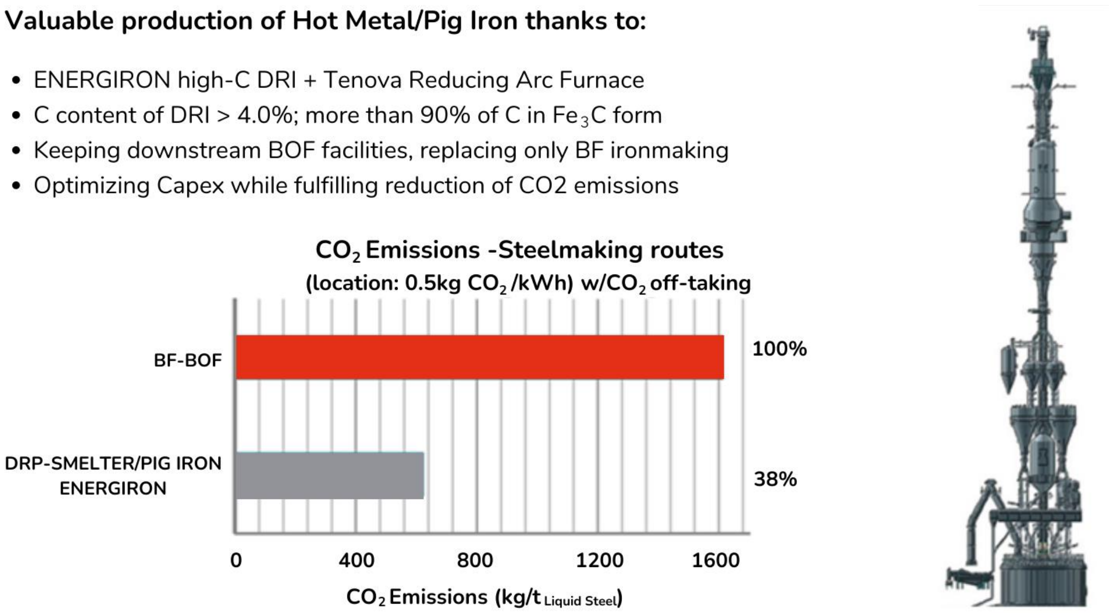
- Circored process: 0.1 - 2 mm - depending on decrepitation behaviour, up to 6 mm can be used and for ultra-fine concentrate and in-plant fines a micro-granulation step is available
- Finored processes: up to 8 mm, depending on decrepitation behaviour
- HYFOR process: up to 0.15 mm (150 μm)

So-called DR grade iron ore (pellets, lump, fines) will conform to the chemical and physical specifications shown above. Internationally traded products include pellets from Vale, LKAB, Iron Ore Company of Canada, Samarco, Bahrain Steel, high grade Sishen lump ore from Kumba Iron Ore, fines from Minas Rio (Anglo American) and, increasingly, others such as Champion Iron in Canada. Indian DRI/sponge iron producers depend largely on domestic, often captive iron ore, as do Iranian, Russian, Mexican, Venezuelan and Canadian producers (together accounting for about 75% of DRI production in 2020).

In times of shortage of DR grade pellets, some DR plants that depend on purchased pellets have of necessity purchased some lower grade (BF) pellets, sometimes from existing suppliers, sometimes from others, for example CIS pellet producers. A shortage of DR grade pellets encouraged some producers of BF pellets to invest in additional beneficiation to enable production of DR grade pellets, notably in Ukraine and Russia.

As mentioned in the introductory chapter, the EAF is not the only pathway to carbon-neutral steelmaking. There is a large capacity of basic oxygen furnace (BOF) converters in Europe and Asia, often with many years of useful life ahead of them. As mentioned in Appendix 1, thyssenkrupp's plan is to produce DRI for conversion to "electric hot metal" feedstock for its BOF steel plants. Most major metallurgical plant builders have their own "(s)melter" concepts, for example, Tenova/Energiron is promoting a process of hot metal/pig iron production via the direct reduction route, as illustrated in Figure 7.

FIGURE 7: NATURAL GAS-BASED PIG IRON (SOURCE ENERGIRON PRESENTATION JUNE 2020)



The BOF is more flexible than the EAF when it comes to ferrous feedstock quality and for this application blast furnace (BF) grade pellets do not carry the same penalty as they do for the EAF process route. Some typical BF grade pellet analyses are given in Table 1.

TABLE 1:BF GRADE PELLET QUALITY %

	IOC Std acid	Samarco	Vale São Luis	LKAB (KPBO)	Ferrexpo Poltava	Brahmani River
Fe	65.0	66.72	65.34	66.6	65.0	64.0
SiO_2	4.75	2.0	1.8	2.2	5.8	3.5
Al_2O_3	0.3	0.5	1.4	0.27	0.4	3.0
CaO	1.0	1.64	1.8	0.46	0.4	0.8
MgO	0.25	0.15	0.05	1.4	0.6	0.5
P	0.007	0.046	0.04	0.025	0.01	0.05
S	0.002	0.004	0.005	0.001	0.001	0.01

FIGURE 8: KOBE STEEL BF CO_2 REDUCTION

CO_2 Reduction Cost

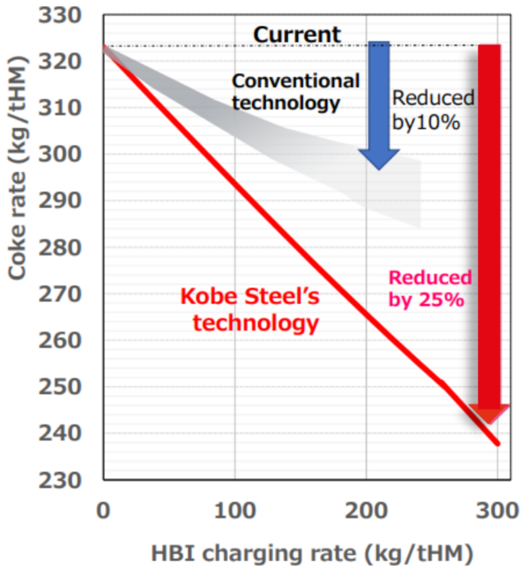
The key to lowering the CO2 reduction cost is how much expensive coke can be reduced by HBI charging

Results of the demonstration test

	Quantity of HBI charged (kg/tHM)	Coke rate (kg/tHM)	Coke rate reduced (kg/tHM)
Kobe Steel	305	239 World's lowest level	85
Previous	250	290	34

Note: The figures above are based on Kobe Steel's research results

The coke rate reduced by 2.5 times compared with the conventional method



Then there is the by now well-known practice of charging HBI to the blast furnace to improve productivity and reduce the fuel rate. Kobe Steel has recently publicised technology whereby BF CO_2 emissions were reduced by about 20% by charging 305 kg HBI per tonne hot metal, as illustrated in Figure 8. The demonstration test was conducted for a month at a 4,844 m^3 blast furnace at Kobe's Kakogawa Works in October 2020. Whilst BF productivity and fuel rate are better with higher HBI metallic Fe content, the BF is of course able to accommodate lower grade (i.e. BF) pellets.

2.2 Iron ore quality trends

Iron ore quality in general has been declining over the last 20 years or so, with declining Fe content, increasing levels of gangue materials and increasing phosphorus content. The principal component of the global seaborne iron ore market is sinter feed fines (direct shipping ore, from Australia, Brazil, South Africa and Mauritania). Figures 9-11 represent an analysis of the development of average sinter feed quality over the period 1998-2019[6].

[6] Source: Raw Materials & Ironmaking Global Consulting

FIGURE 9: DECLINING FE CONTENT

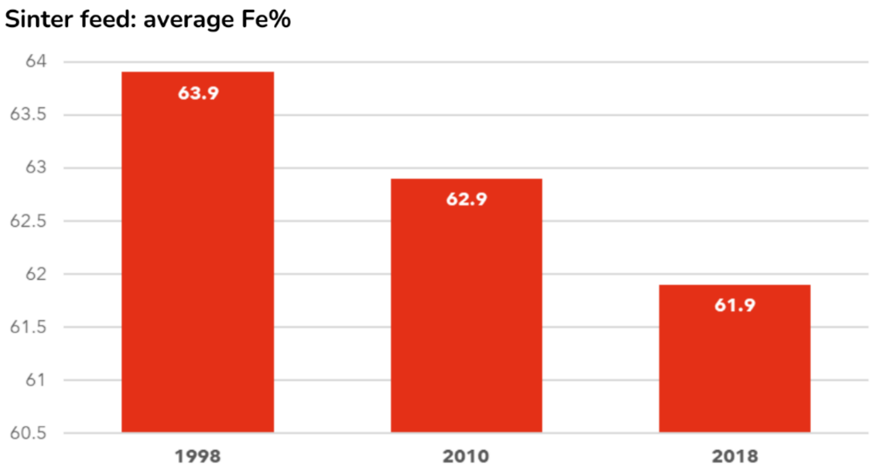


FIGURE 10: INCREASING ACID GANGUE CONTENT

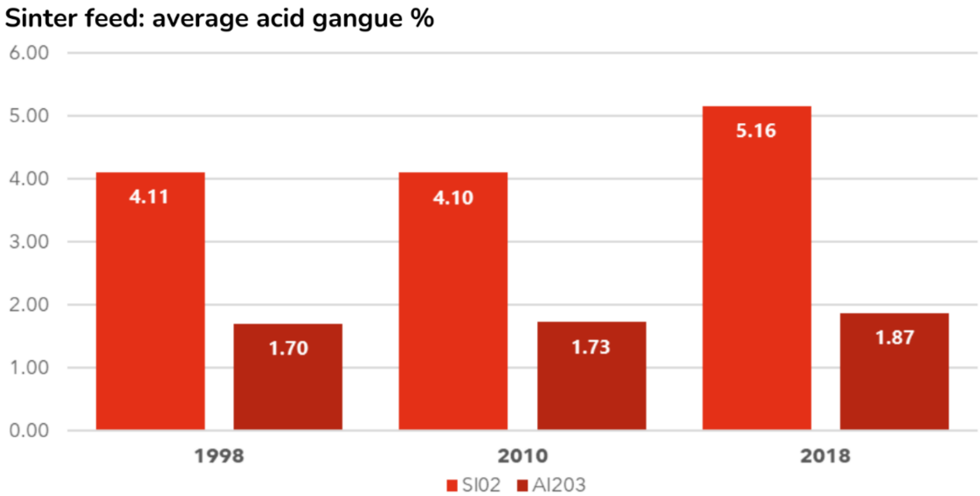
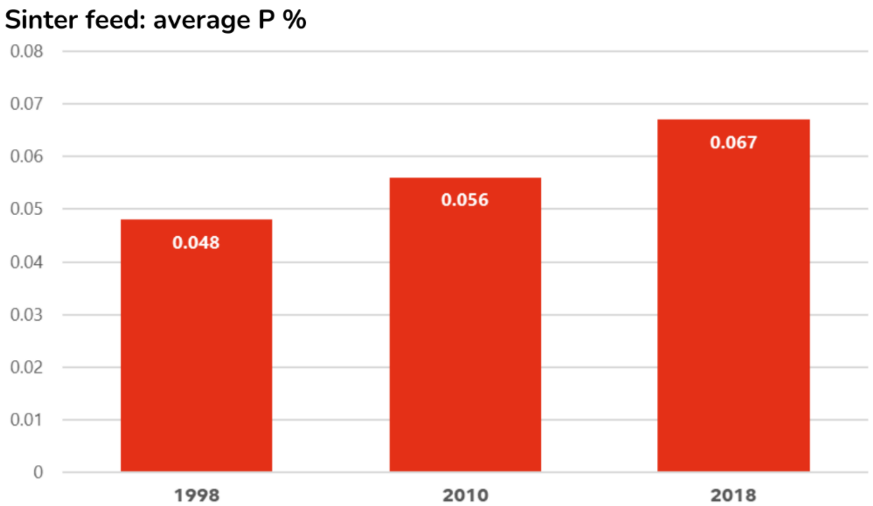


FIGURE 11: INCREASING PHOSPHORUS CONTENT



The deterioration in Fe, SiO_2 and Al_2O_3 levels has several implications for conventional BF/BOF steel production:

- requires increased sinter production to provide the same Fe units;
- results in increased blast furnace slag volumes and therefore increased coke rates;

- increases BOF flux consumption to maintain P removal.

The trend of increasing phosphorus content has implications for EAF operation, not insurmountable, but requiring adjustments to slag practice and better control of certain operating parameters, e.g. tapping temperature. These adjustments may result in greater slag volume leading to higher Fe yield loss and increased energy consumption.

Conversely, the quality of seaborne iron ore pellet feed and concentrates over the same period has remained rather constant, as has the quality of seaborne DR grade pellets, although in some cases this masks the need for additional beneficiation and concentration of the source ore in order to maintain grade.

FIGURE 12: SEABORNE IRON ORE PRODUCT BY GRADE

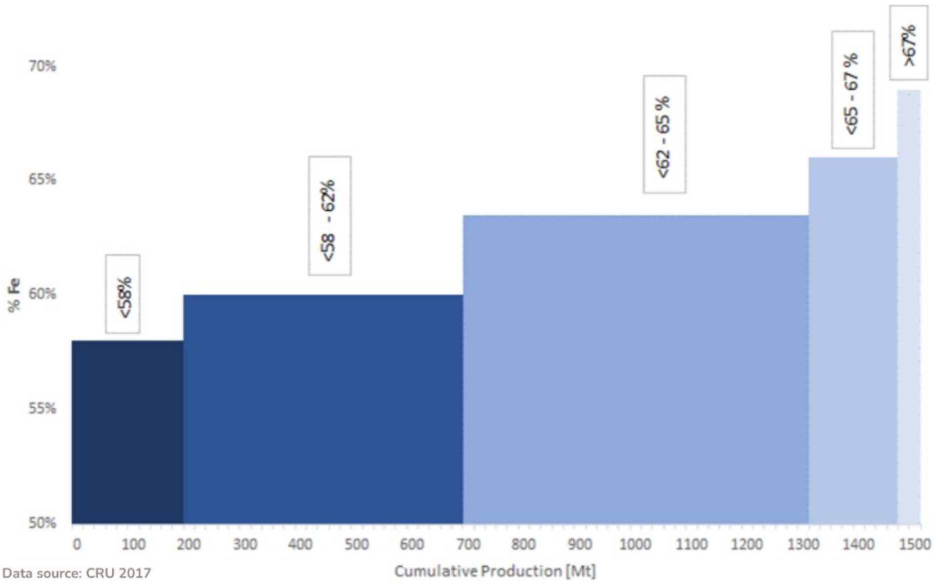


Figure 12, taken from a presentation by Primetals Technologies in December 2021, shows the iron ore quality issue from a different perspective, i.e. that the volume of high grade iron ore with Fe content >67% is very limited.

3 Challenges of future iron ore supply

The short to longer term issues

3.1 Short to medium term

The supply-demand balance for merchant or seaborne pellet supply over recent years has been affected by both supply-side and demand-side issues:

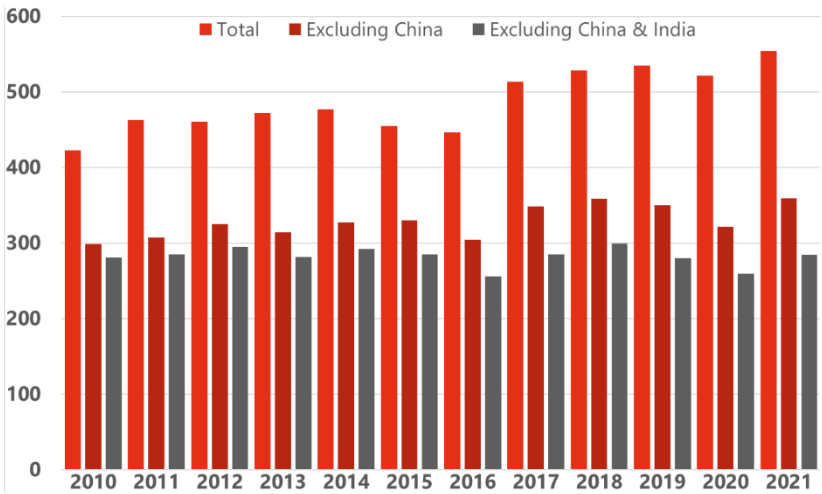
- on the supply-side by natural and man-made disasters, notably the dam collapses in Brazil (Samarco Fundão in 2015, Vale Brumadinho in 2019), strikes, equipment failures, etc.
- on the demand side by market developments such as commodity price movements and their relativities.

IIMA conducts regular analysis of the merchant DR grade pellet supply-demand balance. As this is an almost constantly changing scenario, on the one hand with new DR projects being announced as steel companies develop their decarbonisation strategies (see Appendix 1 for a list of DR projects) and on the other hand, with iron ore supply side developments. In general, the analysis suggests adequacy of potential supply of DR grade pellets by 2026, despite the current market tightness due to increasing DRI production and supply-side constraints. It is important to note, however, that producers of DR grade pellets have the flexibility to sell BF grade pellets or even fines, depending on market demand, margin, etc. There is also the possibility, even likelihood, that more DR projects than currently expected will commence production before 2026.

Looking further ahead, the analysis suggests that by the early 2030s, there will be a significant shortage of commercially available DR grade pellets for which the most practical solutions are use of lump ore, lower grade BF grade pellets, or other iron ore agglomerates. This is not necessarily a problem for the DR plants that will supply DRI/HBI to blast furnaces or those plants incorporating a (s)melter in between the DR and steelmaking steps.

3.2 Longer term

FIGURE 13: GLOBAL IRON ORE PELLET PRODUCTION MT (SOURCE WORLDSTEEL)



Looking beyond 2030 and out to 2050 with DRI production forecast to exceed 400 mt by 2050 per the IEA's SDS, the picture is very different. Some 411 mt of DRI equates to nearly 600 mt of iron ore feedstock which exceeds current global pelletising capacity. Figure 13 shows historical global pellet production data.

From the quantitative perspective, iron ore supply should not be an issue: with BF iron production falling from just under 1.3 billion tonnes in 2019 to 665 mt by 2050 per IEA's SDS (refer Figure 2), equivalent to about 2 billion tonnes and 1 billion tonnes iron ore respectively, the incremental iron ore demand of about 440 mt from increased DRI production could be met, assuming adequate replacement of depleted reserves. However, from the qualitative perspective, there is a potentially serious problem.

With the gradual shift from BF/BOF to DR/EAF, existing pellet producers will shift a commensurate volume of pellet supply from the BF to the DR market, albeit it with some investment in ore beneficiation where practicable to reach DR grade quality. A recent example of this is ArcelorMittal Canada's recently announced decision to upgrade 100% of its 10 mt pellet production capacity to DR quality. Other examples include Cleveland Cliffs' upgrade of its North Shore operation and pellet producers in Russia and Ukraine which have invested in enhanced ore beneficiation to enable production of DR grade pellets for the domestic and international merchant markets.

Some current supply may well progressively disappear from the merchant market: LKAB's announced plans to transition from a supplier of pellets to a supplier of HBI between the late 2020s and mid-2040s could progressively remove more than 20 mt of pellets from the market.

New pelletising capacity will be needed, probably both brownfield and greenfield (brownfield projects will doubtless be less costly to implement than greenfield ones). In the last decade or so, a number of pelletising projects have fallen by the wayside due to the high capital costs involved and inability to secure bankable offtake agreements, e.g. in Canada and Mauritania. One of the only countries to have continued major investment in iron ore concentrate and pellet production for DR is Iran which has invested to supply its planned 55 mt steel capacity.

Something of a wild card is Vale's recently announced development of an iron ore briquette product, produced at low temperature: Vale has three briquette plants already under construction in Brazil with almost 7 million tonnes aggregate capacity and has five other plants under analysis, including production DR grade briquettes at its Oman site. Vale envisages over 50 mt per year eventual production of briquettes. It is thought that Vale's briquettes will be used initially as a CO_2 reduction enabler by facilitating replacement of sinter in blast furnaces.

From the direct reduction perspective, the availability of Brazilian high grade pellet feed for production of DR grade pellets has been a constraint, especially in the post-Brumadinho scenario where wet processing is less and less of an option. In late 2018 Vale acquired a company called New Steel with proprietary dry processing technology for iron ore. The first 1.5 million tonnes per year plant is under construction at Vargem Grande with start-up planned for 2023, with three other plants awaiting approval, notably one in Oman with 8.5 million tonnes capacity.

3.3 Future pellet supply models

Adequacy of supply of appropriate quality iron ore will be a key input into investment decisions on new DRI production capacity, be it domestic/captive supply or purchase from the international market. Whilst the currently predominant business models of captive and merchant pellet supply will not diminish in importance, other models have emerged or are emerging for the merchant market.

One such is the integration of pelletising plants with DR plants, as in the examples of Tosyali Algerie in Oran and SULB/Bahrain Steel where the emphasis changes to sourcing of pellet feed. In the short to medium term, as both Bahrain Steel and Tosyali Algerie have found, supply of suitable pellet feed has not been straightforward in that merchant supply of suitably high-grade pellet feed is rather limited. Bahrain Steel has been able to contract the supply of DR grade pellet feed from Anglo American's Minas Rio mine in Brazil (a recent development has been a three-year toll conversion agreement whereby Bahrain Steel will produce up to 2 mt per year DR grade pellets for Anglo American from Minas Rio pellet feed). Tosyali has resorted to the installation of an ore beneficiation facility in order to upgrade purchased ore fines. It is understood that the recently announced phase two development by Tosyali Algerie will also involve an ore beneficiation plant and pelletising plant.

There is potential new supply of high grade pellet feed from various projects, in Australia, Brazil, Peru, Canada, Ukraine, Sweden, Norway, Mauritania, etc. There is also scope for upgrading of direct shipping ore through beneficiation - indeed as the shift from BF to DR progresses, this will become a necessity. Then there are other potential greenfield iron ore projects, of which Simandou in Guinea is one of the best technically, although with very high capex.

The longer term future for mainstream Pilbara Australian iron ore (which comprised more than 50% of seaborne iron ore supply in 2020 and is difficult and expensive to beneficiate due to its crystal structure) represents an interesting challenge, high on the radars of the major producers. One possible solution understood to be under active consideration is the DR/smelter route. There are various magnetite iron ore projects in Australia with the potential to produce DR grade pellet feed.

What seems certain is that the cost (both CAPEX and OPEX) of seaborne iron ore feedstock for direct reduction plants, especially those serving EAF steel mills, will increase progressively over the coming years as more beneficiation of existing resources is needed, not to mention the new projects (with their associated transportation and logistics infrastructure) that will be needed to deliver the increasing volumes required.

3.4 Fines-based direct reduction technologies

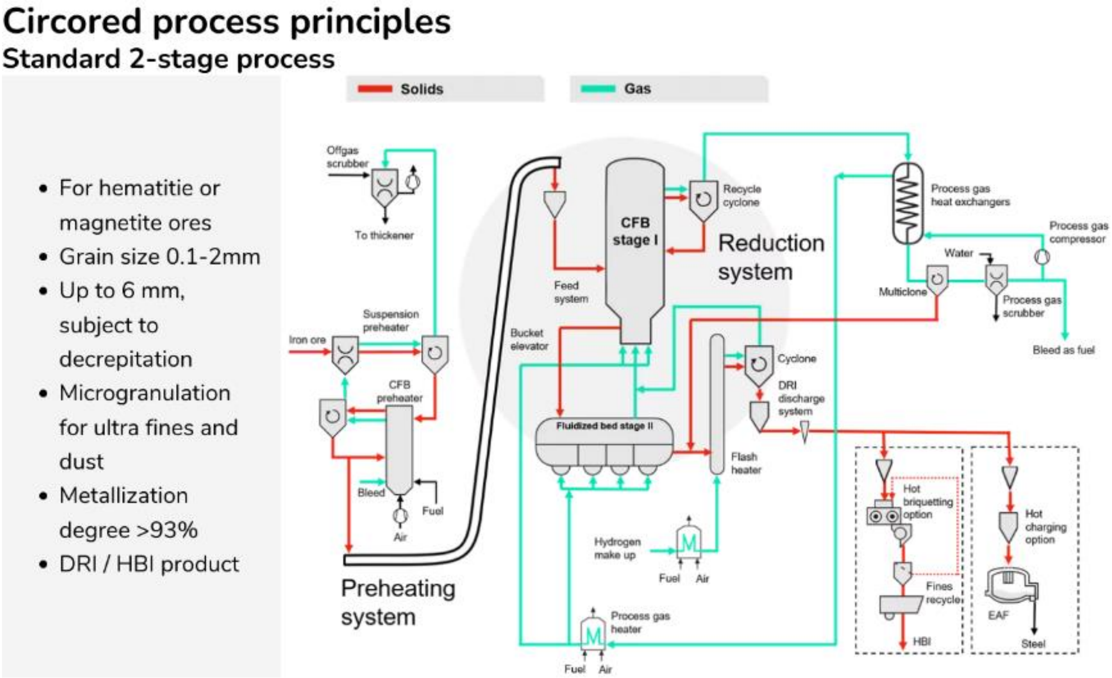
All but one of the larger DR plants utilise iron ore pellets and/or lump ore as feedstock. Only one, Orinoco Iron in Venezuela, uses the fines-based FINMET process (renamed FINORED), a process using multi-stage, fluidized bed reduction. Another FINMET plant, BHP's Boodairie Iron at Port Hedland in Western Australia was shut down in 2006. Other idled or dismantled fines-based plants are the CIRCORED plant in Trinidad, Nucor's Iron Carbide plant in Trinidad, Qualitech Steel's iron carbide plant in Texas, Steel Dynamics' ITMK3 plant in Minnesota and Sivensa's FIOR plant in Venezuela.

FIGURE 14: PILOT SCALE HYFOR DR PLANT

Image courtesy of Primetals Technologies

An emerging iron ore concentrate-based DR technology, HYFOR (Hydrogen-based Fine Iron Ore Direct Reduction), is being developed by Primetals Technologies at the voestalpine site at Donawitz in Austria. A pilot scale plant has started operation (see Figure 14). The HYFOR pilot plant consists of a preheating-oxidation unit, a gas treatment plant and the reduction unit. In the preheating-oxidation unit, fine ore concentrate is heated to approx. 900°C and fed to the reduction unit. The reduction gas, 100% H_2, is supplied "over the fence" A dry dedusting system prevents dust emissions. The hot direct reduced iron (HDRI) leaves the reduction unit at a temperature of approx. 600 °C before it is cooled and discharged from the plant.

FIGURE 15: CIRCORED PROCESS FLOWSHEET[7]



The Circored process was developed by Lurgi Metallurgie (predecessor to Metso Outotec) in the 1990s as a hydrogen-based, fluidised bed direct reduction process, avoiding the need for agglomeration of iron ore feedstock. An industrial scale demonstration plant (0.5 mt HBI capacity) was constructed in Trinidad and operated intermittently between 1999 until 2005 (initially owned by Cleveland Cliffs, latterly by ArcelorMittal). In light of the current interest in H_2 based DRI, Metso Outotec is now relaunching the process with a number of process variants, namely production of HBI, production of hot DRI for direct charging into an adjacent EAF or, for use of BF grade iron ore feedstock, production of hot metal via an electric smelter. The optimum capacity for new plants is currently seen as 1.25 mt. The Circored flowsheet is shown in Figure 15.

3.5 Location of new DR plants

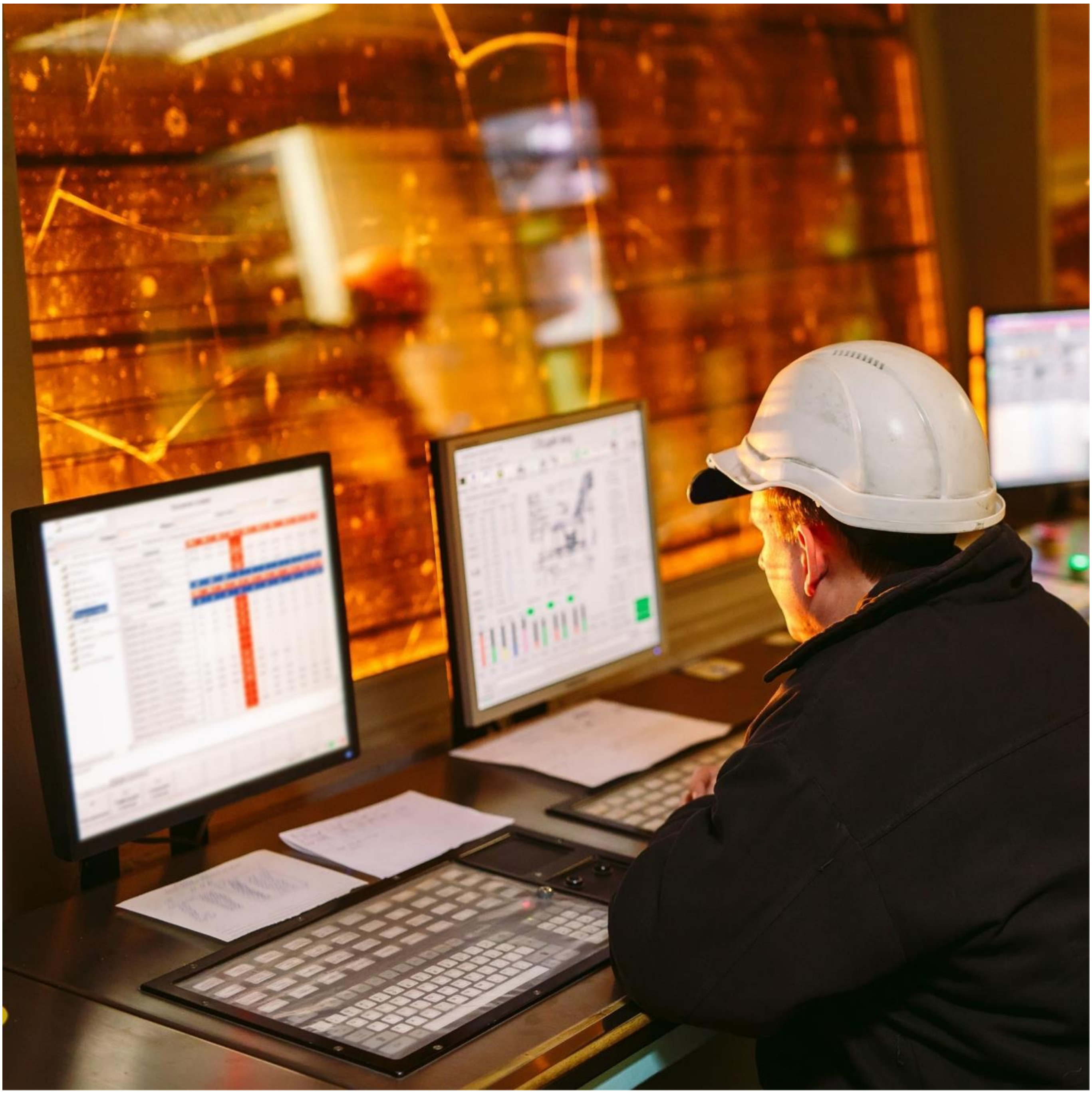
Beyond the basic quantitative and qualitative issues, there are others to consider, one such being the location of the new direct reduction plants that will be needed to enable decarbonisation of the steelmaking process. On the basis of what has already been said and announced, it is clear that there will be a range of solutions depending on individual circumstances, ranging from: DR plants as part of mine/pelletising complexes to DR plants adjacent to steel plants to DR plants located in between mine and steel mill. A partial geographical shift in iron and perhaps even steel production from the traditional steelmaking regions to iron ore producing regions is a distinct possibility.

[7] Source: Metso Outotec presentation, December 2021

Decisions on plant locations will be driven by various factors, not the least of which will be the availability and cost of green hydrogen, the benefits (or not) of integration with steel plants, transportation costs, etc. Given the well-known hazards of handling and transportation of DRI in its various forms, safety should also be a consideration.

4 Value-in-use aspects

Value-in-use modelling gives insight in determining the most efficient and carbon-neutral melts in the EAF process



Computer modelling of the value-in-use (VIU) of various types of pellets was carried out using the IIMA EAF metallics VIU model.[8] Model runs were carried out on a variety of commercially available pellets, Samarco DR grade pellets being used as the base case. Analysis data for DRI produced from the various pellets were derived. Cases modelled were:

- DRI with target 92% metallisation and 2% or 3% carbon
- DRI with target 95% metallisation and 2% or 3% carbon
- DRI with 0% carbon (H_2 based)

For the purposes of modelling it was assumed that the grades of BF pellets are reducible to the same levels as DR grade pellets. This may not be the case in practice, but in order to proceed, this assumption was needed. It was also assumed that fines generation in a typical vertical DR shaft furnace was 2%. In reality, some of the BF pellets may produce greater levels of fines.

Tables 2 and 3 give the oxide pellet analysis data and the assumed EAF operating data respectively. Figures 17 to 29 show the results of the model runs graphically, comparing oxide pellet Fe and gangue content with productivity loss against the base case of Samarco DR grade pellets, the X-axis in descending order of Fe content.

TABLE 2: PELLET ANALYSIS % (SOURCE RAW MATERIALS GLOBAL CONSULTING)

	Samarco DR grade	Severstal	Keetac	CAP Huasco	Vale Carajas	Vale acid
Fe	67.90	66.62	65.89	65.00	65.34	64.00
SiO2	1.23	2.95	4.50	3.50	1.80	5.00
Al2O3	0.49	0.25	0.20	1.25	1.40	1.15
CaO	0.76	1.08	0.68	2.46	1.80	1.50
MgO	0.09	0.17	0.20	0.50	0.05	0.50
Mn	0.04		0.10	0.04	0.05	0.28
P	0.05	0.01	0.01	0.05	0.04	0.04
S	0.00	0.02	0.00	0.00	0.01	0.00
TiO2	0.04		0.01	0.13	0.08	
Na2O	0.04	0.04	0.02	0.25		
K2O	0.01	0.05				
CaO/SiO2	0.62	0.37	0.15	1.23	1.00	0.23
B/A	0.49	0.39	0.19	0.62	0.58	0.33
H2O	1.5	0.9		2.0	2.0	3.0

In considering these charts it should be kept in mind that this model run assumes a 100% DRI charge in each case which is generally not representative of actual EAF practice. Actual EAF charges would typically comprise up to 40-50% ore-based metallics (OBMs) for flat products and up to 10-20% for SBQ products, subject

[8] Developed for IIMA by CIX LLC

always to the availability and quality of the scrap supply. As the availability of high quality scrap decreases and that of obsolete scrap increases (as projected out to 2050 by worldsteel), the ratio of OBM required in the charge will increase.[9]

TABLE 3: EAF OPERATING DATA ASSUMPTIONS

Base Productivity Conditions		
P-On time	37	minutes
Power	425	KwH/tonne
Slag FeO	35.0%	
Slag CaO	30.0%	
MgO Target	10.0%	
Productivity cost	2.00	$/%
% of OBM in charge	100.0%	

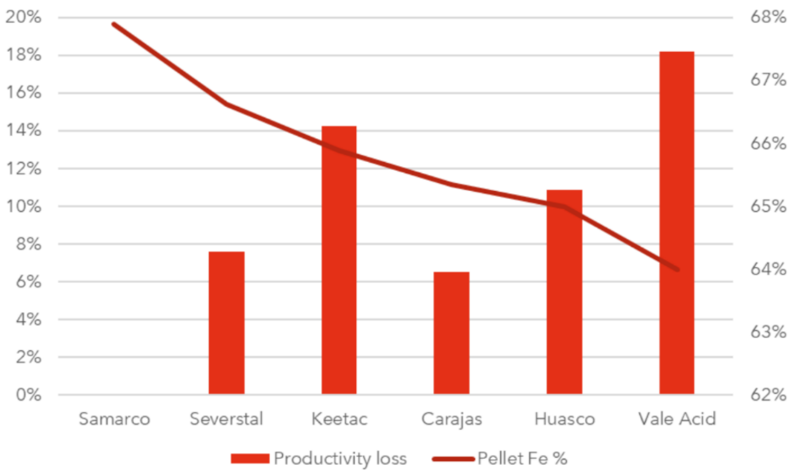
Cost Data	$/unit	
Cu cost	$1.75	per pt
Line	$174	tonne
Dolo-lime	$227.00	tonne
Carbon	$321.00	tonne
Power	$0.04	kWh
Electrodes	$11.51	kg
T-T-T	46.00	min

Operating Data		
C recovery	50%	30 to 80%
Energy efficiency	60%	40 to 60%
Fines losses <4mm	100%	30 to 100%
Fines losses 4-8mm	30%	30 to 100%
FeO recovery	60%	30 to 100%

Flux Data		
Basicity B2 or B3		
	CaO	MgO
Lime	92.3%	**1.1%**
Dolo-lime	60.1%	**30.1%**
Slag basicity	1.80	

The EAF operating data assumptions were based on an actual Midwest USA high capacity mill currently utilizing high levels of DRI/HBI.

FIGURE 16: PELLET FE % V PRODUCTIVITY LOSS -92% METALLISATION, 2% CARBON



[9] Refer companion paper "An Assessment of Future Challenges for the EAF Process Resulting from Efforts to Reduce the Carbon Footprint of EAF Steelmaking"

FIGURE 17: PELLET GANGUE % V PRODUCTIVITY LOSS - 92% METALLISATION, 2% CARBON

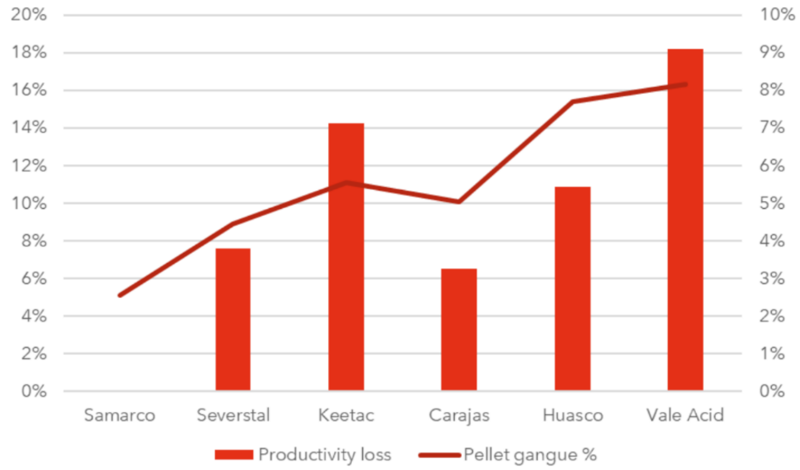


FIGURE 18: PELLET FE % V PRODUCTIVITY LOSS - 95% METALLISATION, 2% CARBON

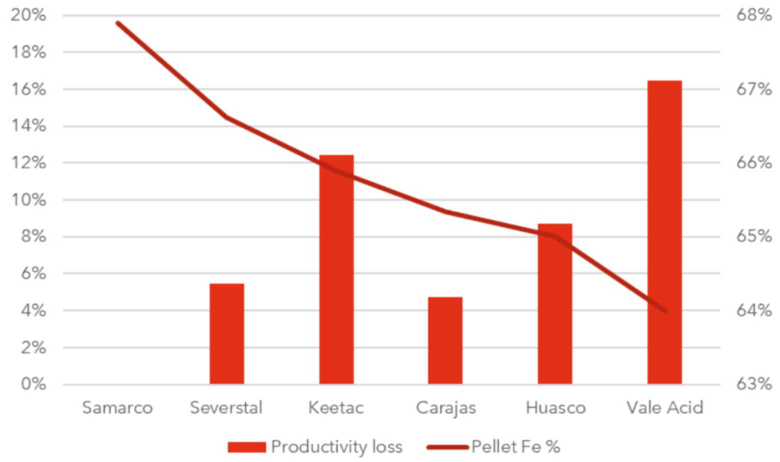


FIGURE 19: PELLET GANGUE % V PRODUCTIVITY LOSS - 95% METALLISATION, 2% CARBON

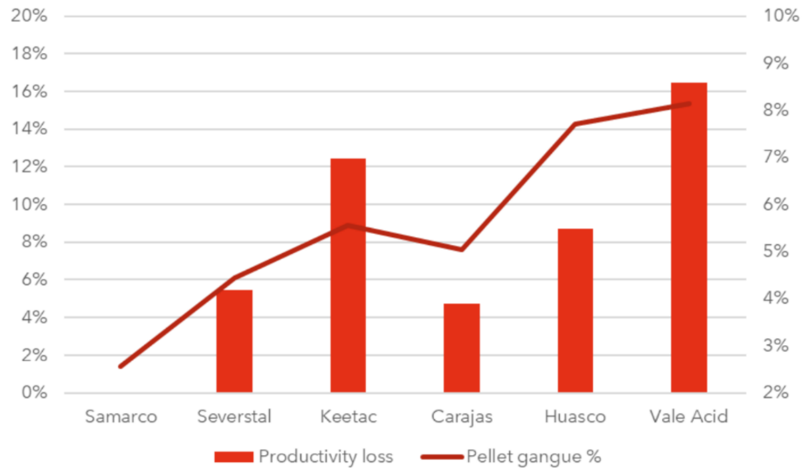


FIGURE 20:PELLET FE % V PRODUCTIVITY LOSS - 92% METALLISATION, 3% CARBON

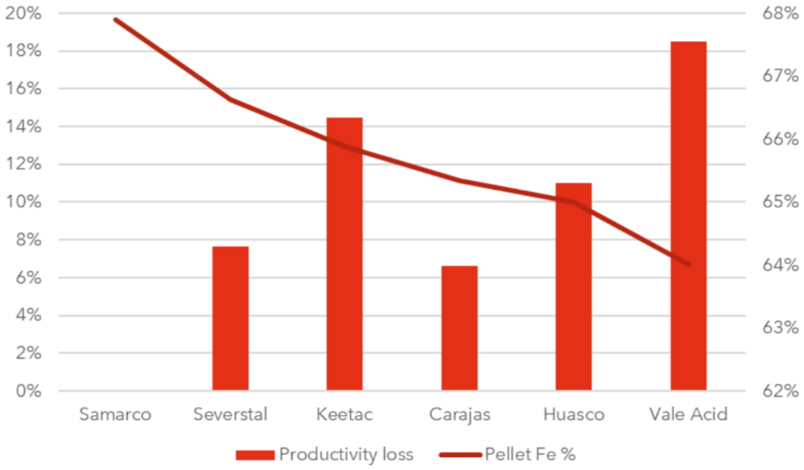


FIGURE 21: PELLET GANGUE % V PRODUCTIVITY LOSS - 92% METALLISATION, 3% CARBON

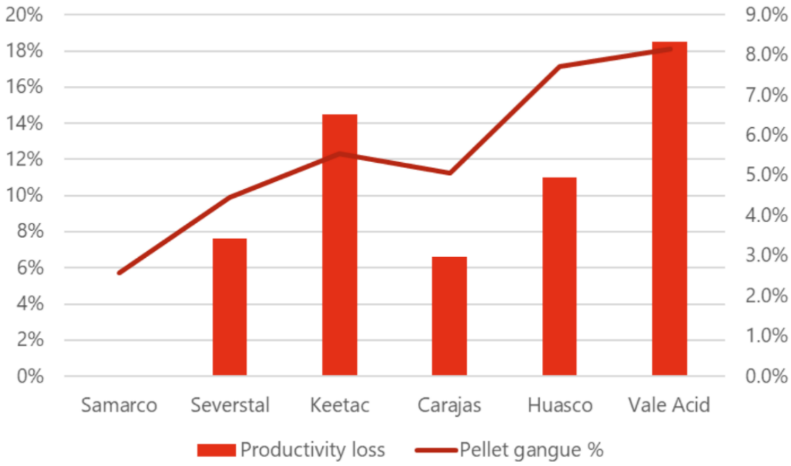


FIGURE 22: PELLET FE % V PRODUCTIVITY LOSS - 95% METALLISATION, 2% CARBON

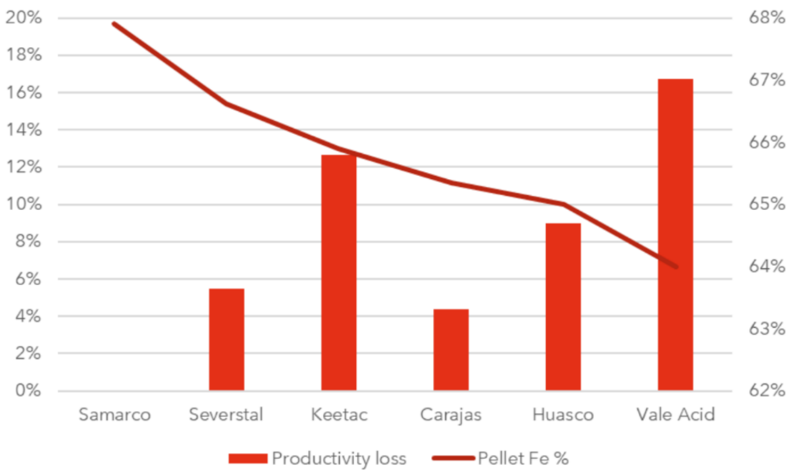
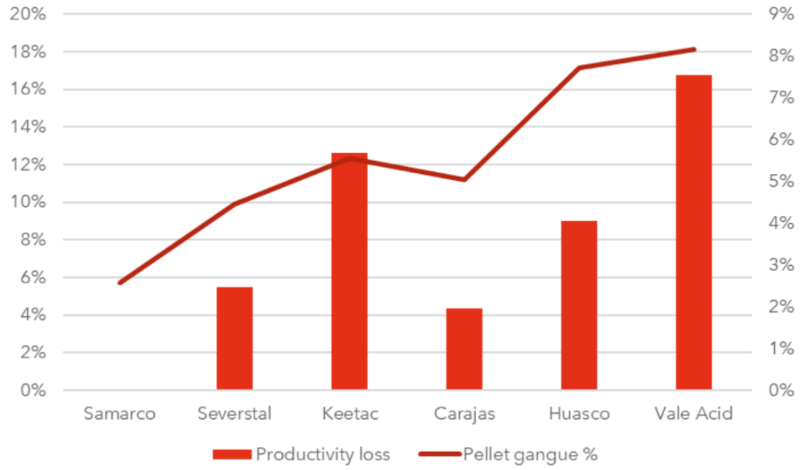


FIGURE 23: PELLET GANGUE % V PRODUCTIVITY LOSS - 95% METALLISATION, 3% CARBON

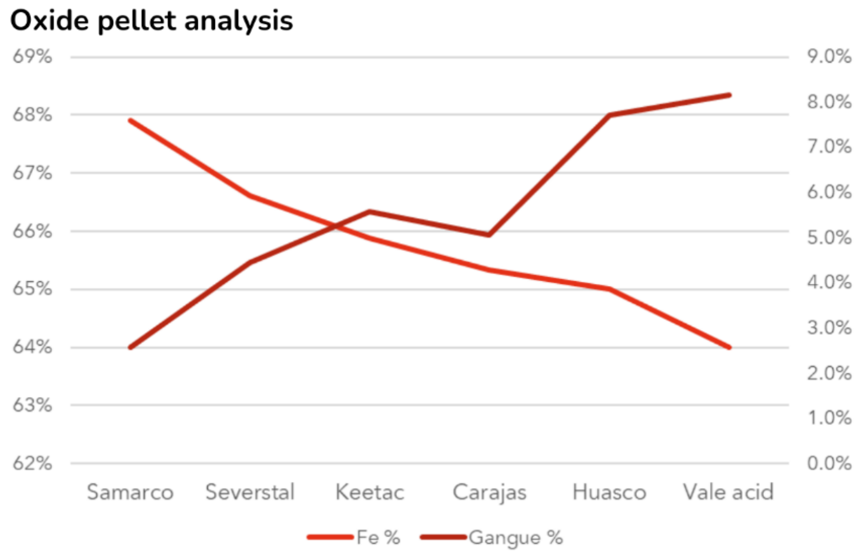


It is clear that for lower Fe pellets, the productivity loss is reduced by producing DRI with a higher metallization. The same trend holds true for the impact of higher gangue levels. This trend has been seen in captive DR operations which have been trending to higher metallization levels (of about 95 %) over the last 5 to 10 years.

The impact of carbon level in the DR product is much more related to the preference and needs of the individual steel plant. What makes sense for one facility might not make sense for another. The decision firmly centres around the cost and recovery for carbon units which varies widely for individual steelmakers.

What can be concluded at a high level from this work is that EAF productivity is driven by both Fe content and gangue content, so neither a high Fe content nor a low gangue content on its own is a complete indicator of productivity impact. Figure 24 summarises the oxide pellet Fe and gangue contents.

FIGURE 24: OXIDE PELLET ANALYSIS



In general, higher gangue content is an impediment to utilization of DRI/HBI within a given steelmaking operation. Likewise, lower pellet Fe content will impact on the amount of DR material to make a given quantity of steel. Without doubt, some steelmaking operations will find it beneficial to utilize some lower grade DRI/HBI. There is no one-size-fits-all solution. The local scrap market and the availability and cost of Fe metallics to the steel plant will play a significant role in these decisions. That being said, the evaluation mechanism (VIU modelling) is in place to enable the steel producer to evaluate various metallics scenarios and strategies and determine how best to utilize the available feedstocks in the future.

Together with the analysis on the impact of lower grade iron ore pellets on the value in use of DRI in the EAF, the scenario of H_2-based DRI has been considered. This is a more difficult scenario to project as there are currently no process data available vis-à-vis the utilization of H_2-based DRI in the EAF. For the sake of consistency, the EAF operational data and cost structure have been set to be consistent with the analysis of carbon containing DRI for the various BF grade pellets. It must be kept in mind that this VIU analysis is conducted as a comparison of various DRI alternatives compared against DRI made using Samarco pellets.

FIGURE 25: PELLET FE % V PRODUCTIVITY LOSS - 92% METALLISATION / 0% CARBON

FIGURE 26: PELLET GANGUE % V PRODUCTIVITY LOSS - 92% METALLISATION / 0% CARBON

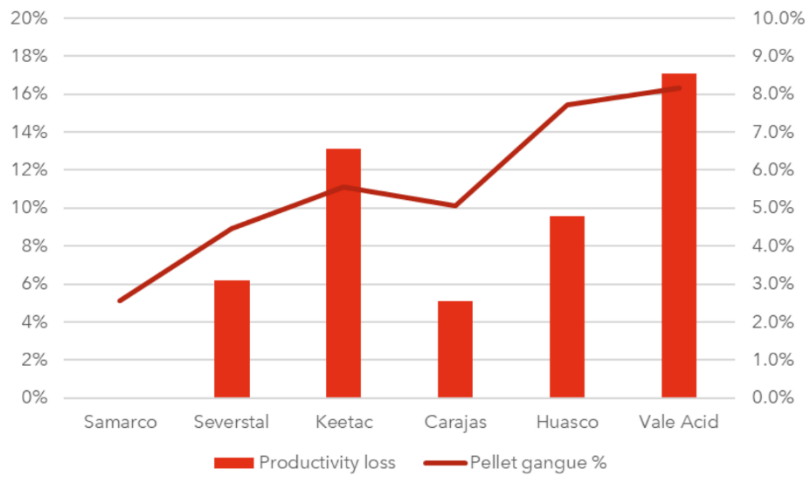


FIGURE 27: PELLET FE % V PRODUCTIVITY LOSS - 95% METALLISATION / 0% CARBON

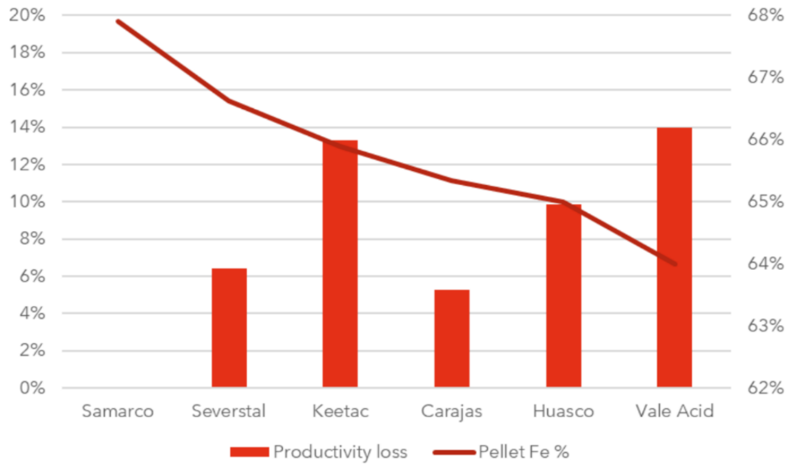
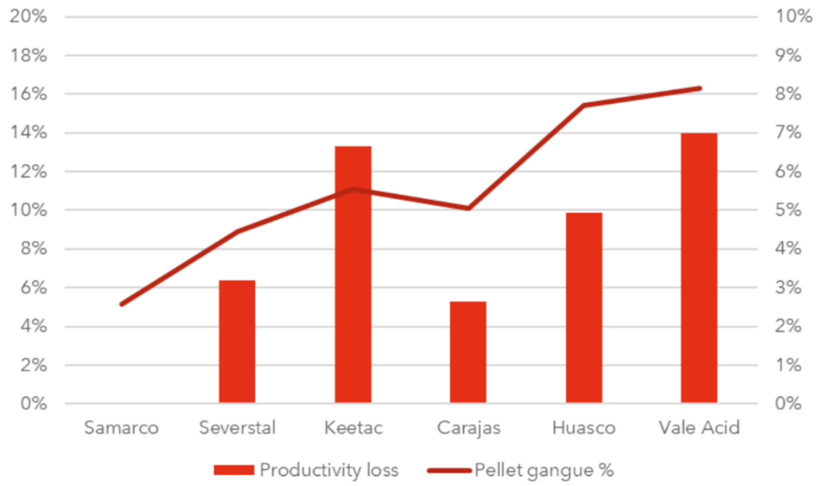


FIGURE 28: PELLET GANGUE % V PRODUCTIVITY LOSS - 95% METALLISATION / 0% CARBON



The H_2-based DRI scenario presents some interesting challenges to EAF operations. At zero carbon content, there is a requirement to provide some other reductant source in the EAF to recover the Fe units tied up as FeO in the DRI. The analysis indicates that as pellet total Fe increases, there is more FeO remaining in the pellet for a given DRI metallization. This is somewhat counter-intuitive, but this effect is offset by the lower feedstock demand per tonne of steel for DRI with high total Fe content. If the objective is to reduce the amount of Fe recovery work done in the EAF, the best option is to produce DRI with a high degree of metallization.

Other challenges for the EAF include the following:

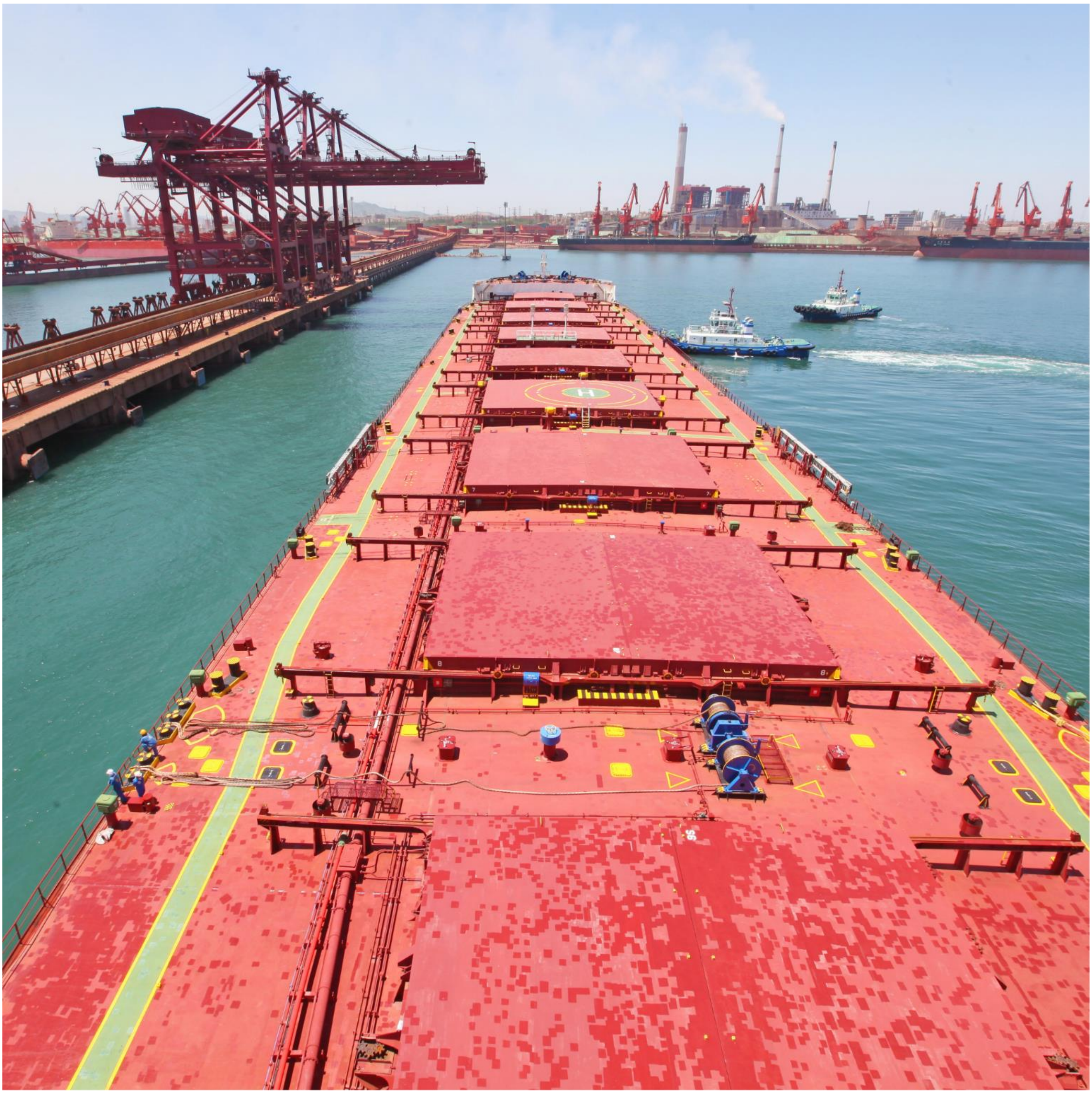
- Zero C DRI may require a higher steel bath temperature in order to melt at the same rate as for carbon-bearing DRI. Conversely, the feed rate of zero C DRI may need to be reduced compared to the rates common for C-bearing DRI.
- Some studies have noted that the reaction of C and FeO in the DRI pellet helps to accelerate the breakdown of the pellet in the slag leading to faster dissolution rates. If this is confirmed, the feed rate of H_2-based DRI may be impacted.

- Carbon-bearing DRI tends to lead naturally to slag foaming, a process that is highly beneficial for both energy efficiency and recovery of injected materials in the EAF. H_2-based DRI will not provide this slag foaming benefit and this may negatively impact EAF efficiency.

Understanding of the impact of zero C DRI on EAF operations will continue to grow and develop as various pilot trials are conducted by industry participants in the coming years.

5 Handling & Transportation Issues

Considering the implications for logistics



International maritime shipment of solid bulk cargoes is governed by the London-based International Maritime Organisation (IMO), a United Nations body.
The IMO sets standards for the safety and security of international shipping. It oversees every aspect of worldwide shipping regulations, including legal issues and shipping efficiency. The IMO code governing solid bulk cargoes is the International Maritime Solid Bulk Cargoes Code (IMSBC Code).

Appendix 1 of the Code contains individual schedules for more than 300 solid bulk cargoes. Cargoes are divided into three groups, A, B and C:

- **Group A** consists of cargoes which possess a hazard due to moisture that may result in liquefaction or dynamic separation if shipped at a moisture content in excess of their transportable moisture limit (this is a revised definition, yet to be formally adopted)
- **Group B** consists of cargoes which possess a chemical hazard that could give rise to a dangerous situation on a ship
- **Group C** consists of cargoes which are neither liable to liquefy (group A) nor to possess chemical hazards (group B)

A sub-set of Group B cargoes is **Materials Hazardous only in Bulk (MHB)**. These are materials that when carried in bulk, possess chemical hazards other than the hazards covered by the classification system of the International Maritime Dangerous Goods Code. These materials present a significant risk when carried in bulk and require special precautions. Such hazards are Combustible solids (CB), Self-heating solids (SH), Solids which evolve flammable gas when wet (WF), Solids which evolve toxic gas when wet (WT), Toxic solids (TX), Corrosive solids (CR) and Other hazards (OH).

The IMSBC Code includes three schedules for DRI and one for pig iron. There is no hazard classification for pig iron. The three schedules for DRI are:

- Direct Reduced Iron (A) Briquettes, hot-moulded *(this is HBI and is Group B)*
- Direct Reduced Iron (B) Lumps, pellets, cold-moulded briquettes *(this is DRI and is Group B)*
- Direct Reduced Iron (C) (By-product fines) *(this is DRI/HBI Fines and is Group B)*

All DRI schedules are classified as MHB SH and/or WF (WF relates to evolution of hydrogen). Each schedule sets out the risk mitigation measures and precautions which are mandatory.[10] The schedule for DRI (C) requires a maximum moisture content of 0.3% whereas the vast majority of shipped DRI Fines typically contain 5-

[10] For more detail click here to refer to **this document**.

6% moisture. A proposed new schedule for such fines, designated DRI (D), is under discussion at the IMO, spearheaded by IIMA. It is essential that there be a mandatory instrument governing shipment of this material - misclassification of a cargo could lead to serious incidents or accidents with consequent reputational damage to the industry.

Of particular significance in the context of carbon-neutral steelmaking is the potential impact of changes in HBI specifications on safe transport and handling, of paramount importance to the DRI industry. The DRI (A) schedule requires HBI to have an apparent density >5,000 kg/m^3. With the probable future use of lower grade iron ore feedstock and hydrogen-based DRI, the question of the applicability of this density requirement arises. IIMA is in the process of instigating a research project, designated HBI-C-Flex, to understand the relationship between HBI reactivity (and its drivers) and the threshold for self-heating. With new variants of HBI, modifications or additions to the IMSBC Code schedules may become necessary in order to ensure market access. The IMO processes can be protracted, and given past incidents with DRI cargoes, any such changes will be scrutinised in detail.

6 The Way Ahead

Considerations for the future of DRI as steelmaking moves towards its carbon neutral goals

What seems clear is that where the future of direct reduction is concerned, given the likelihood of a shortage of DR grade pellets from the early 2030s, interactions between the steel and iron ore industries need to intensify as progress is made along the pathway towards carbon-neutral steelmaking. Furthermore, it is essential that the DR technology and plant building sectors are part of the conversations, as is already the case in most of the projects mentioned in Appendix 1. Beyond these core players, there is a broader value chain of which energy and transportation are vital components - key to carbon-neutrality is the availability of affordable "green" electricity and power across the whole value chain.

Beyond the immediate value chain, it is essential that policy makers and regulators are aware of and recognise the important issues that lie beneath their existing and evolving high level policies and goals. Furthermore, policy makers and regulators should appreciate and take into account the consequent technical challenges. Industry associations have a vital role to play in this respect.

Safe handling and transport of all types of DRI is of paramount importance to the industry and it is essential that maritime and other regulations are kept up-to-date with industry developments in order to maintain market access.

Appendix 1: DRI projects announced or under consideration

In Europe:

- ArcelorMittal (AM) has commissioned Midrex Technologies to design a demonstration H_2-based DR plant for its Hamburg, Germany works with capacity of about 0.1 mt. This would initially use grey hydrogen, but ultimately green hydrogen when economically available. For the existing DR plant at Hamburg, AM plans to first add hydrogen to the reducing gas with eventual conversion to 100% hydrogen.
- AM has announced plans to construct DR plants, coupled with EAFs, at its Bremen and Eisenhüttenstadt plants in Germany, following an announcement about the planned expansion of Germany's hydrogen infrastructure. The DR plants will be based on natural gas initially and eventually electrolytic hydrogen. No timescale is specified, but the company has set itself the goal of reducing CO_2 emissions in Europe by 30% by 2030.
- AM has also announced plans to construct DR plants at its Gijon works in Spain, its Gent works in Belgium and its Dunkirk works in France.
- HYBRIT[11], Sweden, a joint venture of SSAB, LKAB and Vattenfall for production of fossil-free steel. The project involves a hydrogen-based Energiron DR plant to be constructed in Northern Sweden, using iron ore pellets produced with fossil-free energy. A pilot plant started operation in August 2020 and start-up of a ≥1 mt demonstration plant is planned for 2025. The goal is to have a fossil-free steel solution by 2035.
- LKAB announced its long term strategy to transition from supplier of iron ore pellets to supplier of HBI (or sponge iron as LKAB refers to it) over the period between 2029 and 2045; LKAB plans to operate six hydrogen-based DR plants, three each at Malmberget and Kiruna.
- Salzgitter and partners have commissioned a feasibility study for a 2 mt H_2-based DR plant (with an upstream hydrogen electrolyser) at Wilhelmshaven, Germany. DRI or HBI would be railed about 220 km to Salzgitter's steel plant and

[11] Hydrogen Breakthrough Ironmaking Technology

elsewhere. Per a press release dated April 2019, Tenova will provide the Energiron-ZR-direct reduction technology with integrated CO_2 absorption system.

- As part of its SALCOS concept (Salzgitter Low CO_2 Steelmaking) Salzgitter is also studying a DR plant at its Salzgitter works to produce hot DRI as feedstock for the planned EAF steel shop. Most recently, Salzgitter has concluded a MoU with Tenova whereby, subject to funding approvals, Salzgitter intends to order a 2.1 mt DR plant from Tenova, based on Energiron technology, with construction to start as early as summer 2022.
- voestalpine Stahl plans a progressive shift from the BF/BOF steel production route to the hydrogen-based DR/EAF route with an intermediate step of partial replacement of the BF route with a hybrid electric steel pathway. HBI from the captive Texas plant will be fed to the blast furnaces in Linz and Donawitz as an initial step with construction of a DR plant in Austria post 2030.
- SHS-Stahl-Holding-Saar is participating, together with Paul Wurth and Liberty Steel to study a 2 mt DR plant in Dunkirk France, initially using a mixture of natural gas and hydrogen and eventually 100% hydrogen generated by an integrated hydrogen electrolysis unit, the DRI to be used in Liberty's Ascoval EAF in France, also in Liberty's integrated works at Ostrava and Galati and at the Dillingen and Völklingen steel works in Germany.
- Liberty Steel has also announced its intention to construct a 2.5 mt DR plant at Galati, timing unclear.
- thyssenkrupp Steel's tkH_2Steel project involves a 1.2 mt hydrogen-based DR plant at its Duisburg works from 2024, with an electric melter to be added in 2026, the thus-produced "electric hot metal" to be fed to the existing basic oxygen converters. Ultimately thyssenkrupp's concept envisages replacement of all BF iron with electric hot metal. The technical feasibility and scalability of the concept has been validated in a study commissioned by TKS from RWTH Aachen University.
- Tata Steel Nederland has announced that it intends to go down the hydrogen-based DRI route at its IJmuiden plant, using pellets produced at its in-house pellet plant.
- Swedish company H_2 Green Steel plans a green hydrogen-based 5 mt integrated steel complex at Boden in Sweden, scheduled to start up in 2025 and reach capacity by 2030, based on DRI.
- H_2 Green Steel has also announced a green hydrogen venture in Spain with energy company Iberdrola, with the hydrogen to be supplied to a 2 mt DR plant to be owned and operated by H_2 Green Steel.

In the CIS:

- Metalloinvest in Russia has announced the fourth HBI module at Lebedinsky (2.08 mt) to start up in 2025.
- The group of which Metalloinvest is part has announced a 2.08 mt HBI plant at the Mikhailovsky complex.
- NLMK in Russia has signed a memorandum of intent with Russian authorities covering expansion of the existing open-pit mine to increase iron ore output from 43 Mt to 67 Mt per year, the construction of new beneficiation capacities for a total of 10 Mt of concentrate, a pelletising plant with a capacity of 9 Mt of pellets, and an HBI shop with a capacity of 2.5 mt.
- OMK has announced a 2.5 mt DR plant to be constructed by Danieli at its Vyksa Steel Works (OMK does not own iron ore assets). Commissioning is scheduled for 2025.
- Metinvest in Ukraine is studying an EAF steel mill at its Mariupol or Zaporizhia sites, involving two DR modules, the first apparently to be operational by as early as 2028.

In the MENA region:

- Tosyali Algerie has plans to increase its steel production to 8.5 mt, with a 3.5 mt flat products mill due to start up by end 2022. These expansion plans include additional DRI capacity.
- There are reports that Algerian Qatari Steel is considering a second 2.5 mt DR module.
- Libyan Steel has long been thought to be considering the addition of another DR plant.
- Baosteel of China, together with Saudi Aramco, has an early stage project to construct a DR/EAF steel mill in Saudi Arabia.
- Essar group's RAK Steel project is a planned 3 mt integrated steel complex at Ras Al-Khair in eastern Saudi Arabia, with 5 mt DRI capacity in phase 1 and a further 2.5 mt DRI in phase 2, part of the DRI intended for the merchant market.

In East Asia:

- Tenova has signed a contract with the Chinese HBIS Group for the implementation of the "Paradigm" Project, a High Tech Hydrogen Energy Development and Utilization Plant. The project includes a 0.6 mt Energiron DRI plant to be located in Xuanhua City in Hebei province. The DR plant was scheduled for start up in 2021, but the pandemic and the Olympic Winter Games have delayed the construction work. It is understood that a second phase involving another 0.6 mt DR plant is at the planning stage.

- Baosteel Zhanjiang Iron & Steel Co. Ltd., part of the Baowu Group, has contracted (through Sinosteel Engineering & Technology Co. Ltd.) with Tenova for a 1 mt Energiron ZR[12] DR plant, using mainly hydrogen as reducing gas with the ability to mix hydrogen with natural gas and coke oven gas. The plant will also be designed to capture and sell CO_2 to commercial markets. Ultimately the intention is to use 100% green hydrogen as reducing gas. Production is scheduled to start by end 2023. The next phase will involve and EAF and rolling mill.
- Media references in 2019 cited several other DR projects in China. Inner Mongolia Saispu Technology Company was reported to be constructing a 0.3 mt hydrogen-based DR plant. Other projects mentioned were Taihang Mining (0.3 mt plant), Qinghai QinghuaGroup (0.5 mt plant) and Xiyang New Coal Chemical Industry (0.8 mt plant).
- In 2021 it was reported that MME Company in Iran had concluded an agreement with Chinese company CSTM to construct a 0.3 mt DR plant in Taiyuan City, based on Pered technology.

In North America:

- An April 21st 2021 press release by U.S. Steel stated: "To achieve its net-zero goal for 2050 U.S. Steel expects to leverage its growing fleet of EAFs coupled with other technologies such as direct reduced iron, carbon-free energy sources and carbon capture."
- AM Dofasco announced in July 2021 that, subject to government funding support, its Hamilton, ONT works will transition away from the BF/BOF production route to EAF production, involving a 2 mt DR facility, due to be in production by end 2028.

[12] ZR = zero reformer

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