MIDREX

DIRECT FROM MIDREX

1ST QUARTER 2024

▶ **OUTLOOK FOR DRI PRODUCTION AND USE**

COMMENTARY
People, Growth & Technology

NEWS & VIEWS
thyssenkrupp Steel Receives Construction Approval

COMMENTARY

PEOPLE, GROWTH & TECHNOLOGY

By K.C. Woody, *President & COO*

A MIDREX® Plant must successfully complete a series of tests that measure various operating parameters allowing Midrex to complete its performance obligations for our customer. The results of these tests are indicative of what the plant is capable, but in no means are they limiting on the expectation of what can be achieved during the plant's lifetime. We call this test the PGT – Performance Guarantee Test. The PGT is a critical milestone for any project and something everyone at Midrex takes very seriously.

PGT also can be used to describe the "test" Midrex is facing as we play our role in decarbonizing our industry – **People** driving **Growth** with **Technology**.

If not for a group of talented, innovative, and determined people more than 50 years ago, there might not be a Midrex today. They saw a value-added future for their know-how and expertise in changing the way iron ore is prepared for steelmaking – direct reduction. No, they didn't invent direct reduction; they created a better way to make direct reduced iron (DRI) and established a culture of engagement, achievement, and teamwork.

Through the years, Midrex has not only introduced numerous innovations and improvements to its process technology but has been the driving force in establishing DRI as an essential metallic material for sustainable steelmaking. In 1971, when the longest-serving MIDREX® Plant began operating in Hamburg, Germany, DRI production was less than one million metric tons (Mt). DRI production in 2022 was 127.36 Mt, with MIDREX Plants accounting for 73.55 Mt. Today, DRI is essential for production of the highest quality steel grades in the electric arc furnace (EAF) and the use of hydrogen-based DRI in the EAF is generally regarded as the steelmaking route most capable of meeting the carbon dioxide (CO_2) emissions standards of the future.

ArcelorMittal Hamburg: The longest-serving MIDREX Module

People inside and outside the company have asked, "What is Midrex?" Is it a technology company? Is it an

COMMENTARY

> "And judging by the results of our first 50 years, we must invest in the people at Midrex, grow Midrex, and continue to advance our technology."

The 2.1 million tons per year MIDREX H2™ Plant will be located in Boden, northern Sweden.

engineering company? Is it an aftermarket solutions company? There is one simple answer...yes. As Stephen Montague, my friend, colleague, and mentor since I started my journey at Midrex, was fond of saying, Midrex is "a small team doing big work, committed to loving and serving others."

The topic of decarbonization has intensified in the past few years. When I joined Midrex, hydrogen-based DRI plants were a thought for the future. Today, we are designing a 2.1 Mt plant for H2 Green Steel that will use 100% hydrogen as reducing gas and a 2.5 Mt plant for thyssenkrupp Steel paired with a melter that will be capable of producing high quality, low CO_2 DRI from blast furnace-grade pellets.

Sustainability – technological and financial – is foremost in the minds of steel executives across the globe, and we are continuously evaluating our capabilities and adding resources to provide sustainability solutions. We are confident in our culture of innovation, improvement, teamwork, and service. And judging by the results of our first 50 years, we must invest in the people at Midrex, grow Midrex, and continue to advance our technology.

Just like for our projects, P-G-T is the measure of our success.

→

This issue of *Direct From Midrex* provides a deeper insight into MIDREX Flex™ that bridges direct reduction ironmaking from natural gas-based to up to 100% hydrogen based. The other feature article is a view of what the future might hold for DRI production and use by the International Iron Metallics Association (IIMA). News & Views announces a career-oriented Operator Excellence Program to train future panel operators of MIDREX Plants, and an update on the thyssenkrupp Steel project.

Fueling the Future of Ironmaking:

MIDREX Flex™

By GEOFF WALLWORK,
Principal Process Engineer - Midrex Global Solutions

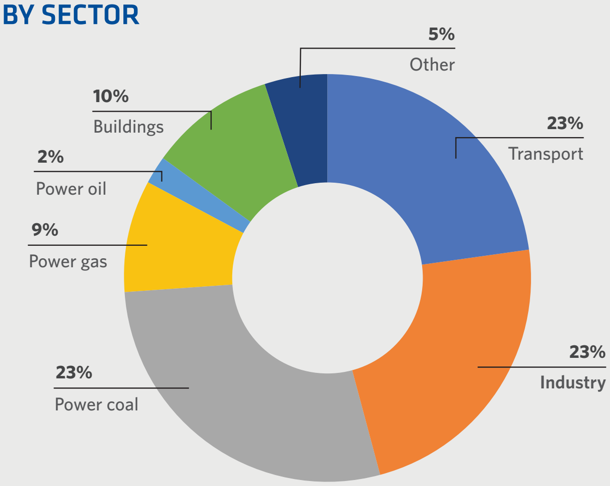
INTRODUCTION

According to the International Energy Agency (IEA), the industrial sector is responsible for 23% of global energy-related CO_2 emissions, and iron and steel accounts for 30% of the sector's total ***(Figure 1)***. That is 2.6 gigatons of CO_2 annually. To realize the long-term transformational change envisioned by the IEA, the CO_2 intensity of crude steel needs to fall an average of 2.5% annually between 2018 and 2030.

To meet the demands and climate goals of IEA's net-zero emissions (NZE) scenario, the iron and steel industry must decrease its CO_2 emissions by at least 50% by the year 2050. Achieving this reduction will not be easy and presents a challenge to the industry.

FIGURE 1.

GLOBAL ENERGY-RELATED CO_2 EMISSIONS BY SECTOR



Industry (IEA 2020)	
Iron & Steel	30%
Cement	29%
Chemicals & petrochemicals	13%
Pulp & Paper	2%
Aluminum	3%
Other Industry	23%

Milestones	2022	2030	2035	2040
Steel				
Crude steel production (Mt)	**1880**	**1970**	**1970**	**1960**
Share of scrap in metallic inputs	**33%**	**38%**	**40%**	**48%**
Share of near zero emission iron production	**0%**	**8%**	**27%**	**95%**
CCUS-equipped	0%	3%	10%	37%
Electrolytic hydrogen-based	0%	5%	15%	44%
Iron ore electrolysis	0%	0%	2%	14%
CO_2 captured (Mt CO_2)	**1**	**27**	**131**	**399**
Low-emissions hydrogean demand (Mt)	**0**	**6**	**17**	**41**

TABLE 1. *Emissions reductions from steel production is challenging due to a heavy reliance on fossil fuels today, process emissions from incumbent routes, and high trade exposure. Increased scrap recycling and mass deployment of innovative technologies are key levers for reducing emissions.*

Short term reductions in CO_2 emissions in recent years have come largely from energy efficiency improvements; however, opportunities for further efficiency improvements will likely soon be exhausted. Thus, innovation to commercialize new low-emissions process routes utilizing hydrogen and carbon capture, utilization, and storage (CCUS) in the upcoming decade will be crucial to realizing the long-term decarbonization goals.

Emerging technologies making use of CCUS are expected to cut emissions mainly after 2030 ***(see Table 1).*** Recently, there has been significant progress in 100% electrolytic hydrogen-based DRI steelmaking (e.g., H2 Green Steel's DRI-EAF steel mill project in Boden, Sweden), which is forecasted to account for nearly half of iron-based steel production by 2050 in IEA's 2023 NZE Scenario.

WHAT IS MIDREX DOING TO SOLVE THE CHALLENGE?

The standard natural gas-based configuration of the MIDREX® Process is the most widely used technology to produce all forms of direct reduced iron (DRI) products and is seen as the most viable near-term response to reduce CO_2 emissions. Steel production via the direct reduced iron-electric arc furnace (DRI-EAF) route already generates 50% less CO_2 emissions compared to the blast furnace (BF)-basic oxygen furnace (BOF) method.

As decarburization is key to the sustainability of the steel industry, and ironmaking represents the majority of CO_2 emissions in steelmaking, DRI technology must lead the way.

The ultimate method for reducing the steel industry's CO_2 footprint is to use 100% hydrogen as the reductant to make DRI in a MIDREX Shaft Furnace. This technology is known as MIDREX H2™, which includes a specially developed electric heater in place of the MIDREX Reformer and reduces CO_2 emissions up to 90% versus BF ironmaking.

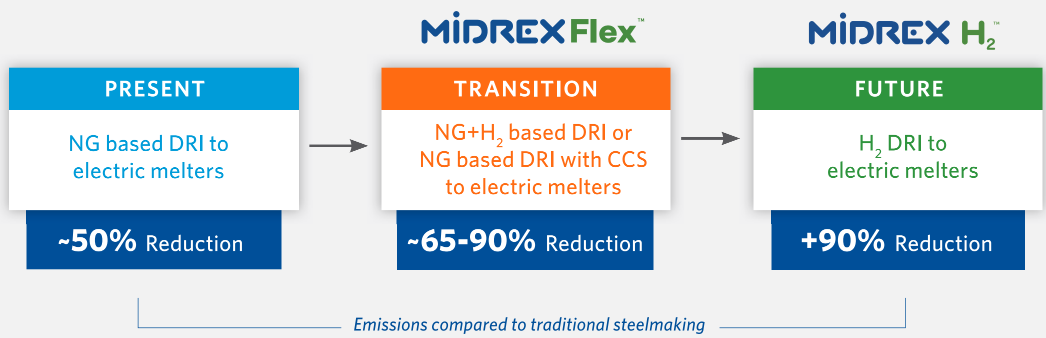
However, Midrex offers another solution that allows steelmakers to adapt to the hydrogen economy at their own pace, which we call MIDREX Flex™. This technology approach allows for the replacement of any percentage of the natural gas feedstock with hydrogen based on the plant's operating goals and provides the flexibility for the plant to respond to ever-changing market needs and feedstock availability. Therefore, as sufficient quantities of hydrogen become available at competitive prices, a standard MIDREX Plant can be easily modified to operate with up to 100% replacement of the natural gas.

Although the MIDREX Reformer does a good job in converting recycled CO_2 into carbon monoxide (CO) in the standard process flowsheet, a MIDREX Plant can be designed with a CO_2 removal system if it is economical (such as for carbon tax credits) or if there is a means to store or utilize the captured CO_2. These systems are typically designed to remove CO_2 from the top gas fuel or the reformer flue gas.

GETTING TO KNOW MIDREX FLEX

Existing natural gas-based MIDREX Plants already have significant percentages of hydrogen in the reducing gas, with a typical hydrogen to carbon monoxide (H_2/CO) ratio of 1.5 corresponding

TRANSITION FROM FOSSIL TO HYDROGEN ECONOMY



to approximately 55% H_2 and 36% CO. So, MIDREX Flex technology can be considered an "evolutionary innovation," as operation of a MIDREX Shaft Furnace with high levels of hydrogen has been proven successfully for decades. For example, the FMO plant in Venezuela has operated with H_2/CO ratios as high as 3.8.

Let's look at key aspects of MIDREX Flex ***(see Figure 2)***:

1 Hydrogen Ready – Use up to 100% H_2 as the reductant. Midrex has solutions ready to accommodate the entire range of input gas compositions at new and existing facilities.

2 MIDREX Reformer – Ensures optimum reducing gas conditions throughout the entire range of the transition.

3 MIDREX Shaft Furnace – Delivers consistent product quality throughout the transition. The influence of endothermic hydrogen reduction is mitigated by the reformer and uniform burden movement.

4 Carbon Capture & Storage – Carbon capture and storage can be applied to several different process streams, from 50% to nearly 100%. Available for addition to existing facilities or new installations.

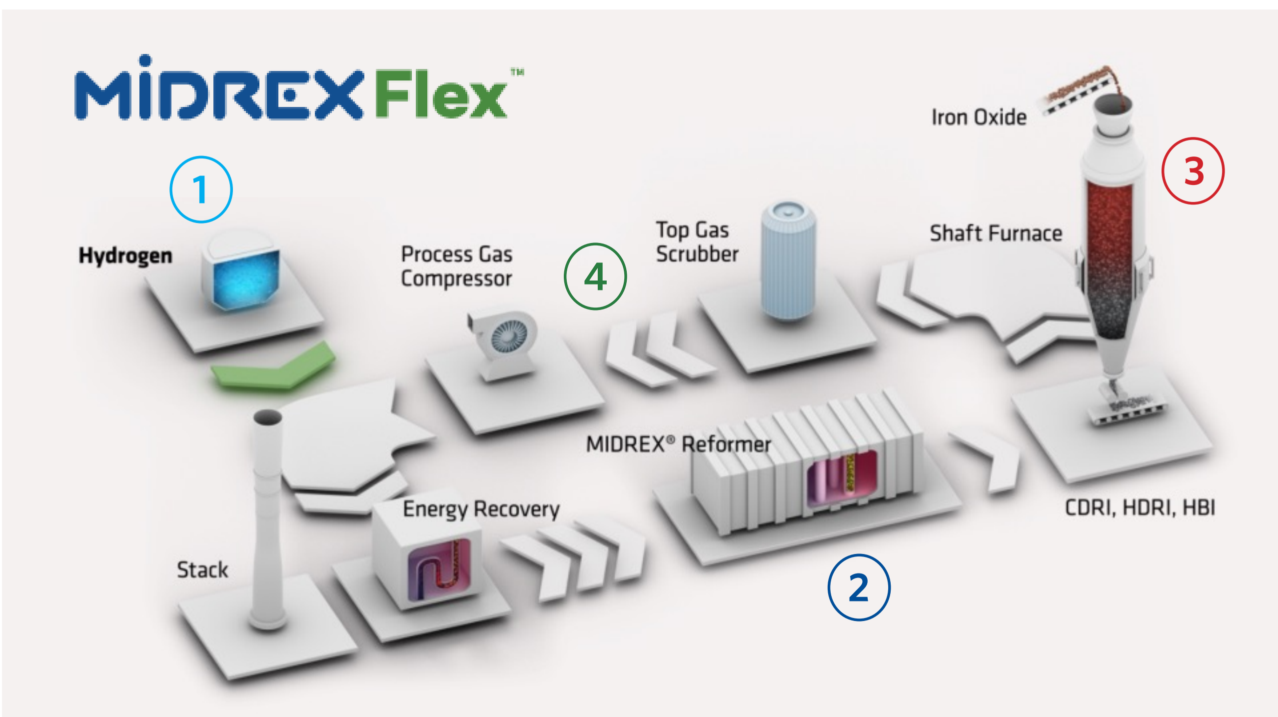


FIGURE 2. *MIDREX Flex*

A plant utilizing the natural gas-based MIDREX Process can be transitioned to accommodate up to 100% hydrogen as the reductant with the MIDREX Flex configuration. No fundamental design changes are required for the MIDREX Reformer or the MIDREX Shaft Furnace. Additionally, a CO_2 removal system can be applied to capture the CO_2 for storage or utilization.

Operational Targets

There are several key operational targets during the transition to hydrogen with MIDREX Flex.

- The full plant capacity is maintained across the entire transition range while minimizing the requirement for equipment modifications or the addition of new equipment to the plant.
- The DRI product carbon is maximized at each point across the full transition range. Generally, this is accomplished by maintaining the transition zone natural gas flow as far into the hydrogen transition as possible.
- Optimum reducing gas quality to the MIDREX Shaft Furnace is maintained by maximizing the hydrogen addition downstream of the reformer.

The required amount of thermal mass flow to support the higher endothermic reduction load in the MIDREX Shaft Furnace is maintained across the entire transition range. The H_2/CO ratio increases as the hydrogen addition increases, which requires a larger mass flow at the bustle.

Injection Points

Generally, minimal changes to the process flowsheet are required for operation with up to 30% replacement of the natural gas by hydrogen. For 100% replacement of the natural gas, additional equipment may be required, but the core equipment is suitable for the transition.

In the initial stages of the transition to hydrogen, a small amount of hydrogen is injected downstream of the reformer without preheating, shown as #1 in ***Figure 3***. Injecting hydrogen at this location allows optimization of the reformer operation so it can be held as close to the standard operating conditions as possible during the transition while maximizing the reducing gas quality to the MIDREX Shaft Furnace. The maximum

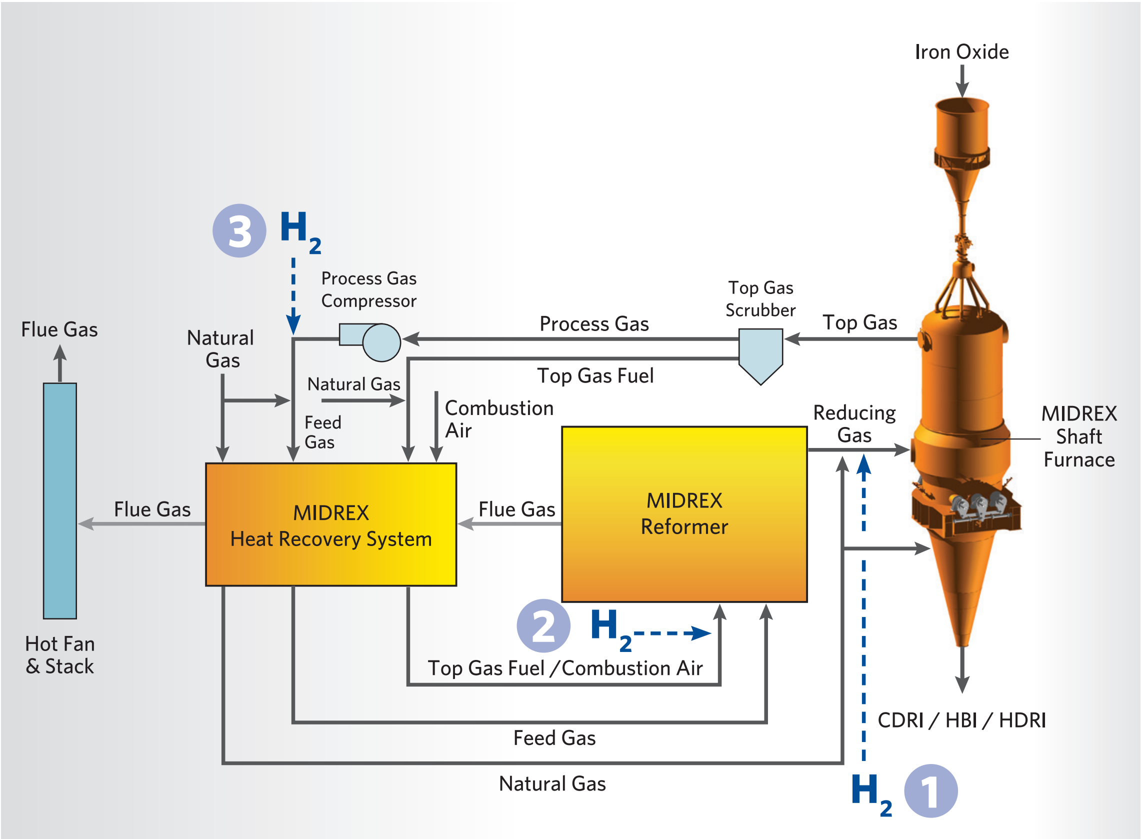


FIGURE 3. *H_2 Injection Points*

	NG (No added H_2)	NG replacement by H_2 (Energy Basis)			
		30%	50%	80%	100%
Natural Gas Consumption (Nm³/t)	275-300	190-215	140-165	50-80	0*
H_2 Consumption (Nm³/t)	0	250-300	450-500	700-750	850-900*
H_2 / CO	1.6	2.8	4.5	10.5	N/A
CO_2 Emissions from flue gas (kg-CO_2/t-DRI)	500	350	250	100	From heater burners only (if fueled by C_nH_m) 0 if fuelled by 100% H_2

TABLE 2. *Typical Consumptions/Emissions*

amount of hydrogen that can be injected downstream of the reformer will be based on the availability of oxygen injection or if preheating the hydrogen is available. Maintaining adequate reducing gas temperatures to the MIDREX Shaft Furnace is critical when injecting hydrogen in this location.

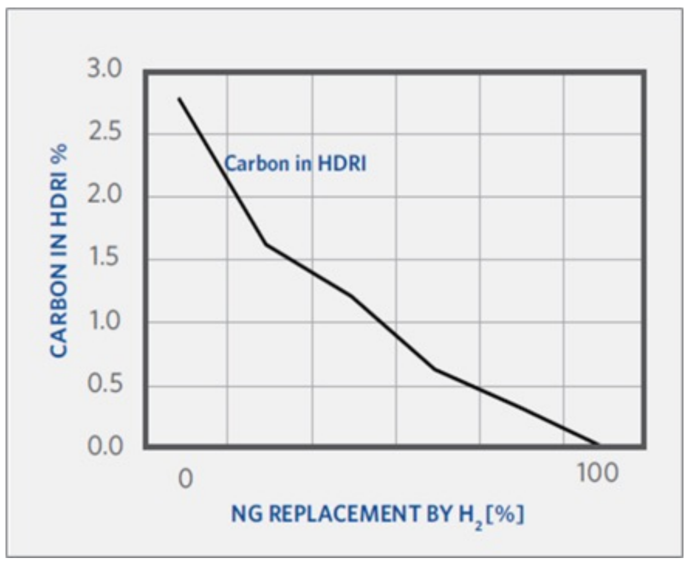
After maximizing the amount of hydrogen injected downstream of the reformer, hydrogen can be added to the reformer burners to maintain the DRI product carbon as far into the replacement as possible and to continue reducing the carbon footprint. This is shown as #2 in ***Figure 3***. Hydrogen injection can also be introduced upstream of the MIDREX Reformer to maintain reducing gas quality and enhance energy efficiency in the process. This is shown as #3 in ***Figure 3***.

Typical Consumptions/Emissions

Table 2 provides the typical consumption and CO_2 emissions for the transition from 100% natural gas to 100% hydrogen. As the hydrogen addition is increased, the natural gas consumption decreases, the H_2/CO ratio increases, and the CO_2 emissions decrease. At 100% hydrogen operation, the natural gas consumption and CO_2 emissions are zero if the heater burners are fueled by hydrogen.

Operational Changes

There are several operational changes to be expected during the transition to hydrogen with MIDREX Flex.



As CO_2 emissions and DRI product carbon are derived from the consumption of natural gas, both the CO_2 emissions and the DRI product carbon will decrease as the natural gas is replaced with hydrogen.

As the hydrogen addition is increased, the H_2/CO ratio will naturally increase as well. Also, the molecular weight of the process gas and reducing gas will decrease due to the relatively lighter weight of the hydrogen.

As mentioned previously, the amount of reducing gas flow must increase to maintain the energy balance in the shaft furnace.

And finally, there will be an increase in the demand for cold water and a corresponding decrease in the demand for hot water.

PLANT MODIFICATIONS

To convert an existing natural gas-based plant to MIDREX Flex requires minimal equipment modifications. Generally, hydrogen replacement of up to 30% of the natural gas, based on the original design capacity of the plant, requires no changes to the major process equipment including the shaft furnace and the reformer.

For natural gas replacement beyond 30% and to accommodate the full range of operation up to 100% hydrogen, some major plant areas will likely require modifications. These areas include the process gas compressors, heat recovery system, cooling gas compressor, and process water system.

Shaft Furnace

The shaft furnace for existing plants requires no fundamental changes across the full range of hydrogen addition. Reduction kinetics actually improve with higher amounts of hydrogen.

Increasing the hydrogen will increase the endothermic load in the furnace. The reduction furnace is an adiabatic reactor, so more heat input is required to sustain the reduction process with higher amounts of hydrogen.

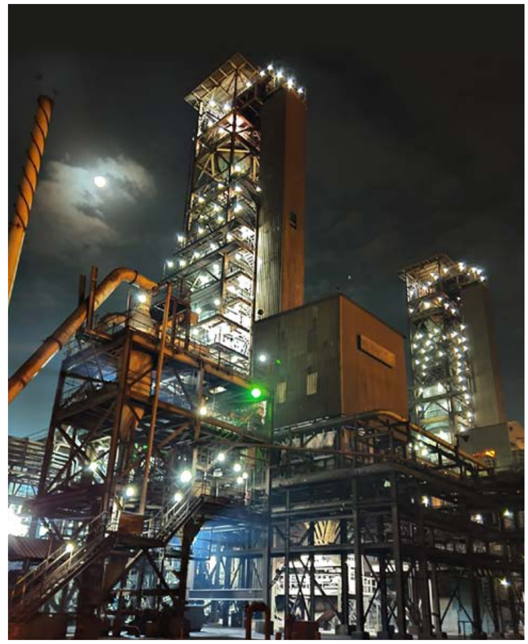
There are two methods to increase the heat input:

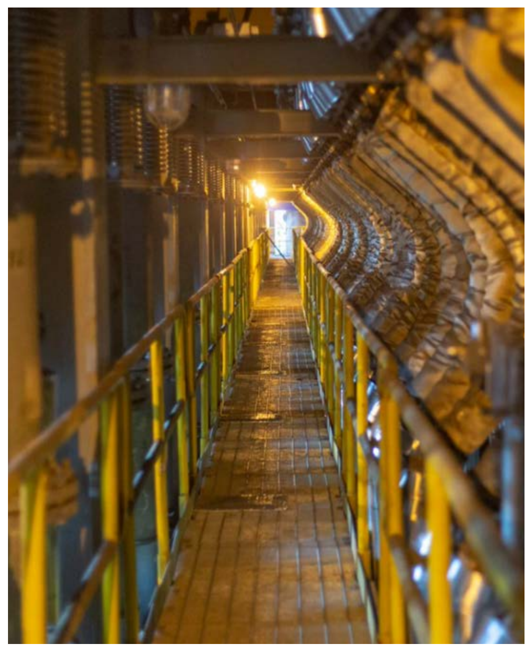
1. Increase the sensible energy entering the reduction furnace by raising the reducing gas temperature.
2. Increase the total energy (or thermal mass) into the reduction furnace by raising the reducing gas flow per ton entering the bustle at any given temperature.

Raising the reducing gas temperature is the simplest method but oftentimes, the ore cannot be elevated to sufficient temperature to provide all the required additional reduction energy. The higher temperature required would cause the ore to become sticky and adversely affect material flow and productivity in the furnace. Acceptable top gas and bustle gas temperatures can be maintained by increasing the amount of reducing gas flow per ton entering the shaft furnace to provide the required energy for reduction.

Reformer

No fundamental design changes are required for the reformer. As the reformer for a standard natural gas-based plant is designed to operate on 100% natural gas, this design criteria provides the highest duty for the reformer operation. As the natural gas is replaced with hydrogen, the reforming overall heat load will decrease. As the amount of hydrogen increases, the amount of reforming required decreases and the reaction heat decreases. As the hydrogen replacement progresses to 100%, the reformer essentially becomes a heater to provide the necessary sensible heat to increase the temperature of the reducing gas.


SHAFT FURNACE


REFORMER

The existing reformer catalyst is suitable throughout the transition. At 100% hydrogen operation, the existing catalyst can be substituted with inert catalyst since there is no reforming and only sensible heat transfer is necessary.

The reformer burners are designed to operate on top gas fuel, which has a heating value similar to hydrogen. The existing burners are suitable for the transition to hydrogen with only minor modifications.

Process Gas Compressors

Since the natural gas is being replaced with hydrogen, process gas flow will need to increase to supply more thermal mass flow to the furnace. In general, the process gas compressor capacity will become a limiting factor at approximately 30% replacement of the natural gas. The addition of a single additional compression stage will allow for operation across the full transition range.

Heat Recovery

During the transition to hydrogen, the overall reformer heat load will decrease. Therefore, flows of flue gas, combustion air, and top gas fuel will ultimately decrease and the heat transfer will need to be reviewed for the heat recovery system.

If there is an existing top gas fuel heat recovery bundle, it can be repurposed for preheating the hydrogen to allow for more hydrogen to be injected downstream of the reformer as the transition progresses to higher amounts of hydrogen replacement.

Cooling Gas Compressor

For existing plants that produce cold DRI (CDRI), the cooling gas compressor will need to be evaluated for the transition to hydrogen. As the transition progresses, natural gas is withdrawn from the cooling zone loop. As a result, the cooling gas composition reverts from a mixture of methane and nitrogen to a mixture of hydrogen and nitrogen. This change in the cooling gas composition will increase the cooling gas flow requirement.

In general, it is expected that the cooling gas compressor capacity will become limiting at approximately 70% replacement of the natural gas.

COOLING GAS COMPRESSOR

PROCESS GAS COMPRESSORS

HEAT RECOVERY

Process Water System

Several changes associated with the transition from natural gas to hydrogen will occur within the process water system. More capacity may be required including such equipment as an additional cooling tower cell, recirculation pumps, and supply pumps.

Increasing the level of hydrogen in the reducing gas will increase the amount of water vapor in the top gas as a product of the reduction occurring in the furnace. This translates to a higher condensation heat load in the top gas scrubber and requires increased water flow to the packing and will create more water for the overall system to handle.

The cold process water demand will increase. On the other hand, the hot process water demand will decrease since the controlled process gas temperature at the exit of the top gas scrubber decreases as the hydrogen addition increases.

PROCESS WATER SYSTEM

EVALUATION OF DRI REDUCED WITH HYDROGEN

Tests were conducted at the Midrex Research & Development Technology Center to compare some of the physical and chemical properties of DRI made with hydrogen versus reformed natural gas.

Table 3 shows the various iron oxides used for the evaluation. It included both lump and pellet oxides with various total iron contents.

Material	T. Fe%	Tumble index +6.73 mm
Lump ore A	54.04	81.8%
Lump ore B	60.41	83.7%
BF grade iron oxide pellet	65.40	95.7%
DR grade iron oxide pellet 1	68.06	95.2%
DR grade iron oxide pellet 2	68.02	94.5%

TABLE 3. *Typical Consumptions/Emissions*

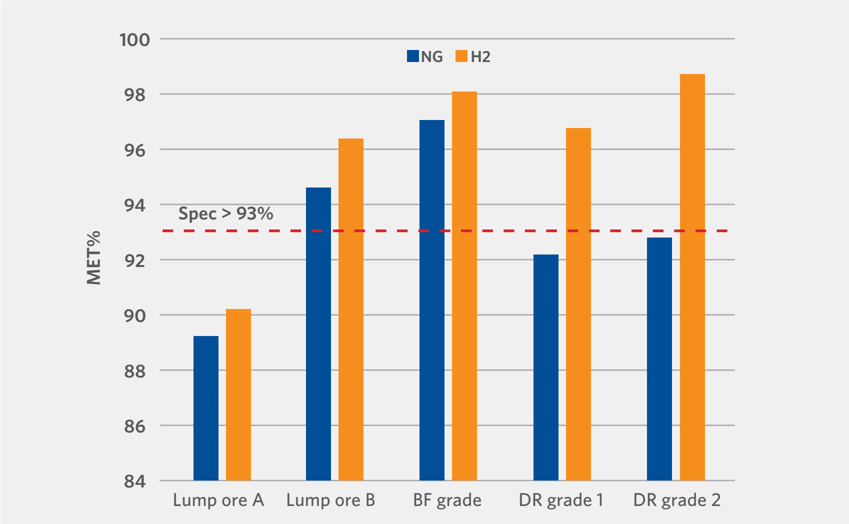


FIGURE 4. *100% hydrogen vs. reformed natural gas*

Reducibility Evaluation

The Linder Test was used to evaluate the reducibility of the oxides according to ISO-11257:

- Reformed NG Condition - 36% CO, 5% CO_2, 55% H_2, 4% CH_4
- H_2 Condition – 100% H_2
- 760˚C for 5 hours
- DRI screened to measure degradation

The results demonstrate that high metallization can be obtained with hydrogen reduction. In all cases, higher metallization rates were achieved with 100% hydrogen versus reformed natural gas ***(see Figure 4)***.

Although lab results cannot be scaled exactly to commercial operation, multiple studies, both within Midrex as well as external to Midrex, have shown hydrogen as a better reducing agent compared to carbon monoxide.

Physical Strength Evaluation

The DRI generated by the Linder Test was also screened to determine the physical strength. The results demonstrate that apart from one lump oxide sample, the oxide reduced with hydrogen had relatively the same or lower fragmentation than those reduced with reformed natural gas ***(see Figure 5, next page)***.

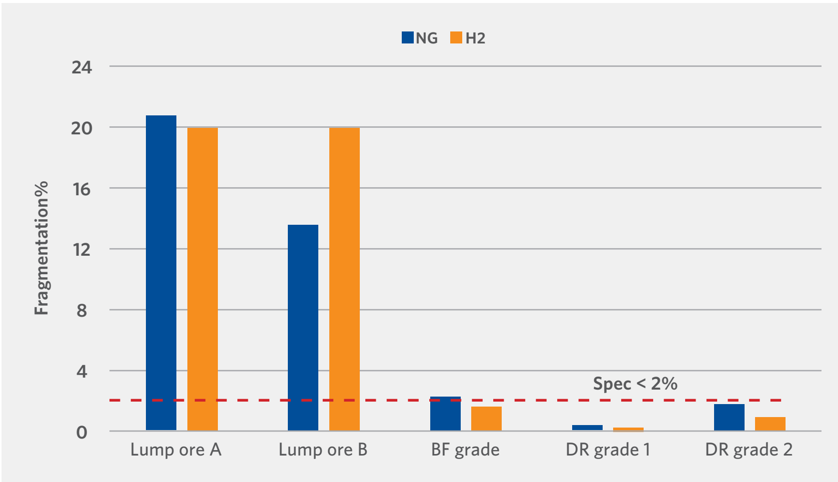


FIGURE 5. *Physical Strength Evaluation*

Clustering Behavior Evaluation

Another evaluation performed was the cluster test. This test is performed at 850 degrees C until 95% reduction is achieved.

Clustering or sticking occurs during the metallization of the oxide and is heavily dependent on the oxide type. It is critical to minimize the clustering behavior to avoid interruptions in the mass flow of the oxide in the shaft furnace and to maintain consistent metallization across the oxide bed.

Apart from one lump oxide sample, the clustering index of the hydrogen reduced DRI is lower than the reformed natural gas reduced DRI ***(see Figure 6)***.

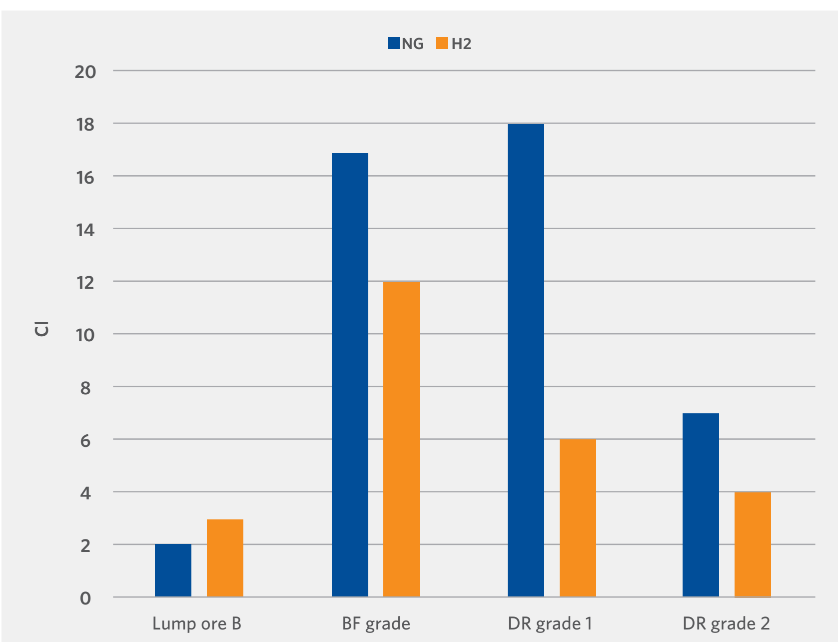


FIGURE 6. *Clustering Evaluation*

CONCLUSION

The desire to decarbonize steel production isbeing driven by changing customer requirements and growing demand for carbon-friendly steel products coupled with a tightening of carbon emission regulations. A recent McKinsey study found that 14% of steel companies' potential value is at risk if they are unable to decrease their environmental impact. The same study concluded that full decarbonization is possible with DRI using green hydrogen in the EAF.

Midrex has the technologies to meet the challenge of achieving net-zero emissions in steelmaking. For those ready to go with 100% hydrogen operation, MIDREX H2 is available and being used in the first-of-its kind green steelmaking facility of H2 Green Steel in northern Sweden. And for those already operating a natural gas-based MIDREX Plant or wishing to transition in steps to complete hydrogen-based DRI, MIDREX Flex is the answer.

As we have for more than 50 years, Midrex is leading the way in innovative ironmaking solutions.

OUTLOOK FOR DRI PRODUCTION AND USE

By ROBERT MAZURAK,
President, Mazurak Resource Consulting, LLC, and Special Advisor- International Iron Metallics Association (IIMA)

INTRODUCTION

Since getting involved in the "alternative iron" space in the late 1980s, I've watched the industry grow, face some setbacks, and rebound even stronger. It is hopeful and energizing to see all the recently announced direct reduced iron (DRI) projects materialize along with the increased attention to hydrogen as a key ore reduction gas helping decarbonize the steel sector in its quest to reach net-zero emissions by 2050. Therefore, I see a bright future ahead for DRI and other ore-based metallics (OBMs).

PAST TO PRESENT

From the late '80s, a period when companies were constructing electric arc furnace (EAF) mills across the USA to make high quality and specialty steels, concerns for the diminishing quality and quantity of prime grades of scrap began increasing and OBMs; i.e., merchant pig iron, DRI in its various physical forms, and iron carbide started to be viewed as essential supplemental feedstocks in steelmaking. OBMs are needed to enrich furnace scrap charges by diluting copper and other unwanted metallic elements inherent in ferrous scrap. An additional benefit of OBMs is the ability to use higher percentages of lower cost obsolete scrap in the charge and still meet exacting steel quality specifications.

On a straight-line basis, the annual growth for global DRI production since the '70s has been about 3 Mt per year. However, there has been accelerated growth in production since 2016 (72.8 Mt) to nearly 8 Mt per year. By product type, the growth rates are decidedly different. In the last 20 years, cold DRI (CDRI) enjoyed a near treble increase in volume, from 39 Mt to 102.1 Mt, with the general growth of widely accepted and proven natural gas-based and coal-based reduction technologies. Hot DRI (HDRI) production has soared nearly eight-fold in the last 20 years, increasing from 1.8 Mt in 2003 to 13.9 million in 2022. The rapid rise in HDRI use in the EAF is from the recognition that it provides the benefits of quicker melting and an energy savings from the retained, latent heat. However, global hot briquetted iron (HBI) production has increased only marginally, from 8.6 Mt in 2003 to 11.4 Mt in 2022, despite being the most desirable DRI form for seaborne trade. The reason largely falls to diminished production in Venezuela, the one-time leader in HBI output, following a second round of nationalizations of the iron & steel industry since the 1970s, most recently starting in 2008 under former President Hugo Chavez.

WILL OBM GROWTH RATES BE SUSTAINED?

I am cautiously optimistic that the answer is "yes," with the accelerated production and use of all forms of DRI. New iron ore briquetting hubs, such as those announced by Vale, will likely rise to serve multiple off-takers in targeted regions to feed both existing and new DRI plants. DRI-to-EAF steel mill complexes will be constructed where energy and raw materials are either most abundant or served at lowest cost. Owners of DRI-EAF steelmaking plants seeking long-term raw material security will increasingly recognize cost and quality benefits of using OBMs. Given that scenario, captive production and merchant HBI sales may once again rise to the higher growth trajectories of CDRI and HDRI.

Some caution centers on how such global growth might be impacted by unknown and unexpected external "black swan" events that can completely interfere with new project investments and plant output. Several new DRI plants were built in the U.S. during the 1990s (including one dismantled and relocated from Scotland to Mobile, AL), only to face steel downturns and volatile natural gas pricing, leading to their shutdown in the 2000s. Two plants, including the one originally from Scotland, were deconstructed and relocated to places where natural gas was abundant and prices less volatile (specifically Trinidad and Tobago and Saudi Arabia). Examples of "black swan" events include past oil crises, the Global Financial Crisis (mid-2007 to 2009), Covid-19, (2020-2023), the Russia-Ukraine war (on-going since Feb. 2022), and now the Israel-Hamas conflict and associated proxy group attacks launched from Lebanon, Yemen, and Syria. Any additional "black swan" events, such as a broadening Middle East conflict or another global financial or energy crisis could easily stop or delay DRI projects and undercut growth projections. Another concern is the long-term availability of DRI plant feedstocks: DR-grade pellet and lump iron ore (+67% Fe, gangue minerals under 2%), and the extent to which higher gangue BF-grade iron ore (64% Fe, ~5% gangue) converted into DRI will be accepted by EAF steelmakers.

THE NEAR TERM

As DRI demand is fundamentally driven by steel demand, let's first look at World Steel Association's (worldsteel) latest Short-Range Outlook, which forecasts demand for finished steel products through 2024. Following a setback in 2022 to 1,782.5 Mt, worldsteel expects 2023 global steel demand will be up 1.8 percent to 1,814.5 Mt, followed by a 1.9 percent increase in 2024 to 1,849.1 Mt (a 34.6 Mt increase led by India and other Asia excluding China. These are rather weak growth rates given what we've witnessed in the last several decades with the rise of China to become the world's largest steelmaker. While the forecast increase in demand is allocated broadly among many countries, the lion's share of growth is expected in India, which has emerged as the world's largest producer of DRI (43.6 Mt in 2022). Based on the historical averages, assuming production increases in line with demand, 2023 global DRI production should rise to around 130-135 Mt, and 2024 production 133-143 Mt (top-end for both at the 8 Mtpa growth rate since 2016).

MID-TERM OUTLOOK (TO 2030)

Given all the recently announced "green steel" DRI and steel industry decarbonization projects, the accelerated growth rate in DRI production may well continue, such that likely we will be seeing another 60 million tons of incremental DRI output by the end of 2030 to reach an annual level of 185 -190 Mt, rising to 13% of the combined BFI plus DRI ironmaking total.

A 2023 worldsteel presentation by IIMA Chief Advisor Chris Barrington tallied nearly 80 Mt of announced and on-going expansions of DRI capacity, with a significant number of projects scheduled to be in production by 2030. The breakdown by region is roughly as follows: Europe (including Russia) – 34 Mt, MENA – 32 Mt, Asia and Other – 14 mt. According to Mysteel tracking, "In 2022, a total of 20 Mt per year of gas-based DRI production capacity is under construction across the world, which will be gradually put into production in coming years."

LONGER RANGE OUTLOOK (TO 2050)

Notable forecasts for 2050 DRI production range from 272 Mt (World Steel Dynamics) to 411 Mt (International Energy Agency's Sustainable Development Scenario), to 549 Mt (Wood Mackenzie's Accelerated Energy Transition 1.5o C Scenario). When respected agencies' 2050 forecasts differ by nearly 277 million tons, who do you believe?

I've been chastened in my belief that breakthrough smelting reduction technologies would have gained more traction by now as competition to the DRI-EAF steelmaking route. It now seems clear that the "tried and true," proven DRI technologies will be the ones to proliferate over the next several decades. Meanwhile, advancements in direct smelting technologies could slowly develop and ultimately impact DRI plant capacity growth rates. But so far, key to successful DRI technology acceptance has been the ability to provide flexible scale-up and capacity-matching to EAFs from small modules below 0.5 Mtpa to mega-modules over 1.0 Mtpa, reaching levels competitive with BF iron plants (having attained 2.5 Mtpy by a single shaft module). It likely will be a long time before breakthrough direct smelting technologies attain those capabilities and gain broader commercial acceptance.

HYDROGEN-BASED DRI-EAF STEELMAKING

Straight melting of scrap in an EAF combined with "green" power sources such as hydrogen results in much lower emissions and carbon footprint compared to traditional steelmaking. Melting scrap and DRI in an EAF is the next best alternative, as shown in the accompanying graphic[9].

On the path to decarbonizing the steel industry, there has been a strong interest in using hydrogen to a greater extent in both iron & steelmaking furnaces along with providing fossil-free electric power from renewable energy sources. Innovative "green steel" technologies in Sweden are employing the two most recognized and proven shaft furnace DRI technologies: H2 Green Steel, using the MIDREX® Process, and the HYBRIT consortium (LKAB, Vattenfall, and SSAB) using Tenova's EnergIron® DRI technology.

H2 Green Steel (Boden, Sweden)

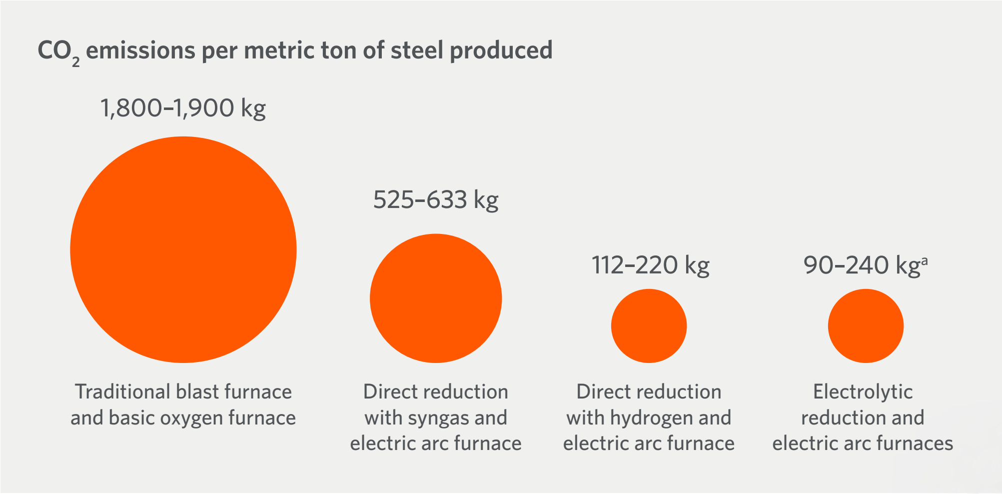
"Green hydrogen is produced by decomposing water into hydrogen and oxygen in a process known as electrolysis. H2 Green Steel will build a giga-scale electrolysis, powered by fossil-free electricity, as an integrated part of our production site, producing the green hydrogen needed to bring 5 million tonnes of high-quality steel to the market by 2030, with a gradual ramp up starting in 2025. The main area of use for our green hydrogen will be to reduce iron ore to direct-reduced-iron, DRI (also referred to as iron sponge, more commonly called "sponge iron"). By using green hydrogen instead of coal, we can reduce CO_2 emissions from the reduction process with around 95 percent."

HYBRIT (Vitåfors, Sweden)

"HYBRIT is already planning a larger demonstration plant in Vitåfors, Sweden, which would reach commercial-scale continuous production of 200 t of DRI per hour. (Martin) Pei (CTO of SSAB) says that this plant should help deliver fossil-free steel—which should have a carbon footprint less than 5% of that of conventional steel—to the market in 2026. SSAB plans to replace all its blast furnaces in Sweden and Finland so that it is entirely fossil-free by 2045."

GLOBAL TRADE IN DRI

Whether hot or cold in product form, most DRI is used in EAF steel plants adjacent to the DRI plants. Internationally traded DRI is relatively smaller in volume (8.8 Mt exported in 2022), representing only 7% of global DRI produced and 0.6% of global iron production. Exports for 2023 are likely to suffer a setback based on annualized ISSB data. DRI/HBI trade in 2024 may remain subdued given weak consumption growth for finished steel, trade sanctions on Russia impacting HBI trade flows in Europe, and rising Houthi attacks on seafarers (and associated military responses) in the Persian Gulf region. *Figure 1 (next page)* depicts the most recent annual export volumes of DRI.



Merchant CDRI is shipped to end users within the same country either by land (rail, truck) or by water (barge on inland waterways). Some is shipped overseas by ocean-going vessel and put to ground storage or transferred to barges. But the bulk of seaborne trade is as HBI, the denser, compacted form recognized to be the best DRI product form for long distance safe handling, transportation and storage. Major trade routes for DRI, as depicted in ***Figure 2*** include Trinidad and Tobago to the USA (CDRI), Russia to China, Turkey and Europe (HBI), USA to Mexico and Austria (HBI), and lower volume and intermittent exports (at or under 1 Mt/year) from Iran, India, Malaysia, Libya, Algeria, Venezuela, and other Persian Gulf countries (CDRI, HBI, and/or DRI chips, fines or off-grade products).

An essential part of defining the picture for total demand for DRI/HBI is understanding Customs trade data. IIMA, as a subscriber to International Steel Statistics Bureau (ISSB) data services, provides for its members access to global trade statistics for DRI/HBI, merchant pig iron, iron ore, and ferrous scrap and generates quarterly reports summarizing trade statistics for the first three products. ISSB uploads the Customs trade data via IIMA-designed Excel workbooks that facilitate sorting, filtering, and delving deeper into the trade patterns. Trade data IIMA receives often contains misclassifications of DRI products, missing information, and occasionally misplaced decimal points in recorded trade volumes. Consequently, IIMA's Trade Statistics Workforce endeavors to identify and address these problem areas with adjustments and/or estimates to provide proper representation of the trade data.

Midrex, likewise uses and analyzes ISSB data to determine what is and is not DRI/HBI trade. It also collects data from specific plants related to shipping to fill in some blanks in the ISSB data. Midrex records DRI/HBI shipments to third parties by land and water and reports the aggregate numbers in its annual DRI statistics report. Their reporting method results in much larger annual volumes of DRI trade than the purely cross-border trade reported by IIMA. According to Midrex, "shipments of DRI increased to a record of 25.7 Mt in 2022, a 13% increase from the previous record of 22.8 Mt in 2021. Land shipments made up the majority of the total in 2022, amounting to 15.7 Mt. However, water shipments showed a 25% increase compared to 2021." Land shipments were primarily in India and from India to neighboring regions. Shipments for 2023 and 2024 will likely increase modestly, with land-based plus inland river-based activity offsetting contraction

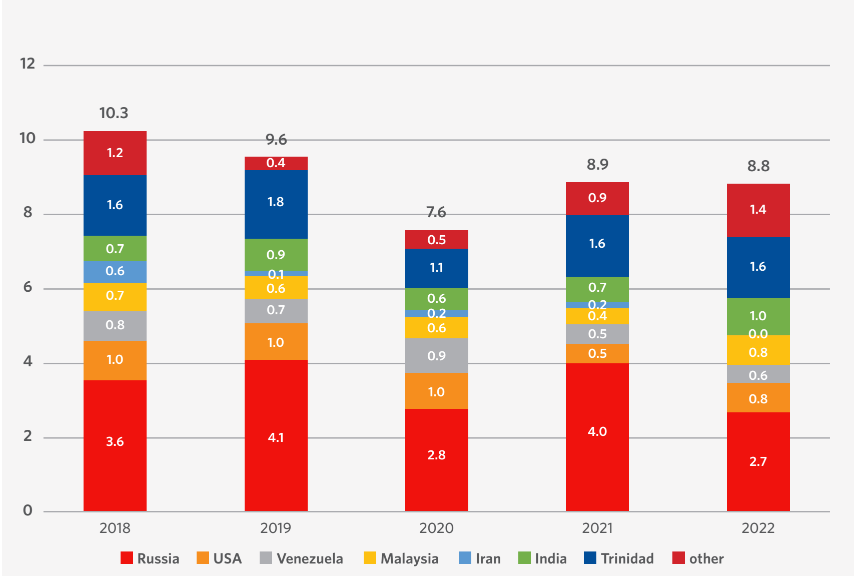
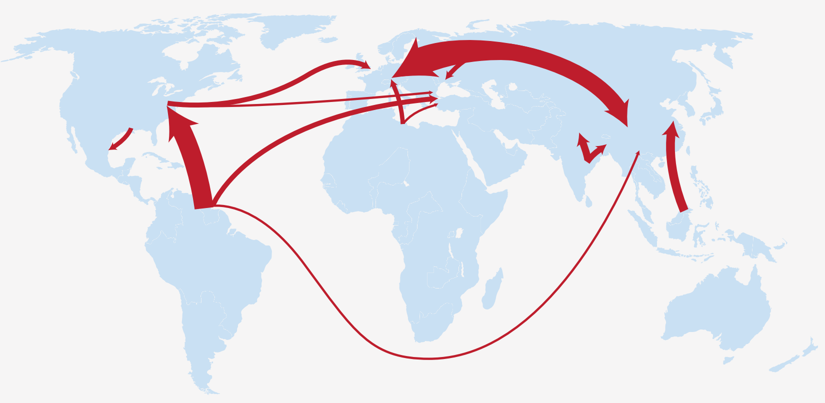


FIGURE 1. *Global Exports of DRI/HBI, 2018 - 2022*



The map shows the major routes of international transport of DRI in 2022. The width of the lines indicates the amount of DRI products that traveled over the individual routes.
NOTE: Domestic and smaller trade routes are not shown.

FIGURE 2. *Major Trade Routes for International Trade of DRI*

of ocean-going trade activity.

GROWTH IN DRI/HBI USE

Once considered a detriment in steelmaking because of extra gangue materials that increased power consumption and slag rates, the growth in production of DRI/HBI and increasing number of steel plants using DRI/HBI implies a growing product acceptance. Being made from virgin iron ore with only trace levels of tramp elements deleterious to steelmaking, a.k.a. "residuals," (oxides of Cu, Cr, Ni, Mo, Sn, Pb), DRI/HBI use allows for dilution of these unwanted elements found in ferrous scrap. Other recognized applications gaining acceptance include HBI use in blast furnaces for productivity enhancement and in basic oxygen furnaces as trim coolant. For some emerging and developing countries short on scrap, DRI/HBI use has been or is becoming a necessity, particularly where the local scrap reservoir is mostly obsolete ferrous scrap high in residuals.

CONCLUSION

At the outset of this article, I noted both the surge in DRI production and newly announced DRI plants; many of the latter attributed to efforts tied to decarbonization of the steel industry. Based on the growth trajectory, particularly since 2016, the use of DRI/HBI in steelmaking is likewise gaining broad acceptance globally. Hydrogen-enriched gas-based reduction of iron ore in DRI plants, plus arc furnace melting of DRI and scrap, currently offers the primary pathway for lowest carbon emission steelmaking. Other decarbonizing processes and breakthrough technologies over the longer range will no doubt be applied where practical and economical. But DRI will continue its strong growth as necessary supplements in making high quality steels and in helping to decarbonize the iron & steel industry.

References:

[1] For a list of DRI projects announced or under consideration, see IIMA website (metallics.org), Presentations, Whitepaper 3 Appendix 1 (May 2023)

[2] Iron carbide technology faced setbacks in the early '90s resulting in two commercial plant closures and technology abandonment

[3] BF Iron tonnages mostly represent "hot metal" transported as a high temperature liquid to steel furnaces, as distinguished from much lower global volumes hot metal poured and cast in molds (pig iron), and/or granulated and cooled for later use or shipment. World Steel Association BFI annual statistics; 2022 World Direct Reduction Statistics, Midrex®, October 2023

[4] World Steel Association SRO, October 17, 2023

[5] Assuming BF iron production remains at constant 2022 levels

[6] "DRI and the Pathway to Carbon-Neutral Steelmaking: Iron Ore Challenges," Chris Barrington, Chief Advisor, IIMA, 58th meeting of the Raw Materials Committee of the World Steel Association, May 2023

[7] SteelMint, "Chinese Mills Eye DRI Usage in Steelmaking to Lower Carbon Emissions," Oct. 28, 2023

[8] Ibid, footnote 4

[9] See H2 Green Steel website; italicized entries by this author for clarification

[10] IEEFA.org, Solving Iron Ore Quality issues for Low-Carbon Steel, August 2022

[11] IIMA 2023 internal whitepaper on OBMs (Customs data from ISSB with interpretive adjustments by IIMA). ISSB data lags of 5-6 months prevent meaningful depiction of 2023 exports

[12] 2022 World Direct Reduction Statistics, Midrex Technologies, Inc., Sep. 12, 2023, p. 9

[13] Pers. Communication with Midrex personnel

[14] Ibid (footnote 12), p. 10

Midrex News & Views

The full news articles are available on **www.midrex.com**

Midrex Preparing Operators & Managers for Sustainable Careers in Direct Reduction

Midrex is introducing a program to recruit and train the next generation of plant operators and managers. The immersive 21-week Operator Excellence Program is designed as a pathway to a career in the most dynamic and sustainable aspect of the global steel industry – direct reduction ironmaking. The OE Program is a blend of classroom and on-site instruction that imparts the knowledge, skills, and mindset needed to commission, operate, and manage the most advanced DRI plants.

The OE Program is structured in three phases:

- Phase 1: Classroom Training – A structured educational setting led by our most knowledgeable and experienced field operators. Our team will cover fundamental concepts and the relevant skills necessary for success in the field.
- Phase 2: On-Site Training – A rotation through positions in three MIDREX® Plants for hands-on training. This phase stresses practical application of the knowledge acquired in the classroom, fostering a deeper understanding and skill development in real-world scenarios.
- Phase 3: Assignment-Ready – An assignment to an actual commissioning and start-up team. The knowledge, skills, and experience acquired through the program empower confidence and leadership to excel throughout this new career.

Candidates for the OE Program should not require sponsorship. They will be full-time Midrex teammates with employment benefits that include comprehensive health insurance, competitive pay, and retirement savings. A high school diploma or equivalent, technical aptitude, experience with Microsoft Excel and Word, and experience working in a team environment are required along with problem solving ability and the flexibility to work overtime and various shifts, as needed. Previous experience in iron and steel production or chemical plant operations, OSHA 30-Hour Certification, and bilingual skills are preferred.

The willingness and ability for up to 90% international and/or domestic travel, often for six (6) months or longer is required. The training involves prolonged periods of sitting and working at a computer, as well as moving around plant sites and climbing ladders and stairs.

"Our carefully crafted learning environment emphasizes excellence and collaboration," according to David Durnovich, Director – Global Solutions, who started his career as an operations trainee at Midrex. "Graduates of the OE Program will emerge as industry pioneers to lead the way in successfully commissioning MIDREX® Plants. We believe in cultivating a community of professionals dedicated to shaping the future of our industry."

Midrex is hopeful of enrolling the initial OE Program class and beginning training in March 2024.

Midrex News & Views

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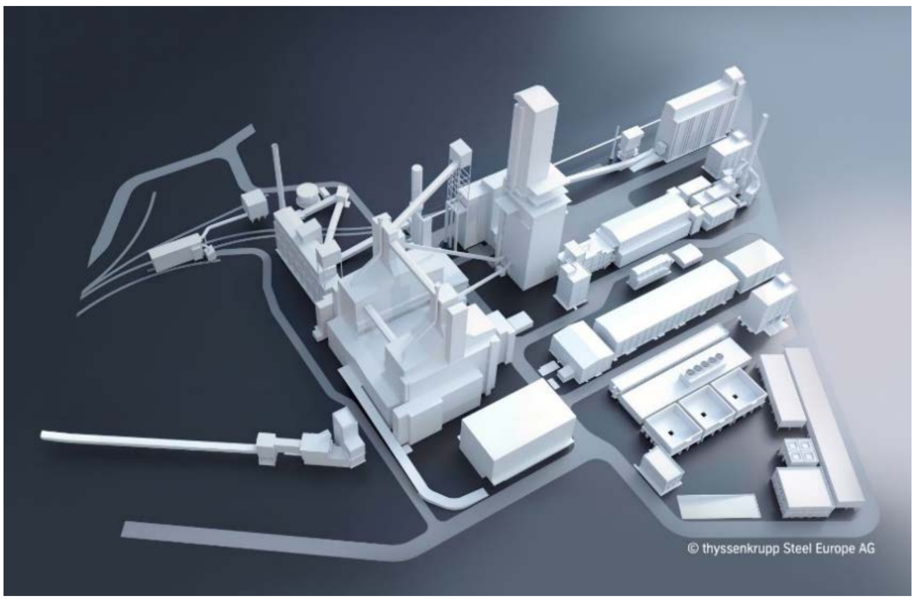
→ thyssenkrupp Steel Receives Construction Approval For Hydrogen-Ready DRI-Smelter Project



(Pictured left: 3D model of planned thyssenkrupp Steel Duisburg plant complex – courtey of thyssenkrupp Steel)

The hydrogen-based DRI plant is a major step in thyssenkrupp's conversion of its integrated steelworks to a climate-neutral production site.

Thyssenkrupp Steel Europe AG (TKS) has received approval from the Düsseldorf district government for early start of construction of the first direct reduction plant for hydrogen-based steel production. The approval notice is an important milestone in the approval process. Final approval is expected by the end of 2024.

"We are very pleased that the Düsseldorf district government has approved our application for an early start of construction so quickly," Dr. Arnd Köfler, Chief Technology Officer at TKS, said. "This means that we have cleared another important hurdle towards the realization of the first direct reduction plant at the Duisburg site and are taking a big step forward on the path to climate-neutral steel production."

Lauren Lorraine: **Editor**

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Midrex Technologies, Inc.

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