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June 2022

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Iron Ore Quality a Potential Headwind to Green Steelmaking

Technology and Mining Options Are Available to Hit Net-Zero Steel Targets

Executive Summary

Switching from blast furnaces that consume coal to green hydrogen-based direct reduced iron (DRI) processes is widely considered a key step in the global steel sector's decarbonisation pathway. However, insufficient supply of suitable iron ore is a potential challenge to a global shift towards zero-emissions DRI processes.

Such a shortfall could handicap a faster switch to DRI technology this decade as well as delaying longer term targets to significantly ramp up DRI operations to reach net-zero emissions targets by 2050.

The global steel sector is still largely focused on existing coal-consuming blast furnace operations, giving iron ore miners an incentive to continue producing blast furnace-grade iron ore, rather than ores with higher iron content used for direct reduction (DR-grade). Options to address the issue include increased focus on the development of mines that can produce high-quality iron ores, further processing of existing ores to improve the grade (beneficiation) and technology solutions that enable the use of lower grade iron ore in DRI processes.

Steel Sector Decarbonisation Focused on Green Hydrogen

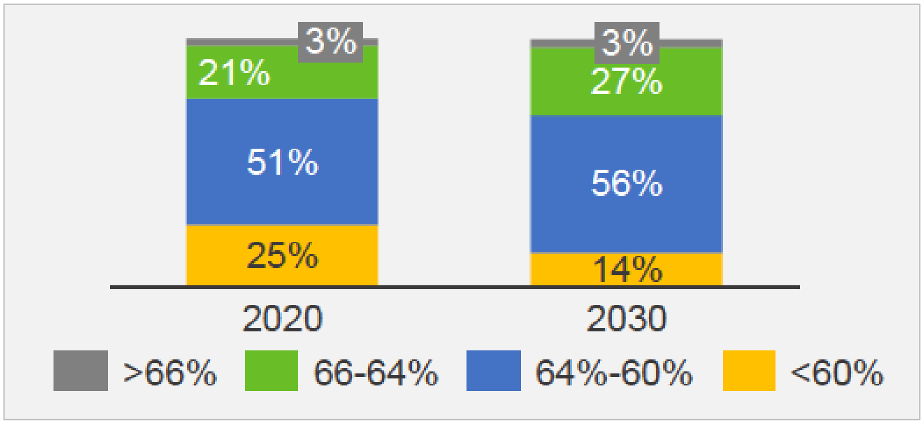
Green hydrogen has gained increasing interest globally as a zero-emissions fuel with the potential to play a significant role in the decarbonisation of many sectors. Green hydrogen can replace fossil fuel-derived hydrogen and carbon monoxide in the DRI steelmaking process, eliminating carbon dioxide emissions. Steel manufacturers are starting to plan pilot or larger scale green hydrogen DRI projects and stating the technology will be an important factor in achieving 2050 net-zero emissions goals.

Steel manufacturers are starting to plan pilot or larger scale green hydrogen DRI projects.

Given that green hydrogen is currently costlier than fossil fuel-based hydrogen, much of the attention given to the future of zero-carbon DRI technology is on green hydrogen cost, scaling up of production and the approaching date at which it becomes cost-competitive.

Another factor has received less attention. DRI steelmaking requires a higher grade of iron ore than blast furnaces, the dominant global process. DR-grade iron ore ideally has an iron (Fe) content of 67% or more and such deposits are scarce -- only a small percentage of global seaborne iron ore comes close to DR-grade (Figure A).

Figure A: Seaborne Iron Ore Supply by Fe Content (%)



Source: Vale.

DRI processes currently account for only a small fraction of global crude steel production. A significant scaling up of global DRI capacity using green hydrogen to reach net-zero emissions in 2050 will require much more iron ore suitable for DRI.

Many net-zero emissions pathways for the steel sector foresee much of the decarbonisation process happening after 2030. However, about 71% of existing global blast furnace capacity will reach the end of its operational life before 2030. To avoid locking in further coal-based steelmaking capacity for decades, some technology switching to DRI-electric arc furnace (EAF) processes will be required before 2030 to achieve net zero by 2050. Agora Industry has already tracked 59Mt of new DRI capacity announcements since 2019, requiring about 80Mtpa of iron ore if all proceed.

The amount of additional DR-grade iron ore capacity to be operational by 2030 is far from certain. In its 2021 iron ore project review, Wood Mackenzie provides data on planned mine projects that are earmarked to start producing ore this decade with Fe content of 67% or higher. This list totals 213Mtpa of new capacity, almost all of them magnetite projects. However, Wood Mackenzie considers only 41Mt of this potential new iron ore capacity to be "probable" or "highly probable" with the remaining four-fifths considered only "possible".

Potential new DR-grade iron ore capacity by 2030 ranges from 40Mtpa to an optimistic high of 100Mtpa. However, according to Wood Mackenzie, there is additional DR-grade ore supply available beyond this should higher demand translate into investment and shift "possible" projects to "probable."

After 2030, DRI capacity expansion will need to accelerate to maintain a net-zero pathway. Bloomberg New Energy Finance (BNEF) anticipates 56% of primary steel production coming from DRI-EAF processes using hydrogen and 3% from DRI-EAF processes based on natural gas by 2050 under a net-zero steel sector scenario. This would mean 840Mt of steel production from DRI-EAF-hydrogen processes and 49Mt from DRI-EAF-natural gas processes by 2050, requiring a tenfold rise in DR-grade supply unless technology innovations allow DRI processes to use lower-grade ore.

The very long lead times for new iron ore projects limit the ability of miners to quickly change their product quality mix.

Big Four Iron Ore Miners Largely Focused on Supplying Blast Furnaces

BHP CEO Mike Henry stated in October 2021 that hydrogen-based steelmaking may still be 20 to 30 years away and that steel sector decarbonisation must remain focused on lower emissions from blast furnaces. BHP has stated "there is simply not enough high-quality iron ore suitable for efficient DRI/EAF production to meet the global steel demand…DRI production must use the very highest quality iron ore, with an average iron content in the range of 67%. Such deposits are scarce."

Rio Tinto sees the decarbonisation of the steel industry happening in at least three phases. Phase 2 involves the roll out of DRI technology using hydrogen. However, the first phase – and the focus of Rio's current attention – is to reduce the emissions of blast furnaces, technology that can use its relatively lower-grade but highly profitable Pilbara iron ores.

In addition to being one of the biggest overall producers, Vale is also the world's largest supplier of high-grade iron ore pellets for DRI plants and blast furnace operations. Vale has stated: "Main ore bodies available face depletion and beneficiation challenges, thus making it difficult to increase supply of high-grade ores." Vale forecasts that, although there will be a shift towards higher quality iron ore over the rest of this decade, there will be no change in the proportion of seaborne iron ore supply over 66% Fe by 2030, remaining at just 3% of the total as it was in 2020 (Figure A).

Fortescue Metals Group (FMG) is committed to developing magnetite ore reserves at its Iron Bridge project, which could potentially add to DR-grade iron ore supply. However, the company has also highlighted that the Iron Bridge product may be blended with its lower quality iron ores to meet market demand. In that case, the resulted blended product will be below DR-grade and intended for blast furnaces.

Outside of the big four, iron ore projects that could potentially increase supply of DR-grade ore are in early stages of development.

Options to Enable Global DRI Expansion Going Forward

The availability of DR-grade iron ore is a potential challenge to the global expansion of DRI technology. Among options to address this issue is a significant switch in iron ore mining focus from hematite towards magnetite. Magnetite ores tend to have a much lower Fe content but are often suitable for significant beneficiation, in part because magnetite is magnetic, enabling easier separation. These can often be beneficiated to DR-grade.

Another option is to improve the quality of hematite iron ores through beneficiation. Some beneficiation has been introduced to Pilbara ores but despite this, the trend in Fe content of Pilbara ores has been to decline as volumes increased. There is renewed interest in making Pilbara iron ores suitable for low-emissions steel -- the Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT-CRC) has a program on the production of green iron products from Pilbara iron ores.

As a result of long lead times for new magnetite project proposals and beneficiation challenges, more DRI may need to be made using lower-grade iron ore. This will necessitate melting the reduced iron before being charged into a basic oxygen furnace. This type of technology combination is being investigated by Rio Tinto in partnership with BlueScope Steel as well as ArcelorMittal. ThyssenKrupp is planning to begin replacing blast furnaces with DRI plants with integrated melting units from 2025.

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Outside of DRI technology, there is also the longer-term potential for new steelmaking processes that are not impacted by the quality of iron ore. Iron ore electrolysis, an early-stage technology that BNEF foresees as reaching commercial readiness by 2035, is not limited to using high-grade ore.

Further support for green steel demand will likely be needed if steelmakers are to accelerate their low-emissions technology transition and iron ore miners are to increase focus on developing higher grade ore projects. Technology enabling low- or zero-emissions steelmaking using lower grade ore is in the early stages of development but such transitions have a habit of happening faster than expected. Evidence of this is the fast maturation of wind and solar power, which were expensive a decade ago but are now set to dominate power generation additions.

When it comes to carbon emissions, steel has a reputation as a “hard to abate” sector. The challenge imposed by limited DR-grade iron ore supply on plans for a large global scale-up of DRI production is significant. Given long mining lead times and technology development requirements, the focus on potential solutions must increase immediately.

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Introduction

Green hydrogen has gained increasing interest globally from policy makers, corporations and financial markets as a zero-emissions fuel with the potential to play a significant role in the decarbonisation of many sectors.

One key sector is steelmaking. Green hydrogen can replace fossil fuel-derived hydrogen and carbon monoxide in the direct reduced iron (DRI) steelmaking process, eliminating carbon dioxide emissions. Steel manufacturers are increasingly announcing pilot and larger scale green hydrogen DRI projects, stating the technology will be an important factor in achieving 2050 net-zero emissions goals.

DRI technology will be an important factor in achieving 2050 net-zero emissions goals.

Given that green hydrogen is currently costlier than fossil fuel-based hydrogen, much of the attention given to the future of zero-carbon DRI technology is on the expected green hydrogen capital and operational cost reductions, scaling up of production and the approaching date at which it becomes cost-competitive.

However, there is another key factor that has been given less attention. DRI steelmaking requires a higher grade of iron ore (DR-grade) than blast furnaces, which dominate steelmaking globally. Supply of DR-grade iron ore is currently limited by demand – steelmaking via DRI processes makes up only a small fraction of global crude steel production. If there is to be a significant scaling up of global DRI capacity using green hydrogen to reach net-zero emissions in 2050, much more DR-grade iron ore will be required.

In this report, we look at the current status of DR-grade iron ore and the plans of the major iron ore producers to determine how much of a headwind iron ore quality might be to steel sector decarbonisation.

Overview of Steel-Making Technology

There are three main steel production processes. The most widespread is the integrated blast furnace and basic oxygen furnace process (BF-BOF), in which iron oxide is reduced to iron inside the blast furnace with coke (derived from coking coal) as a reducing agent. The product of the blast furnace, carbon-rich pig iron, is then processed into steel in a basic oxygen furnace, where oxygen is blown through the molten pig iron to reduce its carbon content. In 2020, global crude steel production totalled 1.88 billion tonnes, and of this 73% was made via the BF-BOF process.[1]

[1] World Steel Association. World Steel in Figures. 2021.

A second primary steelmaking pathway is to produce direct-reduced iron (DRI), which is then further processed into steel in an electric arc furnace (EAF). DRI is produced by direct reduction of iron ore without melting, usually using a mixture of carbon monoxide and hydrogen derived from natural gas, although these can also be derived from gasified coal. DRI does not use coking coal. An increasing number of steel companies are seeking to develop technology that uses 100% hydrogen in the DRI-EAF process -- potentially zero-carbon green hydrogen, produced via renewable energy-powered electrolysis once this technology becomes cost competitive.

As an alternative to primary steel manufacture, scrap steel can be recycled. Also called secondary steelmaking, this technology does not require iron ore or coking coal. An electric arc furnace is charged with steel scrap, which is melted to form new steel. Renewable energy can power EAFs, reducing carbon emissions for the scrap-EAF process to almost zero.

In 2020, steel produced from EAFs amounted to 26% of total global crude steel production. Some of this was produced via the DRI-EAF route in countries like India and Iran but the bulk of production came from the secondary scrap-EAF process, with the U.S. the global leader in scrap steel recycling.

The DRI-EAF route has lower emissions than BF-BOF, the relevant figures being 1.4 and 2.2 tonnes of CO_2 emission per tonne of crude steel respectively (Table 1). The DRI-EAF route also has zero emissions potential if green hydrogen is used and the EAF is powered by renewable energy. The secondary steelmaking route has much lower emissions than both primary routes given its lower energy consumption. This route also has the potential to be zero emissions when powered entirely by renewables.

Table 1: Carbon Emission and Energy Consumption of Different Steelmaking Routes

Sources	Technology Route	Direct CO_2/(t) Crude Steel (t)	Direct and Indirect* CO_2/tonne of Crude Steel	Energy Consumption (GJ/t)		Share of Global Steel Production (%)
				IEA	Worldsteel**	
Secondary	Scrap-EAF	0.04	0.3	2.1	5.2	21.5
Primary	BF-BOF	1.2	2.2	21.4	22.7	73.2
	DRI-EAF	1.0	1.4	17.1	21.8	4.8

Source: IEA, World Steel Association, IEEFA calculate/n.

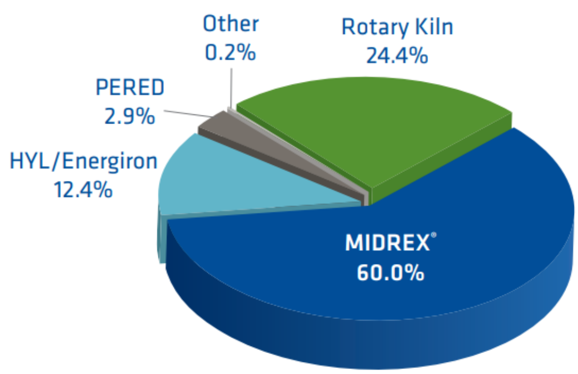
**Indirect emission emissions are indirect GHG emissions from the generation of purchased energy consumed by a company.*
***The IEA states all energy intensities in final energy terms, whereas Worldsteel accounts for electricity consumption in primary energy terms, using a conversion factor of 9.8 GJ of fuel per MWh of electricity (equivalent to a 37% conversion efficiency). This means that processes that consume electricity will appear more energy intensive when quoted using the Worldsteel analytical boundary, relative to the one used by the IEA.*

Current Direct Reduced Iron Processes

In 2020 global DRI production was 104.4 Mt,[2] about 8% of total global iron production.[3]

DRI can be gas-based or coal-based. The gas-based DRI process includes MIDREX and HYL, which are the preferred technology in countries where natural gas is abundant. The coal-based DRI process generates the reducing gas via gasification of coal. Typical examples of the coal-based process include the SL/RN and ACCAR processes. Figure 1 shows the share of the leading DRI production technologies.

Figure 1: World DRI Production 2020 by Technology



Total World Production: 104.4 Mt

	2018	2019	2020
MIDREX®	61.5%	60.5%	60.0%
HYL/Energiron	15.7%	13.2%	12.4%
PERED	2.4%	2.1%	2.9%(e)
Other	0.2%	0.2%	0.2%
Rotary Kiln	20.2%	24.0%	24.4%

(e) estimated

Source: Midrex Technologies, Inc.

Source: Midrex, Note: PERED is gas-based technology and Rotary Kiln is coal-based.

India produced 32.98 Mt of DRI in 2020 – 25.34Mt in coal-based rotary kilns and 7.64Mt by gas-based processes,[4] using domestic iron ore resources. Iran produced 30.2Mt all from natural as. Iran also relies on domestic magnetite reserves for producing DR-grade iron ore. With total proven iron ore reserves estimated to be about 3.3 billion tonnes. Iran produced nearly 50Mt of iron ore concentrate[5] and 46Mt of pellets in the year to March 2020.[6]

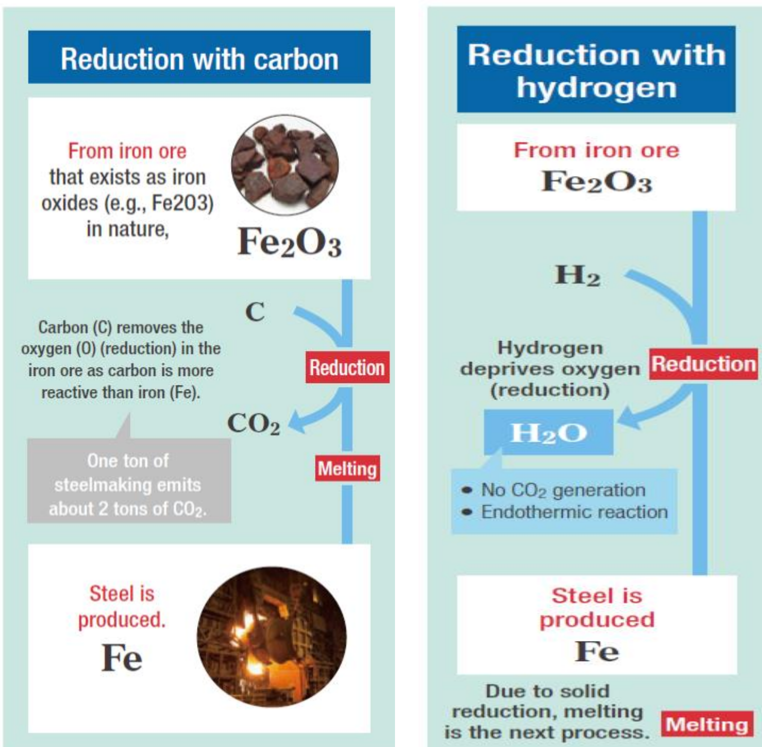
Russia and Saudi Arabia produced 7.93Mt and 5.19Mt DRI respectively. Historically low gas price is the main driver for Middle Eastern producers to adopt DRI technology over blast furnaces. Lack of access to high quality coking coal in India and the Middle East is another reason for them to use DRI technology. However, India has large reserves of lower quality coal that it gasifies to use in DRI. Coal-based DRI produces high carbon emissions, comparable to that of blast furnace technology.

[2] Midrex. World Direct Reduction Statistics. 2020.
[3] Fastmarkets. Understanding the high-grade iron ore market. March 2021.
[4] Midrex. World Direct Reduction Statistics. 2020.
[5] Iran daily. Iran's 12-month iron ore concentrate production near 50m tons. 13 April 2021.
[6] Tehran Times. Annual iron ore pellet output up 10%. 21 April 2021.

Potential for Green Hydrogen Use in DRI

In the DRI process, iron oxide is reduced via carbon monoxide (CO) and hydrogen (H_2) produced from the reforming of natural gas in the shaft furnace route or coal gasification in the rotary kiln route. One of the most promising routes to decarbonisation of the steel industry is to replace these fossil-fuel based gases with green hydrogen produced via the electrolysis of water, powered by renewable energy.

Figure 2: Iron Ore Reduction via Carbon and Hydrogen

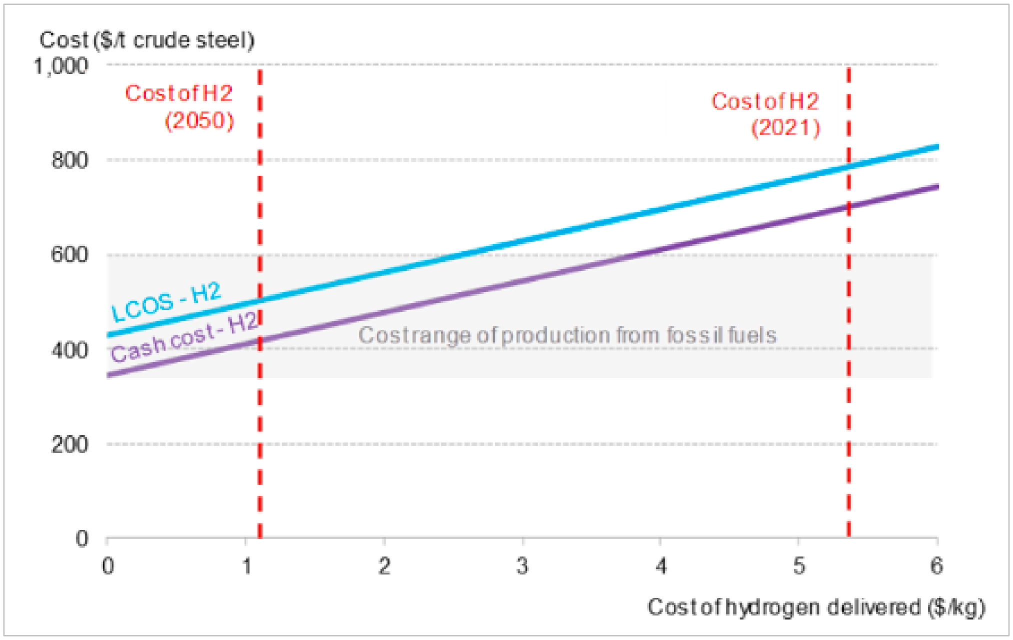


Source: Nippon Steel.

The cost of green hydrogen is expected to decline significantly as renewable energy and electrolyser costs come down. Bloomberg New Energy Finance (BNEF) projected that the delivered cost of hydrogen to a large-scale user could fall to US$0.8 -US$1.5/kg by 2050 in most countries,[7] reducing the levelised cost of the steel from DRI processes using green hydrogen and making it cost-competitive with fossil fuel-based processes (Figure 3).

[7] Bloomberg New Energy Finance. Decarbonising Steel. 25 August 2021.

Figure 3: Levelised Cost of Steel with Hydrogen Prices, 2050



Source: BloombergNEF.
Note: Capex, opex and hydrogen price assumptions are based on Germany. The cost range of production from fossil fuels represents cost for new build steel plants.

This assumes business-as-usual costs for BF-BOF processes although it is highly likely that such operations will incur additional costs in the form of carbon prices or retrofits to reduce emissions, which will bring forward cost-competitiveness for green hydrogen-based DRI. McKinsey estimates that a carbon price of US$50-100/tonne is sufficient to make steelmaking using green hydrogen cost competitive in most regions.[8] The EU carbon price was close to €100/tonne in early February 2022 although steelmakers in Europe currently receive free carbon permits.[9]

Furthermore, green hydrogen will quickly outcompete fossil fuel-based hydrogen with carbon capture (blue hydrogen). According to Australia's Clean Energy Finance Corporation (CEFC), green hydrogen will cost less than blue hydrogen in Australia by 2030 due to economies of scale and declining renewable energy costs[10] as well as escalating gas prices.

Iron Ore Market

The iron ore market is a mixture of various types of iron ores and products categorised according to physical characteristics and chemistry. Fe content, gangue (the commercially worthless material within the ore deposit – mainly silica and

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[8] McKinsey and Company. Hydrogen for Net-Zero: A critical cost-competitive energy vector. November 2021.
[9] Reuters. Europe's carbon price nears the 100 euro milestone. 6 February 2022.
[10] S&P Global. Renewable hydrogen 'cheaper than conventional hydrogen' by 2030: Australia CEFC executive. 27 October 2021.

alumina) and the size of the products are among the most important characteristics that affect iron ore value realisation. The most common iron ore products are listed in Table 2.

Table 2: Most Common Grades of Iron Ore

Description	Size (mm)	Preparation Process	Global Export Share
Lump Ore	>6.3	Direct charge in blast furnace	17%
Sinter Fines	<6.3	Agglomeration (Sintering)	70%
Pellet (BF Grade) 65%	9-16	Direct charge in blast furnace following beneficiation and agglomeration (pelletising)	5%
Pellet Feed concentrate	More than 80% is <0.15	Agglomeration (pelletising)	6%
Pellet (DR Grade) 67%	9-16	Direct charge in DR Shaft following beneficiation and agglomeration (pelletising)	4%

Source: Fastmarkets, IEEFA.

The majority of iron ore is produced in the form of fines. These cannot be charged directly into a blast furnace but have to be agglomerated into sinter or pellets first. Lump ore is valued as it is already appropriately sized for direct charge into a blast furnace without the extra cost of sintering or pelletising.

High grade (high iron content) pellets form a much smaller part of the market with most pellets used as a higher-grade blast furnace feed and a smaller supply for existing DRI plants. The Fe content of pellets used in blast furnaces is lower than that of DR-grade pellets.

Ore Types

Hematite is the most important ore of iron. It is the most commonplace iron ore globally; the recovery process is simple and with physical grinding and screening it is ready for ironmaking. The majority of the direct shipping ores (DSO) are hematite products including Australia's Pilbara region mid-grade iron ore and Vale's high-grade, 65% Fe fines from Brazil.[11]

Magnetite ore is often more suitable and preferable for further processing and producing high-grade concentrate and pellets used in DRI production or blast furnaces. Magnetite can also be used in blast furnaces if passed through sintering plants. Technically it is possible to produce iron ore concentrate and pellets from both hematite and magnetite, though the latter's exothermic reaction in the

[11] Fastmarkets. Understanding the high-grade iron ore market. 2021.

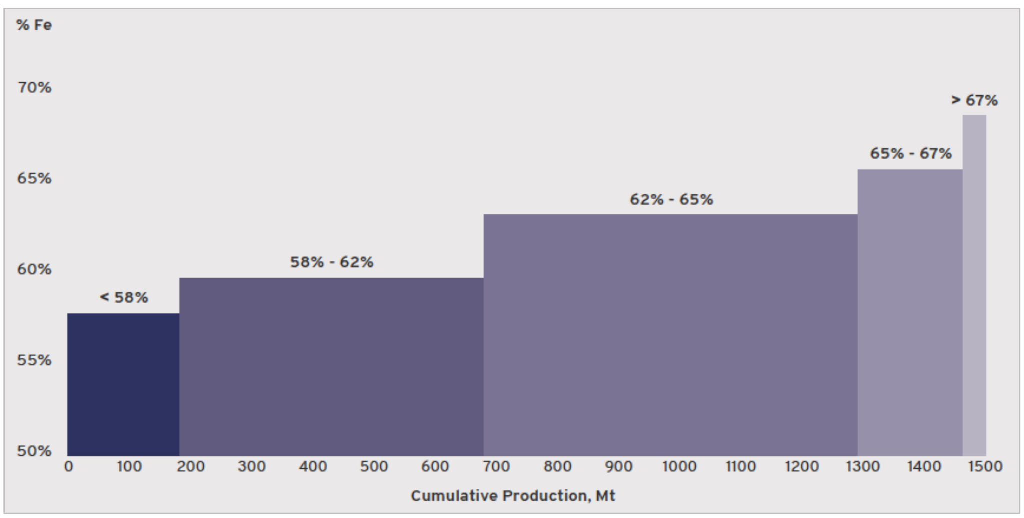
sintering or pelletising process makes it more economical to produce due to lower fuel consumption.

Recovering other iron-bearing ores such as goethite and limonite is more complicated due to higher levels of impurities, making it a more costly and energy-intensive processes.

Iron Ore quality

In global iron ore trading, 62% Fe fines is a benchmark for pricing. Premiums or discounts apply to ore with higher or lower Fe content.[12] Steel mills running blast furnaces may also favour higher Fe content during times of higher coking coal prices as less coal is needed to process such ore. Blast furnace operations seeking to reduce carbon emissions may gravitate to higher Fe% ores, although these would not be the very high-grade ores suitable for DRI. Only a small percentage of global seaborne iron ore supply comes close to DR-grade, 67% Fe (Figure 4).

Figure 4: Seaborne Iron Ore by Fe (%)



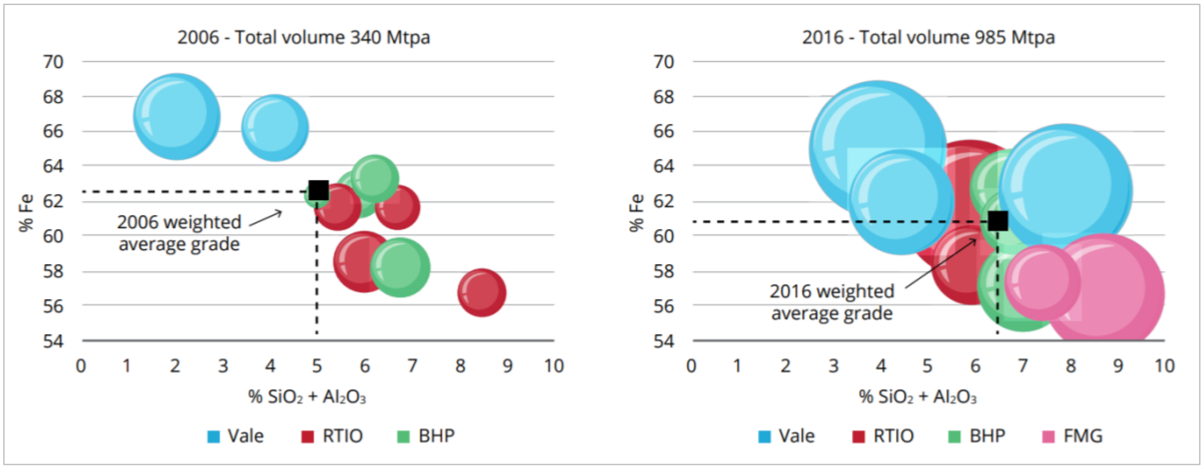
Source: Mission Possible Partnership: Net Zero Steel Sector Transition Strategy.

However, the average quality of iron ore has been in decline for years as higher grades have been mined out and supply was significantly expanded to meet rapidly growing Chinese demand.

Figure 5 illustrates the deterioration of iron ore quality produced by the big four mining companies (Rio Tinto, Vale, BHP and FMG) from 2006 to 2016, as well as the massive scaling up in lower grade ore capacity. Formerly, the average Fe% was above 62% with 5% impurities (gangue) but by 2016 the respective figures were 61% and 6.5%.

[12] Australian Financial Review. Fortescue exports, price penalties soar. 25 January 2022.

Figure 5: Big Four Miners Fe% and Acidic Gangue 2006 and 2016



Source: Minerals Council of Australia,

DRI Dependent on Higher Quality Iron Ore

As the DRI process reduces the iron oxide to iron without melting or refining, the impurities remain and could be detrimental to the steelmaking process in EAFs.

Higher iron (Fe) content in iron ore means fewer impurities. DRI production currently must use the highest quality iron ore (DR-grade), with an average iron content of 67% or more.[13] Such deposits are scarce and only a few producers globally are able to supply DR-grade iron ore pellets and occasionally lump ore.[14] Fe content often needs to be improved via beneficiation including concentrating and pelletising before reaching DR-grade. The availability of DR-grade lump ores with high enough Fe content is becoming increasingly limited so pelletised ore is the primary feedstock for DRI processes globally.[15]

The presence of impurities (gangue) such as silica, alumina, phosphorus and sulphur can affect the EAF process. Silica and alumina content needs to be particularly low to avoid significantly higher costs at the EAF stage. The percentage of both should preferably be below 2%. Excessive gangue not only needs more electric power in the EAF but lowers the melting yield, increasing the cost of the liquid steel significantly.[16]

[13] Midrex. Adapting to Raw Materials Challenges: Part 1-Operating MIDREX Plants With Lower Grade Pellets & Lump Ores. March 2021.
[14] Fastmarkets. Understanding the high-grade iron ore market. March 2021.
[15] Midrex. Maximizing Iron Unit Yield from Ore to Liquid Steel (Part 1 – Ore Selection). December 2019.
[16] Midrex. Maximizing Iron Unit Yield from Ore to Liquid Steel (Part 1 – Ore Selection). December 2019.

Removing sulphur and phosphorus also requires extra processes, again resulting in product yield loss in the slag and adding to the final product's cost.

Table 3 shows the acceptable range of the ore constituent in DRI plants.

Table 3: DR-grade Iron Oxide Chemical Quality Limits (%)

Sources	Practical Limits	Preferred Limits
Iron (Fe)	66.0 Min.	67.0 Min.
Silica Oxide (SiO_2) & Aluminium Oxide (Al_2O_3)	3.5 Max.	2.0 Max.
Calcium Oxide (CaO)	2.5 Max.	
Magnesium Oxide (MgO)	1.0 Max.	
Phosphorus Pentoxide (P_2O_5)	0.03 Max.	0.015 Max.
Sulphur (S)	0.025 Max.	0.015 Max.
Copper (Cu)	0.03 Max.	0.01 Max.
Titanium dioxide (TiO_2)	0.35 Max.	

Source: Midrex.

DR-Grade Iron Ore Demand Set to Rise

Some steel companies, particularly in Europe, are starting to invest in new DRI capacity as they begin to chart their course towards decarbonisation. As a result, demand for DR-grade iron ore is set to rise, starting this decade.

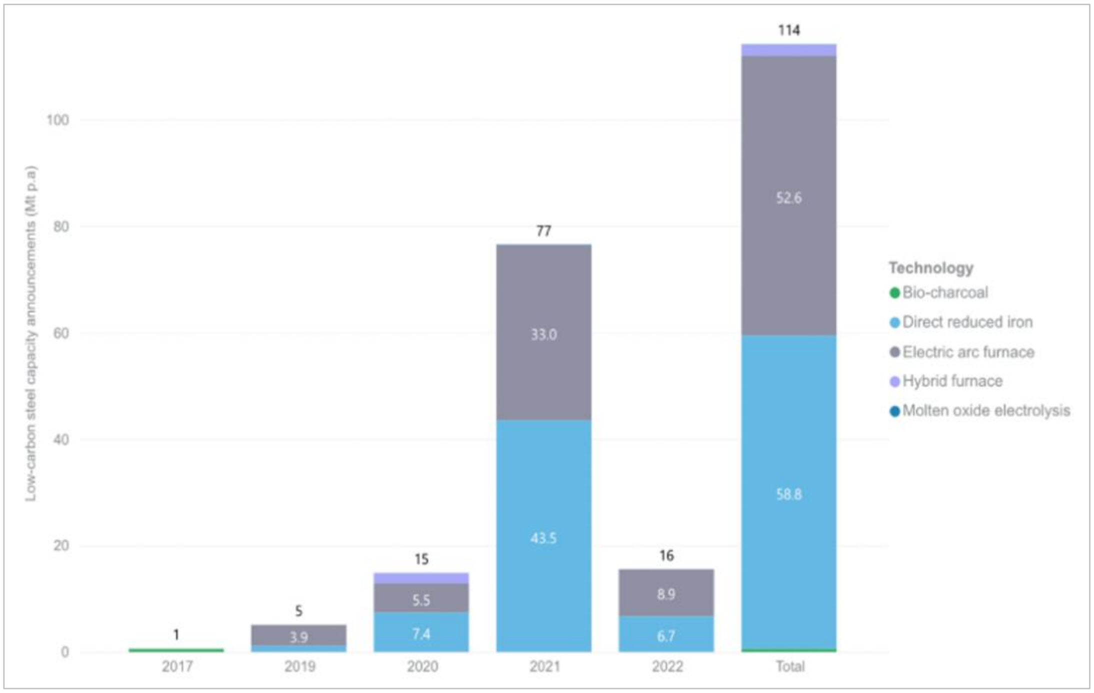
2030 Demand

The International Iron and Metallics Association (IIMA) estimates that merchant DR-grade pellet demand may grow from about 38Mt in 2020 to 81Mt by 2030, an increase of 43Mt, at which point supply may struggle to meet demand.[17] However, this may already be an under-estimate of DR-grade ore demand growth considering the growing number of DRI project announcements. If steelmakers go ahead with investment decisions, demand will increase even further by 2030 Agora Industry has already tracked 59Mt of new DRI capacity announcements since 2019[18] (Figure 6), which would require iron ore supply of about 80Mtpa if all proceed.

[17] S&P Global. DRI to underpin carbon-neutral steel; growth needed in pellet supply. 18 January 2022

[18] Agora Industry. Global Steel Transformation Tracker

Figure 6: Global Low-Carbon Iron and Steelmaking Announcements to be Operational Prior to 2030



Source: Agora Industry based on Green Steel Tracker, Last update 14 March 2022.

Any DR-grade ore supply restrictions threaten potential acceleration in steel sector decarbonisation via a more rapid roll-out of DRI technology. Many net zero emissions pathways for the steel sector anticipate much of the decarbonisation process happening after 2030. However, about 71% of existing global blast furnace capacity will reach the end of its operational lifetime before 2030.[19] To avoid locking in further coal-based steelmaking capacity for decades, some technology switching to DRI processes will be required before 2030 if the sector is to place itself on a net-zero by 2050 pathway. Global steel emissions will need to drop 50% by 2030 for the sector to be on a pathway to limit warming to 1.5°C, according to a study by E3G and the Pacific Northwest National Laboratory.[20]

The amount of additional DR-grade iron ore capacity to be operational by 2030 is far from certain. In its 2021 iron ore project review, Wood Mackenzie provides data on planned mine projects that are earmarked to start producing ore this decade with Fe content of 67% or higher. This list totals 213Mtpa of new capacity, almost all of them magnetite projects.[21] This would be sufficient supply for the production of about 150Mtpa of DRI. However, Wood Mackenzie considers only 41Mt of this potential new iron ore capacity to be "probable" or "highly probable" with the great majority considered only "possible".

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[19] Agora Industry. Global Steel at a Crossroads. November 2021.
[20] E3G & Pacific Northwest National Laboratory. 1.5°C Steel: Decarbonising the steel sector in Paris-compatible pathways. October 2021.
[21] Wood Mackenzie. Iron ore project review 2021.

Alternatively, the IIMA has presented a list of projects that could potentially supply DR-grade ore, totalling more than 140Mtpa.[22] However, it is not clear that all projects could be running or at full capacity by 2030. The IIMA includes projects not on Wood Mackenzie's listing of >67% Fe projects and others that Wood Mackenzie lists as "possible" projects.

From the data in these two lists, it could be considered that likely potential new DR-grade iron ore capacity by 2030 ranges from 40Mtpa to perhaps 100Mtpa as an optimistic high end. However, the Wood Mackenzie data demonstrates that there is additional DR-grade ore supply available beyond this should higher demand translate into investment and shift "possible" projects to "probable."

2050 Demand

In scenarios where the steel sector reaches net-zero emissions by 2050 (as an increasing number of major steelmakers have pledged to do), the role of DRI is greatly expanded, as is the potential DR-grade iron ore shortfall.

Under its net-zero emissions scenario (NZE), the International Energy Agency (IEA) foresees that much of the global carbon emissions reductions up until 2030 come from scrap steel recycling as more scrap becomes available. The use of hydrogen in blast furnaces and DRI plants begins from the mid-2020s in this scenario. However, after 2030 most emissions reductions come from a significant roll out of hydrogen-based DRI and iron ore electrolysis (see Iron and Steel Technology Options below). The IEA foresees that hydrogen-based DRI-EAF steelmaking would account for only 2% of primary steel production in 2030, but this increases to 29% in 2050 under the NZE scenario.[23]

Typically for an IEA scenario, there is a large role foreseen for carbon capture, usage and storage (CCUS) -- 53% of primary steel production in 2050 is produced from CCUS-equipped processes under the NZE scenario, despite little sign of widespread uptake of this technology among steelmakers. No steelmaker has announced an industrial-scale CCUS installation for coal-based processes.[24] The one project in existence for gas-based DRI production, in the United Arab Emirates (UAE), uses the captured carbon for enhanced oil recovery, thereby enabling the release of further carbon emissions.

Other scenarios aligned with net-zero emissions by 2050 rely on an even greater role for DRI (and smaller role for CCUS). The Mission Possible Partnership's net-zero pathway modelling suggests DRI-based steelmaking's share of primary production could grow from 5% currently to more than 50% by 2050 even with business-as-usual global steel production growth reaching about 2.6 billion tonnes by 2050.[25] In a scenario where global warming is limited to 1.5°C, DRI-EAF steelmaking processes account for 37% of global steel production by 2050 using

[22] IIMA. Outlook for DR grade iron ore: issues and challenges for the industry. March 2021.
[23] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. May 2021.
[24] Agora Industry. Global Steel at a Crossroads. November 2021.
[25] Mission Possible Partnership. Net Zero Steel: Sector Transition Strategy. October 2021.

both hydrogen and natural gas as reductants, according to E3G and the Pacific Northwest National Laboratory.[26]

In a net-zero steel sector by 2050 scenario, BNEF anticipates 56% of primary steel production coming from DRI-EAF processes using hydrogen and 3% from DRI-EAF processes based on natural gas. Based on total steel production of 2,747Mt and primary steel production of 1,513Mt, this would mean 840Mt of steel production from DRI-EAF-hydrogen processes and 49Mt from DRI-EAF-natural gas processes by 2050[27] (totalling 889Mt), requiring a tenfold increase DR-grade iron ore supply unless technology innovations allow DRI processes to use lower-grade ore (Table 4, Figure 7).

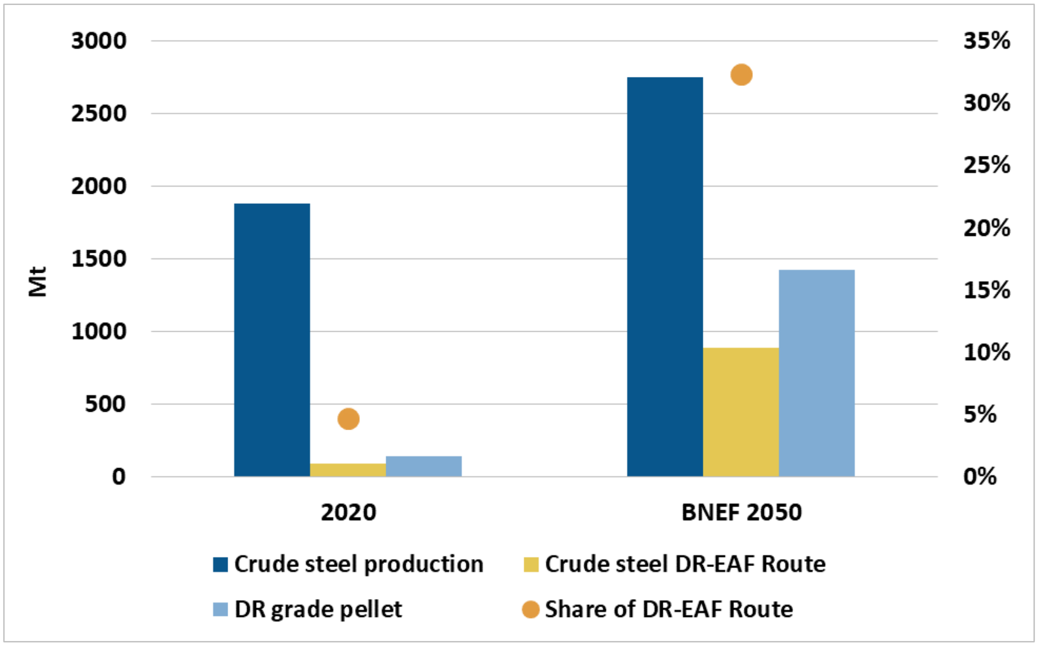
Table 4: DR-Grade Pellet Demand Under BNEF Net Zero Emissions 2050 Scenario (NZE 2050)

	2020	BNEF NZE 2050
Global crude steel production (Mt)	1,878	2,747
DRI-EAF steel production (Mt)	89	889
Direct reduced iron production (Mt)	104	1,040
DR-grade pellet requirement (Mt)	141	1,415
Share of DRI-EAF Route	5%	32%

Source: BloombergNEF, Worldsteel, Midrex, IEEFA calculations.
Note: Assumed conversion ratios are; iron ore pellet to DRI - 1.36 and DRI to crude steel - 1.17. BNEF similarly assumes of 1.6 tonnes of iron ore to 1 tonne of crude steel for DRI-EAF processes.[28]

[26] E3G & Pacific Northwest National Laboratory. 1.5°C Steel: Decarbonising the steel sector in Paris-compatible pathways. October 2021.
[27] BNEF. Decarbonizing Steel: A Net-Zero Pathway. 1 December 2021.
[28] BNEF. Decarbonizing Steel: Technologies and Costs. 25 August 2021.

Figure 7: DR-Grade Pellet Demand Under BNEF Net Zero Emissions 2050 Scenario (NZE 2050)



Source: BloombergNEF, Worldsteel, Midrex, IEEFA calculations.

Outlook of Major Iron Ore Producers

The big four global iron ore miners have, to varying degrees, begun to look at reducing their Scope 3 carbon emissions – the emissions that occur when their mining products are processed by customers. The Scope 3 emissions of iron ore are very significant due to the carbon-intensive blast furnaces which account for the majority of steelmaking and use coking coal.

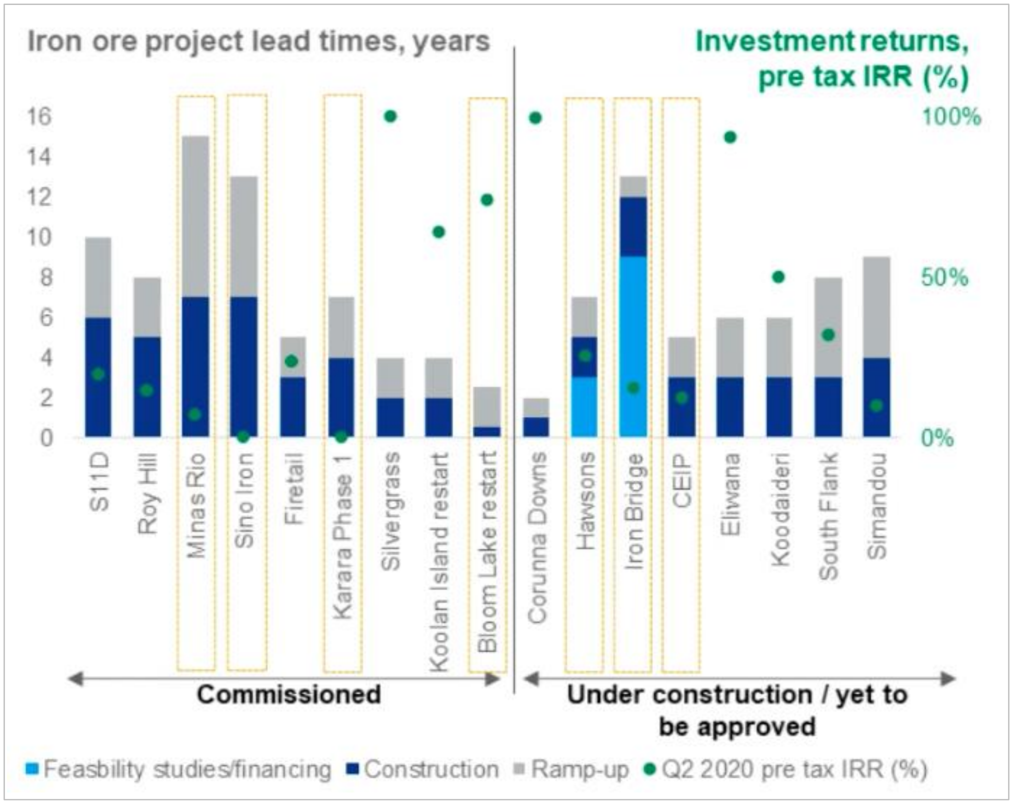
However, despite DRI using green hydrogen having been identified as a key technology for the steel sector to reach net-zero emissions, iron ore miners remain focused on the production of iron ore for blast furnaces. This is a result of historical demand from steelmaking customers who – while sometimes planning or initiating pilot DRI plants – remain focused on the dominant blast furnace technology. Where iron ore miners seek to improve the quality of their production, it is largely for the purpose of meeting the needs of blast furnace operations rather than meeting DR-grade requirements.

The iron ore industry needs 100Mt of new mining capacity each year just to replace depleting mines and maintain current global production of mainly blast furnace-grade ore. This remains the focus of the major iron ore miners and the volumes being planned and developed by junior miners are relatively small.[29]

[29] Reuters. Column: Iron ore may see structural shift on lack of new supply, decarbonisation. 30 March 2022

In addition, the ability of iron ore miners to change their product quality mix in response to shifts in demand is limited by the very long lead times for new iron ore projects (Figure 8).

Figure 8: Iron Ore Project Lead Times (Years)



Source: Wood Mackenzie.
**Orange boxes indicate iron ore pellet feed projects.*

BHP

BHP produced 253.5Mt of iron ore in FY2021.[30] In its 2021 Climate Transition Action Plan, BHP notes that the iron ore it produces is used almost exclusively in BF-BOF steelmaking operations. The company also acknowledges that 34% of its current iron ore sales are to customers that have made commitments to reach net-zero emissions.[31] This percentage will only grow.

BHP does not have a measurable target to reduce total Scope 3 carbon emissions that occur when its customers use its iron ore and metallurgical coal. Instead, BHP is entering into partnerships with some of those customers to fund research and development into steel decarbonisation.

[30] BHP. Operational Review for the year ended 30 June 2021. 20 July 2021.
[31] BHP. Climate Transition Action Plan 2021.

When it comes to improving the quality of iron ore to help reduce carbon emissions in the steel industry, BHP is clearly focussing on incremental reductions at BF-BOF operations and does not consider that DRI will play a major part in that decarbonisation any time soon. BHP CEO Mike Henry stated in October 2021 that hydrogen-based steelmaking may still be 20 to 30 years away, in contrast to many more positive views on the rate of steel technology transition, and that steel sector decarbonisation must remain focused on lower emissions from blast furnaces.[32] Henry noted that this needs to be achieved by improving quality of iron ore (although not to DR-grade) and use of high quality coking coal, which BHP ships in very great quantities as the world's largest seaborne coking coal producer.

BHP does not consider DRI will play a major part in steel decarbonisation any time soon.

As at 30 June 2021, the iron content of BHP's proved and probable reserves ranges between 57.2% and 62.4%, well below that required by DRI plants assuming no beneficiation.[33]

BHP owns 50% of Samarco, whose operations in Brazil were suspended after its catastrophic dam failure in 2015. Samarco had been a major producer of DR-grade pellets with output 29Mt of DR-grade and BF-grade products before the disaster.[34] Samarco restarted operations in January 2021 with BF-grade output and began producing DR-grade pellets the following March, at a greatly reduced level. Total output is expected to be about 7.5Mtpa for the first few years of resumed operation.[35] The company expects to be operating at its full capacity of about 30Mtpa by 2030.[36]

However, BHP considers that the majority of the world's steel will still be produced via the BF-BOF route in 2050.[37] This is in contrast to the technology pathways that enable the steel sector to reach net-zero emissions by 2050 in the scenarios of the IEA and BNEF. The IEA projects that coal's share in steel manufacturing's total

[32] S&P Global. Steelmakers must focus on decarbonising blast furnace use: BHP CEO. 7 October 2021.
[33] BHP. Annual Report 2021.
[34] Australian Financial Review. BHP to restart ore mining five years after fatal dam burst. 16 December 2020.
[35] S&P Global. Brazil's Samarco starts shipping DR iron ore pellets after restart. 29 March 2021.
[36] Australian Financial Review. Creditors want to loosen BHP's grip on Samarco. 9 March 2022.
[37] BHP. Pathways to decarbonisation episode two: steelmaking technology. 5 November 2020.

energy use drops from 75% in 2020 to just 22% by 2050 and even the remaining coal use is dependent on a roll-out of as yet unproven carbon capture technology.[38]

BHP's view that green hydrogen-based DRI will fail to take off any time soon is in part due to a lack of suitable iron ore supply: "There is simply not enough high-quality iron ore suitable for efficient DRI/EAF production to meet the global steel demand… DRI production must use the very highest quality iron ore, with an average iron content in the range of 67%. Such deposits are scarce."[39]

The company is considering the potential for iron ore beneficiation to reduce steelmaking carbon emissions. BHP acknowledges that future advancements in beneficiation and EAF technology may lead to a greater proportion of its iron ore being used in DRI-EAF steelmaking in the longer term. However, its main focus remains on BF-BOF operations: "We are currently assessing the opportunity to implement beneficiation at our Jimblebar operation. By improving our product quality, we can support emissions reduction in the short- to medium-term within the integrated BF-BOF steelmaking process."[40]

Rio Tinto

As with BHP, Rio Tinto does not have a measurable target to reduce total Scope 3 carbon emissions.

Rio has noted that 95% of its Scope 3 emissions occur when customers process its iron ore, bauxite and other products. Of these emissions, 94% take place in China, Japan and South Korea. The latter two have pledged to reach net zero emissions by 2050 and China by 2060. Among Rio's iron ore customers, 28% already have public decarbonisation targets and have announced ne- zero emissions ambitions.[41]

Also as with BHP, Rio has entered into partnerships with some of its iron ore customers (Baowu, Nippon Steel, POSCO, BlueScope) to explore reducing carbon emissions from steelmaking. However, Rio appears to be a little more positive about the role of green hydrogen-based DRI in reaching net-zero emissions by 2050.

Rio Tinto's chief technical officer Mark Davies has stated that the company is developing a project to produce DRI using hydrogen at its Canadian iron ore business – Iron Ore Company of Canada (IOC).[42] IOC produces high iron content pellets and concentrate and will provide DR-grade pellets to the project.[43] IOC produces only a fraction of Rio's total iron ore – 9.7Mt in FY2021 compared to 319.7Mt at Rio's Pilbara iron ore operations.[44]

[38] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. May 2021.
[39] BHP. Pathways to decarbonisation episode two: steelmaking technology. 5 November 2020.
[40] BHP. Climate Transition Action Plan 2021.
[41] Rio Tinto. 2021 Full Year Results. 23 February 2022.
[42] Australian Financial Review. Greening the Pilbara is no easy feat: Rio Tinto. 24 November 2021.
[43] Rio Tinto. Investor Seminar. 20 October 2021.
[44] Rio Tinto. Fourth Quarter Operations Review 2021.

Simandou

Outside of Australia, the company is also intending to bring additional higher-grade iron ore to the market from its Simandou project.[45] Rio has made clear it is committed to its Simandou project in Guinea despite the considerable infrastructure investment needed and has said of the project, "The resources contain a significant proportion of ore that can meet Direct Reduction specifications."[46]

The iron content of Rio's Simandou measured and indicated mineral resource is 65.5%.[47]

Rio Tinto CEO Jakob Stausholm met with the President of Guinea late last year to discuss the project.[48] President Mamady Doumbouya took control of Guinea in a September 2021 military coup. There will be significant focus on how Rio deals with ESG issues relating to the project following its disastrous destruction of Juukan Gorge, a sacred indigenous cave system and one of Australia's most significant archaeological research sites.

Rio controls half of the Simandou deposits along with its project partner Aluminium Corporation of China (Chinalco), with the other half controlled by a consortium of Chinese and Singaporean companies (SMB-Winning). Rio and Chinalco's half could potentially produce 100 million tonnes of high-grade iron ore per year.[49] Taking SMB-Winning's deposits into account, Simandou could produce 200 million tonnes per annum of high-grade, 65-66% Fe ore by the end of the decade if the projects proceed smoothly, making it the most significant project globally for increasing supply of high-grade iron ore. It would also make Guinea the third-largest exporter of iron ore after Australia and Brazil.

Rio Tinto's Simandou mine could make Guinea the world's third-largest iron ore exporter.

However, although some of Simandou output would be suitable for DRI – "the vast majority would only make the cut as premium BF-grade feed".[50] This would mean

[45] Rio Tinto. Annual Report 2021.
[46] Rio Tinto. Investor Seminar. 20 October 2021.
[47] Rio Tinto. Annual Report 2021.
[48] Bloomberg. Rio Tinto CEO Met Guinean President on Simandou Iron Ore Project. 9 December 2021.
[49] Bloomberg. Rio Tinto CEO Met Guinean President on Simandou Iron Ore Project. 9 December 2021.
[50] Fastmarkets. Understanding the high-grade iron ore market. March 2021.

that Simandou would mostly assist early-stage steel industry decarbonisation efforts (blast furnace optimisation) rather than later-stage zero-carbon steelmaking.

In addition, the Simandou projects still face numerous key risks.

There is clear political risk following the September 2021 military coup – at the time KPMG warned mining companies present in Guinea to "prepare for an era of increased geopolitical instability".[51] This has most recently been demonstrated by the military government of Guinea ordering the suspension of all work on the Simandou iron ore projects in March 2022.[52] The government claimed that there has been insufficient progress on the projects and that there are questions to answer over how Guinea's interests are to be preserved. At the time, it seemed likely that the suspension is a way of putting pressure on the two consortia to collaborate on the rail link between mines and port.

Following the suspension, the Guinea government and mining companies reached a new agreement that will allow work to recommence. Under the agreement, the government will own 15% of both the rail and port projects in addition to the mines.[53] However, the government has also stated that Rio and the other consortia members risk losing their mining licenses if they fail to meet strict project development deadlines. Guinea's mines minister has insisted the port and railway must be completed by the end of 2024 with first iron ore production by the end of March 2025[54], a schedule that looks virtually impossible.

The remoteness of the Simandou is also a problem. A 670km rail line is needed at a cost of perhaps US$12billion to US$20 billion to connect the mines to a port that itself still needs to be developed.[55] The SMB-Winning consortium has begun work on the rail line, threatening to leave Rio's project behind unless it can become involved in the rail project. The rail link has been made more complicated by the Guinean government's insistence that the rail link be built entirely within the country and link to a Guinean port instead of taking the shorter route to port through Liberia.

There is also significant corruption risk surrounding the Simandou deposits.[56]

The SMB-Winning consortium has committed to investing US$14 billion on its Simandou project. China may consider this to be money well invested if it reduces dependence on Australia for iron ore imports. There is a risk that much of any Simandou iron ore production will be taken up by China to supply its own steel industry.

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[51] Australian Financial Review. Australian miners brace as Guinea flares. 6 September 2021.
[52] Reuters. Guinea suspends Simandou iron ore project, saying there has been no progress. 12 March 2022.
[53] Reuters. Guinea reaches deal with miners to resume Simandou iron ore development. 2 March 2022.
[54] Reuters. Simandou iron ore mine developers risk penalties if timeline missed, Guinea says. 29 March 2022.
[55] Australian Financial Review. Rio Tinto's African pact brings Simandou a step closer. 28 March 2022.
[56] OCCRP. Swiss Court Sends Beny Steinmetz to Prison for Bribery in Guinea. 25 January 2021.

Pilbara

Within Australia, Rio's Pilbara iron ores are relatively high in impurities with lower iron content than that required by DRI plants. As at 31 December 2021, Rio Tinto's Australian proved and probable iron ore reserves range between 57.6% and 62.1% iron, below the iron content required by DRI plants assuming no beneficiation. The iron content of its Canadian operations is higher at 65%.[57]

Rio has stated a need to "position Pilbara ores for a green steel future".[58] The company is investigating ways that its Pilbara ores can be improved via beneficiation at less cost, although it seems doubtful that the lower Fe content ores of the Pilbara can reach DR-grade.

Rio has entered into a project with BlueScope Steel that will examine whether Pilbara iron ore can be used in DRI production by employing electric melters to remove unwanted minerals such as silicon.[59] However, BlueScope's immediate production focus is its A$1 billion Port Kembla blast furnace reline and upgrade.[60]

Rio has stated a need to "position Pilbara ores for a green steel future".

Despite all these early-stage development projects (among others) that may help reposition Rio's iron ore business in the long term, Rio's immediate focus is not on the use of its iron ore in DRI processes.

[57] Rio Tinto. Annual Report 2021.
[58] Rio Tinto. Investor Seminar. 20 October 2021.
[59] BlueScope. BlueScope and Rio Tinto sign MOU for low-emissions steelmaking at PKSW. 29 October 2021.
[60] BlueScope. BlueScope delivers record underlying EBIT of $2.20Bn. 21 February 2022.

Figure 9: Rio Tinto's Focus Areas for Iron and Steel Decarbonisation

Source: Rio Tinto.

Rio Tinto views the decarbonisation of the steel industry coming in at least three phases.[61] The first phase – and the focus of Rio's current attention – is the optimisation of blast furnaces to reduce emissions. Phase 2 involves the roll out of DRI technology using hydrogen – technology that is already available today – and phase 3 is dependent on the development of new technologies such as iron ore electrolysis.

Given the lower iron content and higher impurities within Pilbara ores and the uncertain timeframe of the its Simandou project, Rio may not be relied upon to add significant volumes of DR-grade iron ore over the rest of this decade and beyond.

Vale

Unlike BHP and Rio Tinto, Vale has a measurable Scope 3 emissions reduction target. The company is targeting a 15% reduction in Scope 3 emissions by 2035.[62] Steelmaking using its iron ore represents 94% of Vale's Scope 3 emissions.[63] In common with BHP and Rio Tinto, Vale is engaging with its iron ore customers on emissions reductions and has entered into a number of Memoranda of Understanding with steelmakers including POSCO, Hyundai Steel and Baowu.

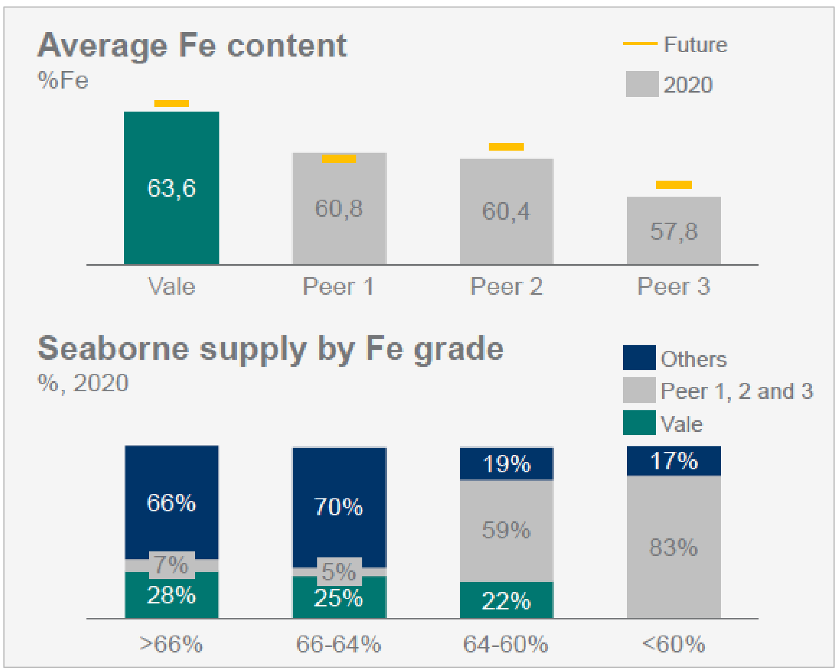
Unlike BHP and Rio Tinto, Vale has a measurable Scope 3 emissions reduction target.

Vale's iron ore production FY2021 was 315.6Mt. In addition to being one of the biggest overall producers, it is also the world's largest supplier of high-grade iron

[61] Rio Tinto. Investor Seminar. 20 October 2021.
[62] S&P Global. Vale targets 15% cut in Scope 3 emissions by 2035, invests in solar energy. 2 December 2020.
[63] Vale. ESG Webinar on Climate Change. 24 June 2021.

ore pellets for both DRI plants and blast furnace operations.[64] However, Vale's pellet production is a small part of its overall output – FY2021 pellet production was 31.7Mt, 10% of total iron ore production.[65] The company's peak pellet production was in 2018 at more than 55Mt but output dropped significantly after the Brumadinho tailings dam disaster in January 2019. Vale had until recently planned to reach pellet output of 50Mt-60Mt in FY2022, however FY2021 production was only 2Mt higher than FY2020 and the company has now advised that pellet production will now only "gradually improve towards the end of 2022".[66]

Figure 10: Vale's Average Iron Ore Fe Content Versus Its Peers and



Seaborne Supply by Iron Content

Source: Vale.

Vale's proven and probable iron ore reserves range in iron content from 46.2% to 65.8%.[67] The company's iron ore production has a higher average Fe content than its peers -- BHP, Rio Tinto and Fortescue (Figure 10).

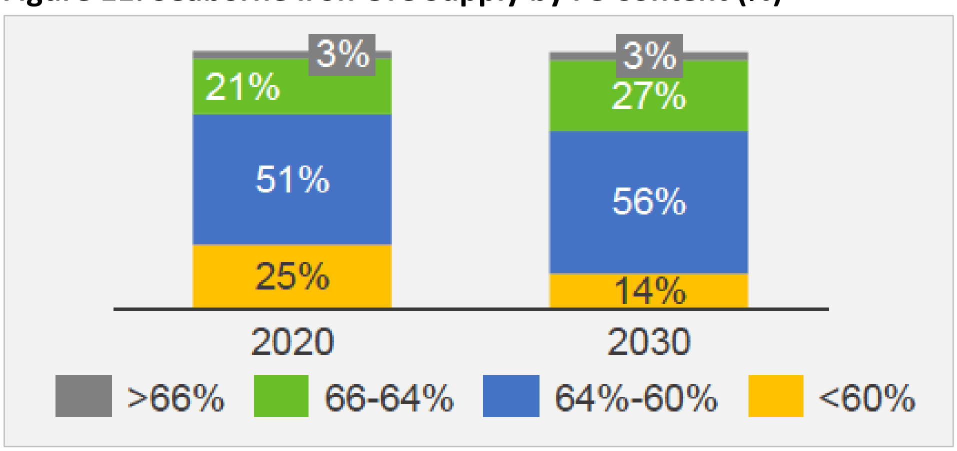
[64] Fastmarkets. Understanding the high-grade iron ore market. March 2021.
[65] Vale. Production and Sales in 4Q21 and 2021.
[66] Vale. Production and Sales in 4Q21 and 2021.
[67] Vale. Form 20-F 2020.

Vale believes its high-grade iron ore gives it a competitive advantage as the steel industry begins to focus on decarbonisation. The company plans to use its proprietary technology to produce more very high grade (>68% Fe) iron ore capable of being used in DRI processes.[68] These plans include the future production of iron ore briquettes which could take the place of pellets in DRI plants. Vale has three briquetting plants under construction and suggests production could reach 50Mtpa by the end of the decade by upgrading current pelletising plants and also installing new plants with the initial annual capacity of about 7 million tonnes[69] although much of the focus for the product appears to be on replacing sinter, pellet and lump iron ore in blast furnaces. Vale also intends to produce DR-grade pellets using its dry concentration technology, a process that results in an end product of up to 68% Fe.

Main ore bodies available face depletion and beneficiation challenges, thus making it difficult to increase supply of high-grade ores.

However, Vale has also stated that "Main ore bodies available face depletion and beneficiation challenges, thus making it difficult to increase supply of high-grade ores."[70] Vale forecasts that, although there will be a shift towards higher quality iron ore over the rest of this decade, there will be no change in the proportion of seaborne iron ore supply over 66% Fe by 2030, remaining at just 3% of the total – the same as it was, Vale says, in 2020 (Figure 11).

Figure 11: Seaborne Iron Ore Supply by Fe Content (%)



Source: Vale.

[68] Vale. ESG Webinar on Climate Change. 24 June 2021.
[69] Vale. Vale Day 2021. 29 November 2021.
[70] Vale. 21st Analyst and Investor Tour. 9 September 2021.

Fortescue Metals Group

Fortescue Metals Group (FMG) is the world's fourth largest iron ore producer with 182Mt shipped in FY2021.[71] However the Fe content of FMG's iron ore is significantly below the Platts 62% CFR Index. In the first two quarters of FY2022, FMG's iron ore received respectively just 73% and 68% of the benchmark price for iron ore with 62% Fe content (Figure 12).[72] FMG is shipping iron ore with less than 60% Fe content, well below DR-grade.

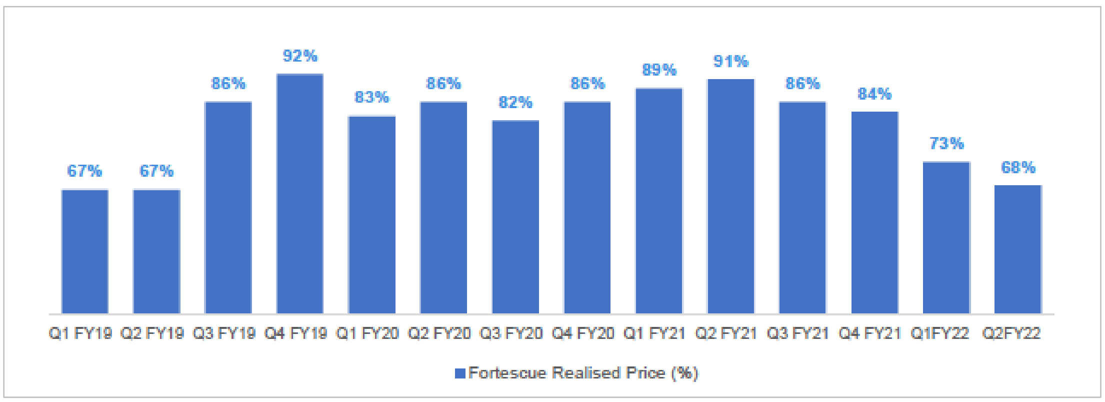


Figure 12: FMG Realisation of the Platts 62% CFR Index (%)

Source: FMG.

As at 30 June 2021, FMG's total proved and probable hematite iron ore reserves had an average Fe content of 57.4%. Its proved and probable magnetite iron ore reserves have an Fe content of 67%.[73]

FMG is committed to developing its magnetite ore reserves at its Iron Bridge project -- one of the few large-scale iron ore growth projects under construction around the world. The Iron Bridge Magnetite Project is an Unincorporated Joint Venture between FMG Magnetite Pty Ltd (69%), and Formosa Steel IB Pty Ltd (31%). The joint venture is to produce 22 million tonnes per annum of high-grade, 67% Fe magnetite concentrate with first output scheduled for December 2022.[74] In April 2022, FMG revealed that there had been a further increase in the expected cost of Iron Bridge project, which will now cost up to US#3.8 billion.[75]

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[71] FMG. June 2021 Quarterly Production Report. 29 July 2021.
[72] FMG. FY2022 Half Year Results Presentation. 16 February 2022.
[73] FMG. Annual Report 2021.
[74] FMG. Iron Bridge Project Update. 28 May 2021.
[75] Australian Financial Review. Fortescue raises export target but Iron Bridge blows out again. 28 April 2022

The company has also entered into a Memorandum of Understanding (MoU) with Sinosteel to assess the latter's Midwest Magnetite Project. The MoU gives FMG the option to acquire 50% of the mine project and 100% of the associated port and rail infrastructure project.[76] Magnetite processing is energy-intensive, though solar power appears to present a means for FMG to manage the cost of processing the ore into concentrate.[77]

FMG has stated that – as a standalone product – the concentrate from Iron Bridge will have both superior pelletising and sintering characteristics[78], potentially adding to the supply of DR-grade pellets globally. However, the company has also said the Iron Bridge product may be blended with its lower quality iron ores if that's where market demand is.[79] In that case, the resulted blended product will be below DR-grade.

FMG Targeting Net zero Scope 3 Emissions by 2040

In its approach to Scope 3 emissions, FMG's stance is significantly different to those of the other three major iron ore producers. Whereas BHP and Rio Tinto don't have overall, measurable targets to reduce Scope 3 emissions and Vale is targeting a 15% reduction by 2035, FMG is aiming for zero Scope 3 emissions by 2040. This seems to imply that, by that date, the company will not sell any iron ore to carbon-emitting steelmakers.

Furthermore, FMG is seeking to transition away from being an iron ore miner to becoming "a vertically integrated green energy and resources company".[80] To that end, Fortescue Future Industries (FFI) – FMG's 100% owned renewable energy and industry company – is building "a global portfolio of green hydrogen and green product operations that will position us at the forefront of the global renewable hydrogen industry".[81]

FMG is seeking to transition to "a vertically integrated green energy and resources company".

Green hydrogen and its applications are a core focus of FFI, which aims to produce 15 million tonnes a year by 2030. In February 2022, FFI announced the start of construction at what it claims will be the world's largest electrolyser manufacturing facility, to double production of the technology used to produce green hydrogen.[82]

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[76] FMG. Fortescue and Sinosteel to commence assessment of Sinosteel's Midwest Magnetite and Infrastructure Project. 21 January 2021.
[77] Australian Financial Review. Fortescue breathes life into Oakajee dream. 21 January 2022.
[78] FMG. Iron Bridge Project Update. 28 May 2021.
[79] FMG. Iron Bridge Magnetite Project update: Investor and Analyst Call transcript. 28 May 2021.
[80] FMG. FY22 Half Year Results. 16 February 2022.
[81] FMG. Climate Change Report FY21.
[82] FMG. Construction commences on world-leading electrolyser facility in Gladstone, Queensland. 28 February 2022.

FFI is looking at other areas, including the use of green hydrogen in fertiliser production and various renewable energy projects to reduce the emissions of FMG's mining operations. FFI is also seeking to develop and commercialise zero-emissions processes to remove oxygen from iron ore using green hydrogen and electricity. It has produced "green iron" with an iron purity of 97% in a research environment. FFI states that its mission is "to accelerate the decarbonisation of this hard-to-abate sector through the global supply of green electricity and green hydrogen in the iron and steelmaking process".[83]

FFI's green hydrogen focus could help ensure there is sufficient, cost-competitive green hydrogen in the long term to help steelmakers transition to zero carbon DRI processes. However, as it stands, FMG does not appear likely to add the volumes of DR-grade iron ore to feed the number of DRI plants needed to bring steel production to net zero emissions.

Other

Outside of the big four, there are iron ore projects that could potentially increase supply of DR-grade ore. Many are in early stages of development.

These include Anglo American's Minas-Rio project in Brazil, which produced 23Mt of 67% Fe pellet feed product in FY2021 -- the company is forecasting 26-28Mt in FY2024.[84] Also in Brazil, Sul Americana de Metais is seeking to open up a 27.5Mtpa mine producing 66% Fe iron ore[85] and Eurasia Resources Group's BAMIN iron ore project is seeking to add 15Mtpa of DR-grade concentrate and pellet feed (67%-68% Fe) by 2026.[86]

Of the projects that could increase supply of DR-grade ore, many are in early stages of development.

In Canada, Champion Iron's Bloom Lake expansion project proposes to double annual production to 15Mt of 66.2% Fe iron ore concentrate with a 20-year mine life.[87] The first ore from this expansion project was shipped in May 2022.[88] The company is also undertaking a feasibility study to consider the development of

[83] FMG. Climate Change Report FY21.
[84] Anglo American. 2021 Results. 24 February 2022.
[85] Reuters. Honbridges's SAM confident $2 billion Brazil iron mine will go ahead. 8 February 2020.
[86] S&P Global. Brazilian BAMIN iron ore mine to raise output to 26 mil mt/year in 42 months: ERG CEO. 31 January 2022.
[87] Champion Iron. Bloom Lake.
[88] Champion Iron. Champion Iron completes first rail shipments from the Bloom Lake mine's Phase II expansion. 3 May 2022.

facilities to produce a 69% Fe DR-grade pellet product which would process half of Bloom Lake's expanded 15Mtpa production.[89]

ArcelorMittal has announced a CAD$205m project at its existing Port-Cartier pellet plant to convert its entire 10Mtpa pellet production into DR-grade product by the end of 2025.[90] The project involves the installation of a flotation system that will enable production of higher quality pellets through the reduction of silica. The plant will become one of the world's largest producers of DR-grade pellets. ArcelorMittal has announced several DRI projects that will need a DR-grade feedstock, including one in Canada.[91] ArcelorMittal's DR-grade pellet production looks unlikely to supply the wider DRI market.[92]

In addition, ArcelorMittal is expanding the DR-grade pellet production capacity at its Serra Azul mine in Brazil from 1.6Mtpa to 4.5Mtpa. It is also expanding pellet production at its Las Truchas mine in Mexico from 1.3Mtpa to 2.3Mtpa, although only 0.3Mtpa will be DR-grade. Both expansion projects are to supply ArcelorMittal's Mexican DRI-based steelmaking operations.[93] The company is also planning to triple production at its Liberian iron ore mining operations to 15Mtpa and construct a new concentration plant to produce a "premium" iron ore concentrate product, although it is not clear if this will be DR-grade.[94]

ArcelorMittal's DR-grade pellet production looks unlikely to supply the wider DRI market.

Iron Road's Central Eyre Iron Project in South Australia is seeking to develop a mine producing 12Mtpa of 66.7% Fe magnetite concentrate over a 22-year lifespan. The company states the concentrate will be suitable for pelletising into DR-grade product[95] although it has been tested as a blast furnace feed product.

There are numerous other Australian magnetite projects in the early stages of development including Hawsons Iron's 10-20Mtpa 70% Fe proposal,[96] Magnetite

[89] Champion Iron. Champion Iron reports its FY2022 third quarter results, declares an inaugural dividend and advances the Bloom Lake Phase II expansion project. 26 January 2022.
[90] ArcelorMittal. ArcelorMittal announces CAD$205 million decarbonisation investment in its flagship Canadian mining operations with support from the Quebec government. 03 November 2021.
[91] ArcelorMittal. ArcelorMittal decarbonisation project in Hamilton, Canada confirmed with the announcement of a CAD$500m investment by the Government of Ontario. 15 February 2022.
[92] IIMA. The Global HBI/DRI Market: outlook for seaborne DR Grade pellet supply. March 2021.
[93] ArcelorMittal. 4Q 2021 and FY 2021 Financial Results and Strategic Update. 10 February 2022.
[94] ArcelorMittal. ArcelorMittal signs landmark agreement with Government of Liberia; signals commencement of one of the largest mining projects in West Africa. 10 September 2021.
[95] Iron Road. 2021 AGM: CEO's Presentation. 24 November 2021.
[96] Hawsons Iron. Company Update. 7 March 2022.

Mines' Razorback Iron Ore Project (67.5-68.5% Fe)[97] and Grange Resources 10Mtpa, 69.5% Fe Southdown project.[98]

In addition, Hancock Prospecting – owner of the Roy Hill iron ore mine in the Pilbara – has signed a Heads of Agreement with South Korean steel giant POSCO to investigate the feasibility of a Hot Briquetted Iron (HBI) plant in Western Australia.[99] The HBI would be produced via a DRI process using green hydrogen and the study includes the feasibility of a new mine development that presumably would produce iron ore of sufficient quality.

In Africa, Glencore owns 50%[100] of the Zanaga Iron Ore Project in Congo-Brazzaville, and proposes to mine up to 30Mtpa of 66% Fe hematite and 68.5% magnetite.[101]

Impact of Russian Invasion of Ukraine

Whilst there is some potential for new DR-grade iron ore projects to increase supply, it looks likely there will also be some supply constraints in the short term, and very possibly for longer, resulting from Russia's invasion of Ukraine.

Russia and Ukraine are together responsible for 30% of iron ore pellet supply (both DR-grade and BF-grade) according to Vale, the world's largest supplier.[102] Ukrainian iron ore miner Ferrexpo is itself the world's third largest supplier of iron ore pellets behind Vale and Sweden's LKAB. Ferrexpo has been planning to significantly expand its production of DR-grade pellets.[103] The company has issued force majeure notices to some customers as it is now unable to export.[104] Metinvest is another Ukrainian producer of high-grade iron ore whose operations are clearly now uncertain. Canadian-listed Black Iron was seeking to advance its Shymanivske iron ore project in Ukraine, set to produce a 68% Fe product,[105] but which is clearly now in doubt.

Sanctions on Russia seem likely to affect supply of Russian iron and steel for the foreseeable future. Russian steelmakers such as Metaloinvest and Severstal are producers and exporters of DRI and HBI to Europe. Before the invasion, Russian DRI capacity was expected to double, requiring a similar scaling up of Russian DR-grade iron ore production.[106] The EU extended its sanctions on Russia to include iron and steel imports with effect from 12 March.[107]

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[97] Magnetite Mines. Razorback Iron Ore Project.
[98] Grange Resources. Southdown.
[99] POSCO. POSCO Examines Feasibility of Production of Low Carbon Steel Materials with Australian resource development company. 4 April 2022
[100] Glencore. 2021 Reserves and Resources Report
[101] Zanaga Iron Ore. Investor Presentation. 28 March 2019
[102] Bloomberg. Ukraine invasion to squeeze high quality iron market, Vale says. 25 February 2022
[103] Ferrexpo. A low carbon pathway
[104] The Guardian. Ukraine port closure hits exports at UK-listed Ferrexpo. 25 February 2022
[105] Black Iron. Project Overview
[106] S&P Global. Feature: Russia's hot-briquetted iron, direct-reduced iron capacity set to double. 18 February 2022
[107] S&P Global. EU adds Russia sanctions to ban import of key iron/steel products. 11 March 2022

Options to Enable Global DRI Expansion Going Forward

The availability of DR-grade iron ore is a potential challenge to the global expansion of DRI technology. This is true both in the shorter term (up to 2030) and in the longer term if significant proportions of steel production are to come from DRI-EAF processes as steelmakers increasingly commit to net-zero emissions. However, there are options to address this supply issue.

Mining Options

One such option is a significant switch in iron ore mining focus from hematite towards magnetite. Hematite currently dominates iron ore mining - the majority of direct shipping ores (DSO) are hematite products such as Australia's Pilbara region mid-grade iron ore. Magnetite ores tend to have a much lower Fe content but are often suitable for significant beneficiation, in part because magnetite is magnetic, which can make separation easier. As a result, magnetite iron ores can often be beneficiated to DR-grade and may provide part of the answer to increasing DR-grade iron ore supply going forward.

Almost all of the 213Mtpa of new mining project capacity identified by Wood Mackenzie to produce ore with at least 67% Fe content is from magnetite mining proposals (although 172Mt is considered only "possible" by Wood Mackenzie).[108] One of the projects on Wood Mackenzie's listing is FMG's Iron Bridge magnetite project, due to begin production by the end of 2022. Numerous other magnetite project proposals in Australia (see 'Other' section above) are in earlier stages of development.

Another option to address DRI iron ore supply issues is to improve the quality of hematite iron ores through beneficiation. This process can involve grinding, separation and dewatering and such extra steps represent an additional cost. However, whether such beneficiation can improve Pilbara hematite ores to DR-grade is another matter. Some beneficiation has been introduced to Pilbara ores but this has been an attempt to maintain ore quality in the face of declining Fe content (Figure 5) rather than improving quality.[109] Despite the introduction of beneficiation processes, the trend in Fe content of Pilbara ores has been to decline as volumes increased.

However, interest in making Pilbara iron ores suitable for a low-emissions steel future is increasing. In 2021, the Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT-CRC) was established to lead collaboration between governments, researchers and heavy industry to accelerate the latter's transition to a low carbon future. Part of its program on Process Technologies is proposed to look at the production of green iron products from Pilbara iron ores.

[108] Wood Mackenzie. Iron ore project review 2021.
[109] Magnetite Mines. Where will future iron ore supply come from? 8 December 2021.

Core HILT-CRC partners include iron ore miners FMG, Roy Hill and Grange Resources.[110]

Outside of the Pilbara, Vale is seeking to make fuller use of existing pelletising capacity although beyond that, additional pelletising capacity would be required to make increased DR-grade pellet supply ready for DRI operations. There are alternative DRI technologies that could help deal with a lack of pelletising capacity. The majority of DRI processes today use shaft furnace technology, which requires ore to be pelletised before entering the furnace.[111] Technologies under development such as Circored[112], HyREX[113], ZESTY[114] and HYFOR[115] have the ability to use iron ore fines, without the extra cost and energy involved in pelleting. However, the issue of Fe content in the ore remains.

Iron ore electrolysis is an early-stage technology that BNEF forecasts to reach commercial readiness by 2035.

Iron & Steel Technology Options

As a result of long lead times for new magnetite project proposals and beneficiation challenges, more DRI may need to be made using lower-grade iron ore. This will necessitate melting the reduced iron before being charged into a basic oxygen furnace, which can more easily remove the higher level of impurities than an EAF.[116] This could enable the use of blast furnace-grade pellets in DRI processes.

ThyssenKrupp is planning to begin replacing blast furnaces with green hydrogen DRI plants beginning in 2025. A succession of new DRI plants will combine an integrated melting unit (submerged arc furnace) powered by renewable electricity.[117] The resultant liquid iron will then be processed at ThyssenKrupp's existing metallurgical plant at Duisburg. This configuration will allow the new DRI processes to use blast furnace-grade iron ore pellets. After the first DRI plant replaces a blast furnace in 2025, three more are planned to be introduced with a second blast furnace replaced by 2030 and four replaced by 2045.

ArcelorMittal is also investigating the integration of DRI with a submerged arc furnace melting step which could allow the use of lower grade iron ore. In March 2021, the company signed a Memorandum of Understanding[118] with Air Liquide for

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110 HILT CRC. Programs.
111 IIMA. Outlook for DR grade iron ore: issues and challenges for the industry. 18 March 2021.
112 Metso:Outotec. Circored.
113 POSCO. The Future of Steel — Hydrogen-based Steelmaking. 3 March 2021.
114 Calix. Calix files a new patent for zero emissions iron and steel. 23 November 2021.
115 Primetals Technologies. HYFOR plant under operation – the next step for carbon-free, hydrogen-based direct reduction is done. 24 June 2021.
116 Mission Possible Partnership. Net Zero Steel: Sector Transition Strategy. October 2021.
117 ThyssenKrupp. Charts on Q1 FY 2021/22: Facts & Figures. March 2022.
118 ArcelorMittal. Air Liquide and ArcelorMittal join forces to accelerate the decarbonisation of steel production in the Dunkirk industrial basin. 17 March 2021.

a project that aims to reduce emissions at ArcelorMittal's Dunkirk site by combining these two technologies, potentially to allow use of lower grade ore, charging the resultant liquid iron into a BOF in the steelmaking step.

Major carmakers are leading growing demand for green steel.

Rio Tinto has entered into a Memorandum of Understanding with Australian steelmaker BlueScope to investigate the use of Rio's lower-grade Pilbara iron ore in DRI-based steelmaking.[119] A key area of investigation will be to melt DRI produced from Pilbara iron ore in an electric furnace powered by renewable energy before charging the melted iron into an existing BOF to convert it into steel.[120]

Outside of DRI technology, there is also the longer-term potential for new steelmaking processes that are not affected by the quality of iron ore. Iron ore electrolysis is an early-stage technology that BNEF forecasts to reach commercial readiness by 2035 and to contribute 9% (138Mt) of primary steel production by 2050.[121]

Electrolysis uses a direct electric current to separate chemical compounds. Iron ore electrolysis would be an electricity-intensive form of steelmaking but can be zero emissions if powered by renewable energy. The ability to use any grade of iron ore is an advantage relative to current commercial DRI technology. There are two basic forms of electrolysis under development. Molten oxide electrolysis (MOE) is being developed by Boston Metal, whose investors include Vale and BHP.[122] The second is solid oxide electrolysis – also known as electrowinning – being explored by 12 European partners led by ArcelorMittal.[123]

Green Steel Demand

The options outlined above involve new technology, new iron ore mining priorities and additional beneficiation steps. A rise in demand for green steel – and a willingness to pay a premium for it – will likely be required to support investment by steelmakers in low-carbon technology and by iron ore miners in high-grade ore projects.

This process has already started with major carmakers leading growing demand for green steel.[124] Car manufacturers are among the largest users of steel globally. This is currently being led by Western brands including BMW[125] (which is also an

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119 BlueScope. BlueScope and Rio Tinto sign MOU for low-emissions steelmaking at PKSW. 29 October 2021.
120 BlueScope. DRI – Melter – BOF Pathway. 29 October 2021.
121 BNEF. Decarbonizing Steel – A Net-Zero Pathway. 1 December 2021.
122 Boston Metal. Who We Are.
123 Siderwin. Consortium.
124 Argus Media. European steel mills propose green steel premiums. 14 September 2021.
125 BMW Group. BMW Group significantly increases use of low-carbon steel in series production at European plants. 1 February 2022.

investor in Boston Metal via its venture fund BMW i Ventures), Volkswagen[126] and Volvo[127] but Asian makers can be expected to follow suit. Toyota has pledged to reach net-zero emissions by 2050 and to reduce its European supply chain emissions by 33% by 2030.[128]

Governments will also need to play a key role in boosting green steel demand by using the purchasing power of government procurement to support low-carbon steelmaking investment. At the 2021 UN Climate Change Conference in Glasgow, the governments of the U.K., India, Germany, Canada and the United Arab Emirates pledged an intention to buy low-carbon steel and cement under the new Industrial Deep Decarbonisation Initiative, coordinated by the United Nations Industrial Development Organisation. Public procurement of steel and cement in these five countries represents 25%-40% of the domestic market for these key building materials.[129] Specific 2030 targets for this initiative are expected to be released in mid-2022.

Further support for green steel demand will likely be needed if steelmakers are to accelerate their low-emissions technology transition and iron ore miners are to increase focus on developing higher grade ore projects. The technology that can allow low- or zero-emissions steelmaking using lower grade ore is in the early stages of development but technology transitions have a habit of happening faster than expected. This has most recently been demonstrated by the fast maturation of wind and solar power, which were expensive a decade ago but are now set to dominate power generation additions in the first half of the 21st century and beyond.

When it comes to carbon emissions, steel has a reputation as a “hard to abate” sector. The challenge imposed by limited DR-grade iron ore supply on plans for a large global scale-up of DRI production is significant. Given long mining lead times and technology development requirements, increased focus on the potential solutions to this issue is needed immediately.

[126] Volkswagen Group. Volkswagen Group and Salzgitter AG sign Memorandum of Understanding on supply of low-CO2 steel from the end of 2025. 21 March 2022.
[127] Volvo. Volvo explores fossil-free steel in industry first collaboration. 20 August 2021.
[128] Wall Street Journal. Green steel becomes a hot commodity for big auto makers. 13 September 2021
[129] United Nations Industrial Development Organisation. World’s largest steel and concrete buyers make game-changing push for greener solutions. 9 November 2021.

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