MIDREX

DIRECT FROM MIDREX

3RD QUARTER 2024

PATHWAYS TO GREEN STEEL

SYNERGIES BETWEEN SMS GROUP & MIDREX OFFER INNOVATIVE IRONMAKING SOLUTIONS

Rendering: thyssenkrupp Steel in Duisburg

COMMENTARY

INVESTING IN SERVICE EXCELLENCE

By Sean Boyle
Vice President – Commercial

Service isn't just about meeting needs—it goes beyond to encompass a holistic approach to partnership and collaboration. It's about understanding complex needs, delivering tailored solutions, and consistently driving mutual growth. When companies invest in service excellence, they don't just fulfill contractual obligations — they build trust, foster innovation, and create long-term value.

Service is a key aspect of buying a MIDREX® Plant. From the initial feasibility study to aftermarket parts, equipment, and upgrades, Midrex is there alongside the client to ensure they receive the full value for their investment.

As a company, Midrex is known for designing direct reduction plants and engineering ironmaking solutions that are specific to the individual needs of clients and have long, productive operating lives. Through our in-house expertise, together with strategic partnerships and the world's most knowledgeable plant operators, we assist in making the dream of energy-efficient, environmentally-responsible steelmaking a reality.

A direct reduction project typically involves four phases: Planning, Contracting, Constructing/Execution, and Operation. In the Planning Phase, we work with potential clients to frame the basic concept and perform a pre-feasibility study. This leads to either a more detailed feasibility study or directly into development of a technical specification and design basis for a plant. During this process a project manager is assigned, who works closely with the client to select the most effective technology configuration, develop the basic plant design, evaluate the economics and risks, and develop a commercial/technical proposal.

By the Contracting Phase, the design basis of the plant has been agreed to and the pace of the project accelerates. Discipline engineering proceeds and equipment specifications are developed which define the basis for the project. Schedules for utilities and raw materials consumption are calculated and negotiated. Midrex also assists in preparing the documentation required for project financing and in obtaining loan commitments from lenders. At the end of the Contracting Phase, final project contracts and agreements between the client and Midrex (sometimes with a consortium partner) are signed.

The Construction/Execution Phase opens with Midrex performing basic and detail engineering and procuring key plant equipment. During this time, Midrex will work alongside the client to finalize financing, project schedules, and offtake agreements. As plant construction starts, Midrex will deploy personnel to the site to advise on best practices for constructing a DR Plant. When construction is complete, a start-up and commissioning team prepares the plant for operation and conducts the Performance Guarantee Test, following which the plant is turned over to the client's personnel, who have completed intensive training including hands-on experience at an established MIDREX Plant.

The final phase is Operation, and Midrex continues to support our clients through our Technical Services department which is available to provide on-call assistance for any issues that may arise during plant operations. We also provide aftermarket support through our Midrex Global Solutions group which can assist with spare parts procurement, develop engineered solutions, and also deploy experienced field personnel to assist with any activities at the plant.

By partnering with Midrex, you become a vital member of an interactive family of owners and operators, dedicated to mutual success. As we navigate the complexities of the modern market, let us remember that at the heart of every thriving partnership lies a commitment to service excellence. It's this unwavering dedication to going above and beyond that will pave the way for continued growth and innovation in our industry.

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This issue includes articles about the role of the MIDREX® Reformer in hydrogen-based direct reduction and innovative ironmaking solutions on the pathway to green steel by SMS Group & Midrex. News & Views announces the Vale and Midrex cooperation, the Blastr Green Steel project in Finland, reports on 2023 DRI production, and recognizes significant MIDREX Plant anniversaries in 3Q.

PATHWAYS TO **GREEN STEEL**

SYNERGIES BETWEEN SMS GROUP & MIDREX OFFER INNOVATIVE IRONMAKING SOLUTIONS

By TIM OCHEL
Head of Green Steel, SMS group

By THIAGO CAMPOS
Head of Green Steel, SMS group

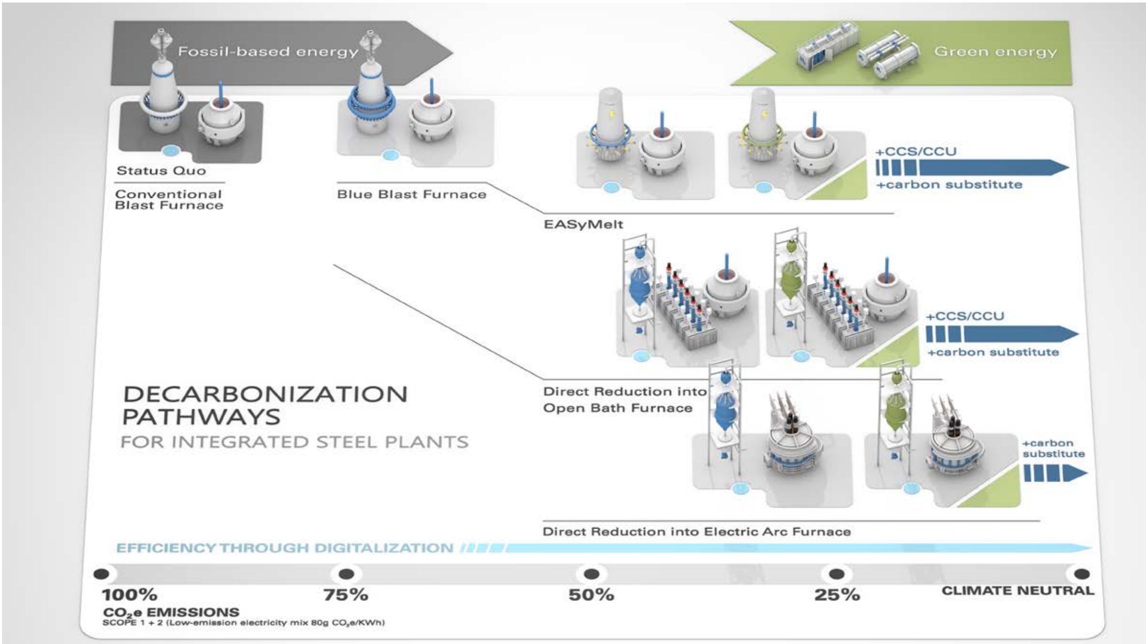
The green transformation of the steel industry is a marathon, not a sprint. By the middle of this decade, the partnership between SMS Group and Midrex Technologies, Inc. will launch the lighthouse projects, H2 Green Steel and thyssenkrupp Steel, demonstrating that carbon-neutral steel production is achievable. However, due to the long investment cycles for metallurgical plants, a large part of future carbon dioxide (CO_2) savings must come from the conversions of existing mills that take into consideration local conditions, such as iron ore quality, energy infrastructure, and existing equipment, as well as local policies, rules, and regulations.

In order to accelerate the decarbonization of the steel industry, it is essential to focus on the primary stage of ironmaking, as this stage accounts for more than 80% of the greenhouse gas (GHG) emissions from steel production. The technologies for achieving climate-neutral steelmaking are available right now – ready to be implemented in existing and future plants.

All three major decarbonization routes – direct reduction into electric arc furnace (EAF), direct reduction with intermediate melting, and upgrades to conventional ironmaking – have the potential to achieve climate neutrality by introducing innovative integrated process solutions in new (greenfield) or existing steel (brownfield) plants and by putting in place additional infrastructure for the use of fossil-free energy sources like hydrogen, biomass, or green electricity. Carbon capture can further be applied to go the last mile towards climate neutrality.

FULL RANGE OF DECARBONIZATION TECHNOLOGIES

Local conditions have a huge impact on the economic viability and feasibility of each of the decarbonization routes. Some decarbonization options rely on the availability of large amounts of electrical energy (preferably low-carbon) and



The Paul Wurth EASyMelt, the solution for conventional ironmaking.

occasionally, on an appropriate short circuit power supply. Other factors, such as raw material availability and local policies, rules, and regulations play a major part in technology selection.

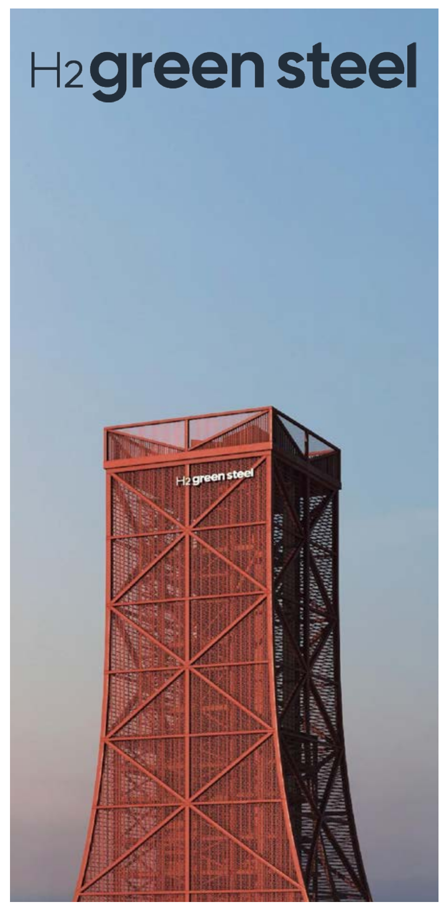
In greenfield facilities, the key to reducing GHG emissions to below 100 kg CO_2 per ton of hot rolled coil is the combination of green hydrogen, direct reduction, and the electrification of all downstream processes. The H2 Green Steel project in Boden, Sweden, is an excellent example. This first of its kind project aims to demonstrate the feasibility of producing high-quality direct reduced iron (DRI) using 100% hydrogen as the feed gas.

The assets and infrastructure of existing integrated steelworks (brownfield sites) can be transformed in a step-by-step process, with significant potential to replace carbon-based fuels. This process requires the ongoing reassessment and reorganization of energy balances and flows. SMS group and Midrex are supplying a hydrogen-ready direct reduction plant in combination with two open bath furnaces (OBF) to thyssenkrupp Steel in Duisburg, Germany. This groundbreaking project will allow the use of the broadest range of raw materials and the sustainable transition to 100% hydrogen-based ironmaking.

GREENFIELD CASE: DIRECT REDUCTION INTO AN ELECTRIC ARC FURNACE

For a greenfield project with green hydrogen available at competitive prices and in sufficient quantities, the DRI-EAF combination is the best solution. Case in point is H2 Green Steel, the world's first industrial-scale iron & steel plant based on hydrogen and electricity from renewable sources.

SMS group is supplying the technology for the first green steel plant in the world, which reduces CO_2 emissions by as much as 95% compared to conventional



integrated steel plants. The energy supply of H2 Green Steel is completely based on hydrogen and green electricity from renewable sources. SMS group and its consortium partner, Midrex Technologies, Inc., will provide a MIDREX H2™ plant, an EAF-based melt shop, a CSP® Nexus casting and hot rolling plant, as well as an advanced cold rolling and processing complex for the production of a broad product mix including Advanced High Strength Steel and automotive steel grades.

The landmark facility, located in Boden in northern Sweden, marks an important milestone in the transition of the European steel sector towards climate neutrality. Steel production is scheduled to start in 2025, followed by a ramp-up phase in 2026. Initial production will be over 2.5 million tons of green steel per year.

BROWNFIELD CASE: DIRECT REDUCTION INTO OPEN BATH FURNACE

The leading solution for decarbonizing existing sites is the combination of the well-proven MIDREX® Direct Reduction Process with an SMS Open Bath Electric Furnace (OBF) to replace blast furnace (BF) ironmaking. The first example of this technology will be installed at thyssenkrupp Steel (TKS), with expected start-up in 2026.

TKS expects to avoid as much as 6 million metric tons of CO_2 by 2030, representing well in excess of 30% of its emissions. The transformation to carbon-neutral production should be completed by 2045, at the latest.

The technology combines two key processes: the direct reduction of iron ore in a shaft furnace and the conversion of the resulting DRI into high-quality steel. The 2.5 million metric tons per year MIDREX Flex® plant will be operated with natural gas (NG) until sufficient hydrogen (H_2) becomes available. The OBF is similar in design to a conventional Submerged Arc Furnace (SAF) operated in a so-called 'brushed arc' mode. SMS group has several hundreds of references for these kinds of furnaces.

The combination of NG-based direct reduction together with an OBF already reduces CO_2 emissions by about 50% compared with the conventional BF-BOF route that requires coking coal. These emission savings are achieved thanks to the higher hydrogen content in NG. In a second step, the NG can gradually be replaced with H_2 as a reducing gas, which allows for further CO_2 reduction of up to around 65%.

The DRP-OBF combination will be seamlessly integrated into the existing iron and steel plant, thereby allowing all subsequent process steps from the steel mill onward to be maintained. Shaft furnace-based direct reduction plants (DRPs) typically require high-grade pellets or lump ores when paired with an EAF due to the EAF's inefficient processing of low-grade iron ores. Thanks to the reducing nature of the OBF, iron ores with lower iron content (low-grade) can be used in the DRP, thus making the production of H_2- based green steel from low-grade ore feasible in the future. The OBF accepts any pre-reduced iron ore feed including HBI, hot or cold DRI (HDRI or CDRI) pellets, and even DRI fines. Up to 10% of the OBF material feed can be comprised of agglomerated waste or free-flowing scrap. This allows steel plants to consume waste from their existing facilities by utilizing an inexpensive agglomeration process to prepare these for addition to the furnace. The OBF can also generate a slag similar to BF slag that can be granulated and sold to the cement industry.

BROWNFIELD CASE: UPGRADE BF WITH Paul Wurth EASyMelt

Although based on but going beyond the emission reduction potential of the blue blast furnace (i.e., the generation of synthesis gas consisting primarily of carbon monoxide and hydrogen and its injection into the lower shaft portion of the blast furnace), SMS group has developed the Paul Wurth EASyMelt. This electrically-assisted syngas smelter will function as an alternative to direct reduction and as a complementary method for filling the gap between iron ore availability and green steel demand.

EASyMelt is an electrified direct reduction and melting process, using a minor quantity of coke to entirely replace the traditional hot blast with gases like COG, NG, H_2, and ammonia (NH_3). Depending on the energy input, the technology can achieve emission savings of above 60% compared to the traditional BF-BOF route. Remaining direct emissions can be reduced by applying carbon capture or through the use of biomass. Using existing plants as a basis, EASyMelt is less CAPEX-intensive than other low-carbon ironmaking technologies.

The process is flexible in its input, adds resilience against supply shortages and market volatility, and can be adapted to various scenarios. Most importantly, traditional sinter feed can be used in EASyMelt, avoiding the fierce competition for the limited supply of high-grade pellets. Just like the blue blast furnace, EASyMelt can be realized in a step-wise approach of implementing several technological elements that work together to achieve net-zero ironmaking. The central elements are injection of reducing gas into the BF shaft, plasma-based superheating of the tuyere injection, and capturing of remaining emissions for storage or utilization.

THE FUTURE IS NOW

The technologies for achieving climate-neutral steelmaking are available right now, ready to be implemented in existing and future plants. The partnership with Midrex is a fundamental asset for SMS group to lead key projects for the steel industry transformation, such as H2 Green Steel in Sweden and TKS in Germany. To complete the benefits brought by direct reduction technologies for steelmaking decarbonization, SMS group counts on the fully integrated Paul Wurth blast furnace technology and the melting furnace know-how, environmental protection solutions, as well as gas recycling and slag granulation of SMS group. Together, we are focused on solving the metallurgical challenges and advancing hydrogen technologies for a greener steel industry.

THE ADAPTABLE MIDREX® REFORMER

A BRIDGE TO THE HYDROGEN ECONOMY

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INTRODUCTION

Decarbonization is key to the sustainability of the steel industry, and the use of green hydrogen is the ideal solution for reducing CO_2 emissions. A promising pathway to decarbonize iron and steelmaking is to replace the energy from fossil fuels with green hydrogen (H_2) and use it as the reducing gas to produce direct reduced iron (DRI). However, green H_2 is currently not widely available in sufficient quantities and at a cost that makes it competitive with existing direct reduction energy sources, such as natural gas (NG).

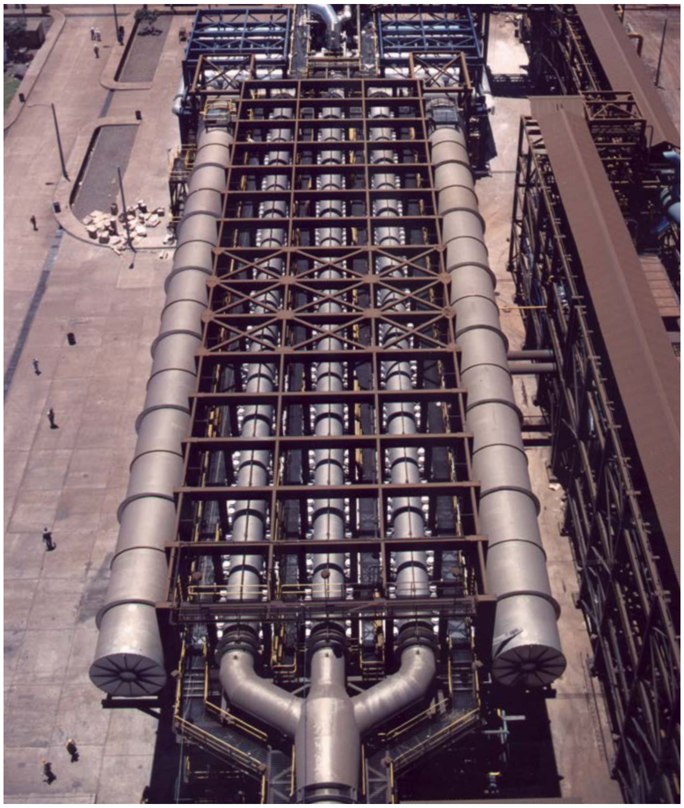
Clean-burning NG is typically used in the MIDREX® Direct Reduction Process, where 50% or more of the reformed reducing gas is composed of H_2. With MIDREX Flex® technology, steelmakers can adapt to the Hydrogen Economy at their pace while significantly reducing the CO_2 emissions associated with coking coal-based blast furnace (BF) ironmaking. The adaptability of the patented MIDREX Reformer, which mixes recycled gas from the MIDREX Shaft Furnace with fresh natural gas and catalytically reforms the mixture to create CO/H_2-rich reducing gas, allows operators to increase their use of H_2 up to 100%.

In 2023, Midrex constructed a full-scale single-tube reformer loaded with REFORMEX® catalyst at its Research & Development Technology Center to examine the effect of various H_2 concentrations on carbon deposition reactions in the reformer. This was used to demonstrate the performance of the catalyst across a wide range of operating conditions as the process transitioned from natural gas-based operation to hydrogen operation.

MIDREX REFORMER DEVELOPMENT

Currently, steam methane reforming (SMR) is the most widely used method to produce hydrogen, known as *gray hydrogen*. The SMR is a mature production process that uses high-temperature steam (700°C–1,000°C) with a methane (CH_4) source, such as natural gas, to produce H_2 and CO_2. This reaction is called *reforming*. There are approximately nine kilograms (kg) of CO_2 emitted per kg of H_2 production. When carbon capture and sequestration (CCS) technology is combined with SMR, from 50-90% of the H_2 can be recovered from the CO_2, which is called *blue hydrogen*.[3]

The MIDREX Reformer was developed to go beyond the capability of SMR and reform recycled, spent reducing gases from the direct reduction furnace, which include large quantities of reductants (H_2 and carbon monoxide, CO). In the direct reduction furnace, H_2 and CO are converted to oxidants (CO_2 and H_2O) as a result of the reduction process. The CO_2 and H_2O and the remaining H_2 and CO are mixed with CH_4 and recycled as feed gas to the MIDREX Reformer, which prepares fresh reducing gas. As there is a gas volume expansion, it is also used to fuel the burners.



When the designers set to work on the MIDREX Reformer, their goal was to allow spent reducing gases (a.k.a., furnace top gas) to be recycled and replenished in a directly coupled reformer. The benefits are numerous:

- Production of high-quality reducing gas with near stoichiometric CO_2 reforming allows 2/3 of the reduction furnace top gas to be recycled.
- Dual burner combustion system disposes of remaining spent reduction furnace top gas.
- CO_2 and H_2O in recycle gas provides oxidants needed for reforming.
- Proprietary technique prevents formation of Boudouard carbon on reformer catalyst*.
- High temperature catalytic reforming produces reformed gas temperatures (925-950°C) sufficient to be fed directly to the reduction furnace.
- High CO content provides close control of reduction furnace burden temperature and DRI carbon content.
- Reformer tubes arranged in rows facilitates uniform heating and single zone control.
- Ability to idle (stop reforming) and maintain reformer box internal temperature.

MIDREX REFORMER OPERATION

The MIDREX Reformer is a refractory-lined, gas-tight, welded steel structure containing bays of catalyst-filled alloy tubes arranged in equally spaced rows. The mild steel construction of the reformer bays allows for local fabrication in small, modular units for easy transport and erection.

The tubes are anchored at the roof of the reformer and allowed to expand downward through the reformer casing. The tubes have a heated length of approximately eight meters and measure either 200 or 250 mm internal diameter.

The bottom of each tube is fitted with a flexible expansion seal to prevent air infiltration into the reformer's combustion

* The Boudouard reaction describes the reaction of solid carbon (char) with carbon dioxide (CO_2) to produce carbon monoxide (CO). The reaction is highly endothermic, meaning the process absorbs energy from its surroundings usually in the form of heat.[1]

chamber. The pressure is kept slightly negative in the tubes to prevent leakage of flue gas. The reformer structure is anchored at its center and allowed to expand freely lengthwise in either direction to allow for thermal expansion on a series of lubricated bearing plates.

Preheated feed gas is distributed to the reformer tubes through headers running underneath the length of the reformer. The feed gas is supplied to the bottom of the individual reformer tubes through a flexible hose, which accommodates expansion of the tube, and the gas flows upward through the tube's catalyst. Hot reformed gas from each tube is collected in ducts located parallel to the longitudinal axis of the reformer. The ducts converge into a single supply duct to the reduction furnace.

The reformer is designed for up-flow of the feed gas and bottom-fired burners; thus all orifices, valves, and burners are located underneath the reformer box for convenience of operation and maintenance.

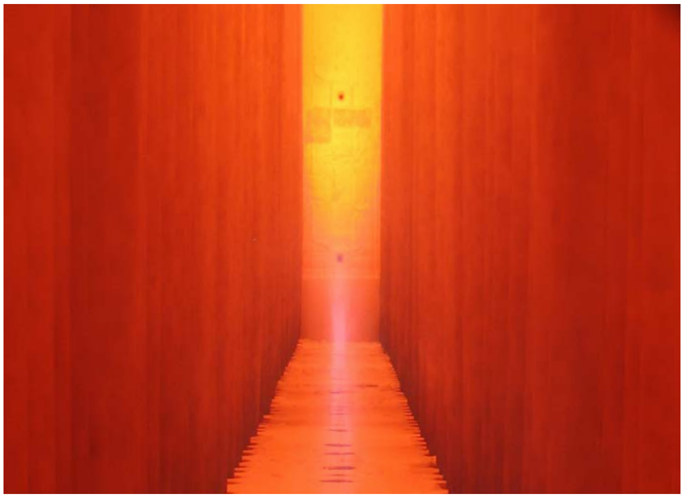
The reformer roof and sidewalls are covered by ceramic blanket insulation developed by Midrex, which replaces the traditional insulating firebricks and is less costly, faster to install, and easier to repair and maintain.

Both the main burners and the auxiliary burners are operated near stoichiometric combustion with about 1-2% oxygen in the flue gas. This results in high combustion efficiency and makes the flue gas suitable for use as inert gas elsewhere in the reduction process. Reformer temperature is uniformly maintained by a series of flues near the roof, which provide even collection of flue gas.

The reformer flue gas is used to preheat both the reformer main combustion air and feed gas streams. This heat recovery system provides an increase in reformer capacity and a reduction in the net plant energy consumption. The heat recovery system consists of combustion air recuperators, feed gas preheaters, natural gas preheaters, and an ejector stack.

The ejector stack pulls flue gas from the reformer through the heat recovery system before releasing it into the atmosphere. This flue gas exhaust system controls the reformer box pressure, which is important for protecting the reformer structure and maintaining fuel efficiency.

The combustion air recuperators are designed to preheat the combustion air to approximately 675˚ C, which lowers the energy consumption of the reformer and increases the combustion rate.



The feed gas preheaters are designed to heat the feed gas to approximately 540˚ C, which reduces energy consumption and increases reformer capacity.

REACTIONS OCCURING IN THE MIDREX REFORMER

Reforming reactions

$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ (1)

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ (2)

Water-Gas Shift (WGS) reaction

$CO + H_2O \leftrightarrow CO_2 + H_2$ (3)

Carbon Depositing reaction

$CO + H_2 \leftrightarrow C + H_2O$ (4)

$2CO \leftrightarrow C + CO_2$ (5)

$CH_4 \leftrightarrow C + 2H_2$ (6)

Reactions 4-6 are carbon depositing reactions and must be avoided in the reformer to prevent deactivation and degradation of catalyst. The CO reduction (4) and Boudouard reactions (5) are exothermic and are favored at lower temperatures (< 860 ˚C), whereas methane cracking (6) is endothermic and favored at higher temperature (> 1000 ˚C).[2]

Rostrup-Nielson and Christiansen proposed three different ways to evaluate the potential for carbon deposition for a given gas mixture in syngas production.[2,4] The first one is the *Principle of the Equilibrated Gas* in which carbon formation is to be expected on a catalyst if the gas shows affinity for carbon, the methane reforming is established, and the water-gas shift reaches equilibrium. The other two approaches are not at equilibrium conditions.

A second approach is the *Principle of Actual Gas*, in which the three carbon-forming reactions are considered separately. Carbon activity is calculated for each reaction, resulting in three different values. When the carbon activity for at least one reaction is ≥ 1 , carbon deposition may be expected. This method is the easiest because no complicated calculations are required. The *Principle of Actual Gas* is often used to assess the risk of carbon formation in a non-equilibrium, steady state process. In such case, the reaction quotient -instead of equilibrium constant - is calculated for actual, non-equilibrium concentrations[6].

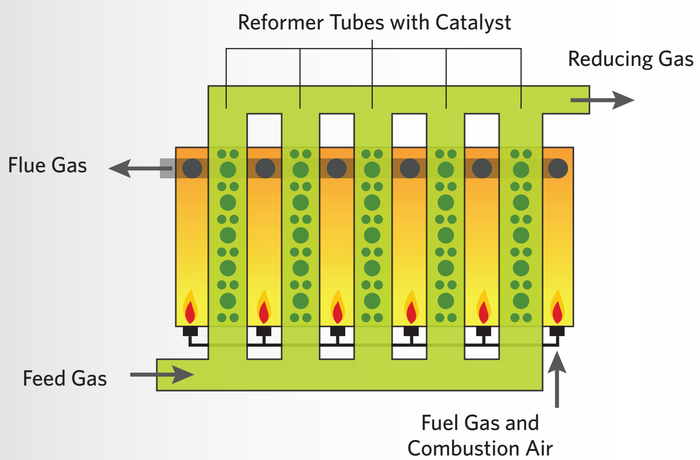
The third method is based on the steady-state carbon activity, in which the possible formation of carbon will be the result of the rates of carbon deposition for all three reactions. This is the most complete method since it encompasses both reaction thermodynamics and kinetics of carbon deposition. However, calculation of the rate of carbon deposition for each reaction is usually complicated.

Besides the approaches proposed by Rostrup-Nielson and Christiansen, surface carbon activity also plays an important role in the formation and morphology of carbon structures on nickel catalyst. Leung et al.[5] discovered that the morphology and rate of formation of carbonaceous species are controlled by a ratio of pressures $\chi = P_{CH4}P_{CO}/ P_{CO2}$ or $\psi = P_{CH4}P_{H2}/ P_{H2O}$ that uniquely determines the carbon activity on the metal surface and the thermodynamic driving force for carbon diffusion and filament formation. The carbon formation rates from the CH_4 – CO_2 and CH_4 – H_2O reactions on supported nickel catalysts are proportional to the pressure ratio χ and ψ. Details of the derivation and explanation of χ and ψ can be found in reference 5.

The carbon formation rates and the associated range of surface carbon activity can be divided into three regimes (depending on the χ and ψ) that determine the thermodynamic activity of carbon at the metal surface. Per Leung et al, in Regime I, surface carbon activity is insufficient to nucleate carbon filaments and no carbon structure is detectable. In Regime II, multiwalled carbon filaments similar in diameter to the nickel nanoparticles affixed to their ends are formed and the gradual growth of this "whisker" would eventually penetrate the pore wall and destroy the catalyst. At higher pressure values and the concomitant high carbon activity (Regime III), carbon supersaturation and simultaneous incipient nucleation of multiple carbon patches occur that ultimately coalescence to form carbon layer structures that encapsulate the nickel particles and block active surfaces for C–H activation reactions.

MANAGING THE TRANSITION TO H_2

The typical reducing gas of a natural gas-based MIDREX Plant is 55% H_2 and 35% CO ***(see Figure 1)***. However, hydrogen can displace up to 30% of the natural gas with little or no modification of the plant equipment. That means 20,000 Nm³/h of natural gas can be substituted by approximately 60,000 Nm³/h of H_2 in a 2.0 million t/y plant. The maximum hydrogen addition without modification of the flowsheet depends on a number of factors including the desired carbon level in the DRI.



TYPICAL COMPOSITION

	INLET	OUTLET
H_2	35	55
CO	19	35
CO_2	15	2
H_2O	13	6
CH_4	17	1
N_2	1	1
Temp. (°C)	580	980

FIGURE 1. *MIDREX Reformer cutaway and gas composition*

This technology is called MIDREX Flex® because it provides the flexibility to replace most of the natural gas feedstock with H_2 based on the plant's operating goals. MIDREX Flex technology allows for initial operation with reformed natural gas to take advantage of the reductions in CO_2 emissions compared with the production of blast furnace iron (reformed natural gas produced by the MIDREX Reformer contains ≈55% H_2). Over time, when hydrogen becomes available in sufficient quantities and at competitive prices, H_2 can displace increasing quantities of natural gas.

This approach offers the ability to make a sustainable transition while minimizing technology risks. The intermediate step of hydrogen addition requires few modifications to an existing plant and can be pre-engineered in a new plant. Converting to 100% H_2 operation will require modifications of some of the process equipment, as the process duties (flows, temperature, gas composition etc.) will change. However, the MIDREX Reformer is adaptable for the entire transition, as it becomes purely a heater when using 100% H_2. *(See "Fueling the Future of Ironmaking: MIDREX Flex™" by Geoff Wallwork in 1Q2024 DFM.)*

The key aspects of MIDREX Flex are shown in *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.

The MIDREX Process owes much of its success to energy efficiency, which is the result of a well-developed recycling system that minimizes waste. The process engineer for a natural gas-based MIDREX Plant can choose the material balance of a proposed plant with little effort because the reformer performance is well understood. As the industry transitions to a hydrogen economy, the feed gas composition will necessarily change and the MIDREX Reformer will be asked to operate with larger amounts of hydrogen injection. Thermodynamic data

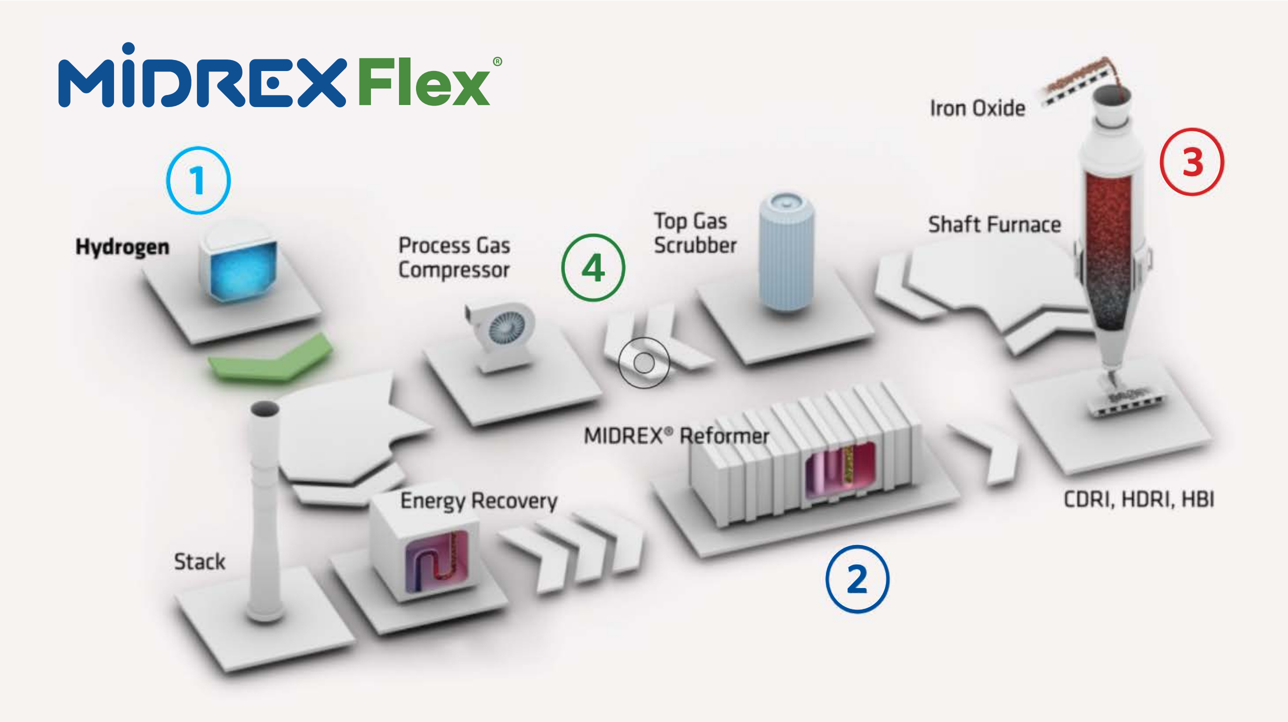


FIGURE 2. *MIDREX Flex*

can provide a reasonable guess of reformer behavior, but the answer cannot be fully known until these conditions are tested.

MIDREX REFORMER ADAPTABILITY TEST

In 2023, Midrex constructed a full-scale 10" diameter, single-tube reformer loaded with active catalyst at the Midrex Research & Development Technology Center to conduct a comprehensive study that examined the effect of varying H_2 concentrations on carbon deposition reactions in the reformer. In this Catalyst Pilot Facility (CPF), hydrogen was introduced upstream of the reformer to match the MIDREX Flex feed gas conditions so the robustness of the reformer design could be examined. The test cases with NG replacement ranging from 0-80% are shown in ***Table I***. Cases 1-4 were performed at the same reformer feed gas temperature of 580° C. As H_2 addition to the process increased, the amount of reforming required to maintain the flow of reductant to the shaft furnace decreased significantly. During the test, the reformer feed gas flow rate was adjusted to account for the drop in reformer heat load as the H_2 transition progressed while the reformed gas temperature and system temperature were held constant. The first case simulated 100% NG condition and was performed to confirm that the CPF can adequately replicate commercial operation. Once this baseline case was conducted with acceptable agreement to established plant data, the other cases with different levels of hydrogen replacement were tested.

The carbon activities, Gibbs free energies, and surface carbon activities of reactions 4 and 5 are shown in ***Figure 3***. From ***Figure 3***, we can see that although the Gibbs energy for carbon formation in all cases is within the same magnitude, the pressure ratios, which are proportional to the surface carbon activity, are the lowest in case 4. Nevertheless, the pressure ratios of all these cases fall within Regime III. According to Leung's theory on surface carbon activities, the carbon would form an encapsulating structure around the nickel rather than filament that would destroy the catalyst. Therefore, we hypothesized that carbon would accumulate on the nickel catalyst over time accompanied by a gradual decrease in reforming and carbon deposition rates, similar to the current operation[6].

	UNIT	CASE 1 (NG)	CASE 2 (30%)	CASE 3 (50%)	CASE 4 (80%)*
Temp	°C	~580	~580	~580	~580
Pressure	Barg	2.8	2.8	2.8	2.8
Nominal Flow	Nm³/h	> 500	> 479	> 484	> 630
CO	Vol%	> 15	> 10	> 10	> 5
H_2		< 30	< 40	< 55	< 70
CH_4, CO_2, N_2, H_2O		Bal	Bal	Bal	Bal

** Replacement based on energy*

TABLE I. *Reformer Feed Gas Composition*

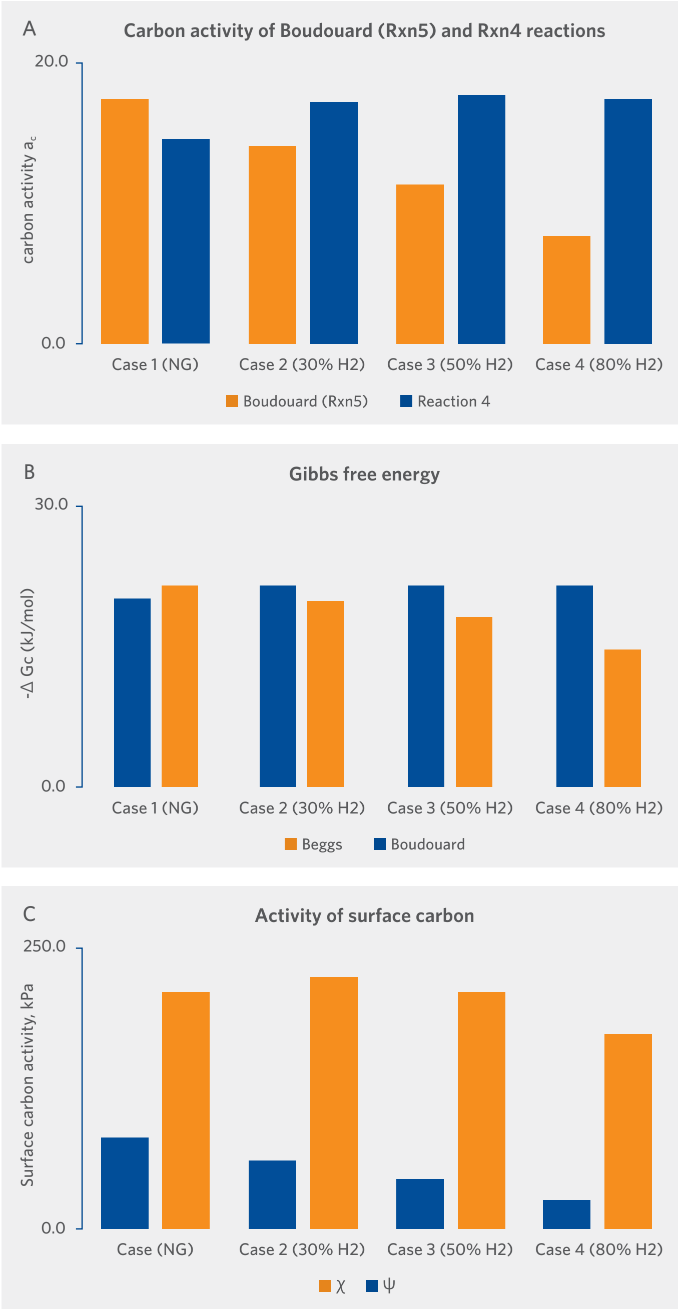


FIGURE 3. ***a)*** *Carbon activities (ac) of Boudouard reaction and reaction 4 calculated using the Principle of Equilibrated Gas.,* ***b)*** *Gibbs free energy of carbon formation of the Boudouard reaction and reaction 4.* ***c)*** *Comparison of pressure ratios (χ and ψ) of the four cases.*

As the reformer transitions from 100% NG operation to H_2 operation, there is a steady change in the operating mode of the reformer. The reformed gas quality is a critical operating target of the MIDREX Reformer. Reformed gas quality is defined as $(CO + H_2)/(H_2O + CO_2)$ in the reformed gas. Reformed gas quality in the operation of a 100% natural gas-based reformer is controlled by balancing the reformed gas H_2/CO ratio, the reformed gas CO_2 level and to a lesser degree, the reformed gas temperature. For example, higher H_2/CO ratios and reformed gas CO_2 levels result in lower reformed gas quality. Maintaining the reformed gas quality ≥ 9.5 is always a priority during H_2 transition for the optimum performance of the shaft furnace.

The Midrex CPF campaign was launched and successfully completed in fall 2023. During this period, the CPF - particularly the catalyst - had been revolving from natural gas case through a series of hydrogen cases with varying degree of carbon activity, and alternating between start-up, idling, operation, and shutdown conditions, while still retaining its qualities. The achieved reformed gas compositions as the reformer operation transitioned from 100% natural gas to the 80% case are presented in ***Table II***.

SUMMARY & CONCLUSIONS

The heat transfer properties of the MIDREX Reformer tubes among the different cases were a major area of interest during the test campaign. It is true that overall heat load is expected to decrease with higher levels of hydrogen replacement since reforming is endothermic and there would be less of it. However, it was prudent to verify that the MIDREX Reformer can sustain the change in reforming reaction kinetics and sensible heat load and heat the reformed gas to the appropriate temperature with the same physical design and arrangement while transitioning to hydrogen operation. The test campaign answered this question in the affirmative for the 10" diameter reformer tube. It was found that as hydrogen replacement increases, the ratio between sensible heat and reaction increases without compromising the integrity of the tube. It was also determined that the existing MIDREX Reformer tube design can produce the required quantity and quality of reformed gas.

The Catalyst Pilot Facility (CPF) test campaign successfully proved that the existing MIDREX Reformer design can adapt to the change in reformer feed gas composition and thermophysical properties, flow rate, feed gas temperature, and reforming heat load, while maintaining the performance of the REFORMEX® catalyst.

	UNIT	CASE 1 (NG)	CASE 2 (30%)	CASE 3 (50%)	CASE 4 (80%)
RG temp	°C	956	980	978	995
RG flow rate	Nm^3/h	779	740	618	700
H_2/CO		> 1.5	> 2.0	> 3.0	> 6.5
RG quality		> 11	> 10	> 10	> 13
CH_4 slip	Mol%	< 0.6	< 0.6	< 0.4	< 0.4
CO_2 slip	Mol%	< 2	< 2	< 2.0	< 1.0

TABLE II. *Test results of the different cases examined during the catalyst Pilot Facility (CPF) campaign.*

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This article is based on a paper titled, "A Study on the Patented MIDREX Reformer and Its Adaptability to the H2 Economy." Presented at the AISTech Conference and Exposition, May 6-9, 2024, in Columbus, OH.

Midrex News & Views

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

135.7 Mt of DRI Produced Globally in 2023

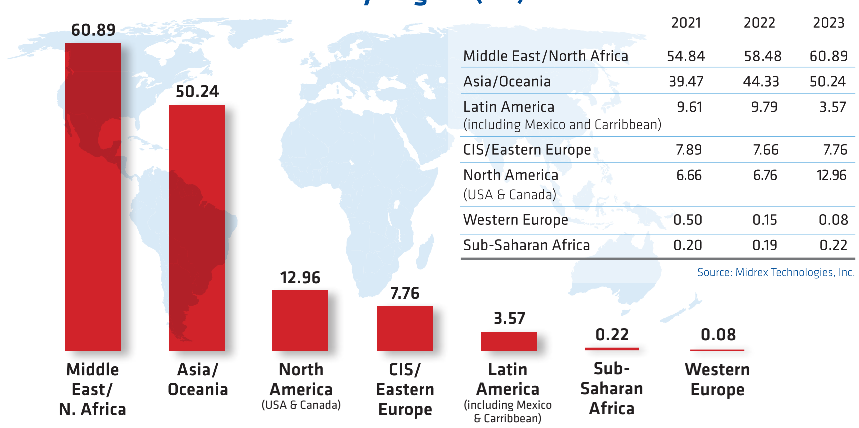
MIDREX PUBLISHES *WORLD DIRECT REDUCTION STATISTICS*

Global direct reduced iron (DRI) production in 2023 was 135.7 million tons (Mt), up by 8.3Mt or 6.5% from the previous record of 127.4 Mt set in 2022. In the last five years, worldwide DRI output has grown by almost 27.6 Mt, or approximately 25.6%.

MIDREX® Plants produced 75.7 Mt of DRI in 2023, which is 3.0% more than the 73.6 Mt produced in 2022. MIDREX Technology continued to account for ~80% of worldwide production of DRI by shaft furnaces in 2023: 95.4 Mt. MIDREX Plants have produced a cumulative total of approximately 1,400 Mt of all forms of DRI (CDRI, HDRI, and HBI) through the end of 2023.

Each year Midrex Technologies, Inc. compiles and publishes World Direct Reduction Statistics as a resource for the global iron and steel industry. World Steel Dynamics (WSD) audits the data collection and preparation processes used by Midrex to confirm that the methodology and accuracy of the data to be published is representative of the global direct reduction industry in a given year.

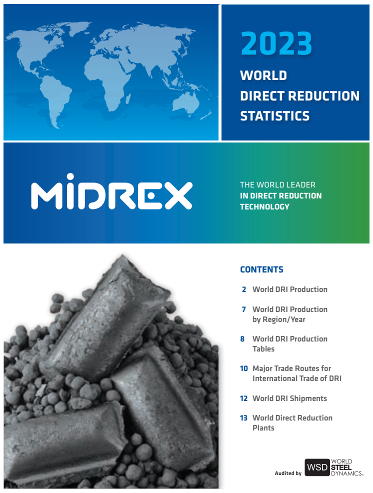
2023 World DRI Production by Region (Mt)



	2021	2022	2023
Middle East/North Africa	54.84	58.48	60.89
Asia/Oceania	39.47	44.33	50.24
Latin America (including Mexico and Carribbean)	9.61	9.79	3.57
CIS/Eastern Europe	7.89	7.66	7.76
North America (USA & Canada)	6.66	6.76	12.96
Western Europe	0.50	0.15	0.08
Sub-Saharan Africa	0.20	0.19	0.22

Source: Midrex Technologies, Inc.

2023 World Direct Reduction Statistics is available for download at www.midrex.com



Midrex Technologies, Inc. compiles and publishes ***World Direct Reduction Statistics*** annually as a resource for the global iron and steel industry. To prepare the annual statistics, Midrex requests inputs from every known direct reduction producer either directly or indirectly through partner organizations. Where plant information is not available directly or indirectly from producers, Midrex obtains the information from publicly available data.

World Steel Dynamics (WSD) audits the data collection and preparation processes used by Midrex to confirm that the methodology and accuracy of the data to be published is representative of the global direct reduction industry in a given year.

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Vale and Midrex to Cooperate for Use of Iron Ore Briquettes in Direct Reduction Plants

Vale and Midrex Technologies, Inc. have agreed to cooperate in advancing a technical solution for the use of iron ore briquettes in direct reduction plants. Executives of the two companies met at the Midrex Research & Technology Development Center and signed a Technical Cooperation Agreement, united by a common vision for steelmaking decarbonization.

The agreement extends the parties' technical cooperation and test work developed over the last year. Vale's proprietary briquetting technology enables the production of high-quality iron ore agglomerates from the low-temperature process using a technological solution of binders, which gives the final product high mechanical strength.

Initial test results have shown promising results in using iron ore briquettes in the direct reduction process. Once the technology has been successfully demonstrated in MIDREX® Plants, both partners plan to evaluate the creation of a joint venture to exclusively provide briquette technology and facilities to the market.

Currently, most direct reduction plants use iron ore pellets as a feedstock. Vale's briquette production process represents an alternative to the pelletizing process with lower production costs, lower investment intensity, and approximately 80% less CO_2 emission.

Through direct reduction technology, Direct Reduction Iron (DRI) is produced. DRI is a critical feedstock to produce high-quality steel with fewer impurities in Electric Arc Furnaces (EAFs). DRI can also be used in Blast Furnaces (BFs) to supplement and replace iron ore, reducing the need for coke and carbon emissions.

Direct reduction technology has a lower CO_2 footprint compared to other ironmaking processes, as it uses natural gas as the reduction agent instead of coke – an input obtained from mineral coal. Using green hydrogen instead of natural gas enables the production of green steel with near-zero GHG emissions.

VALE

Vale is a global mining company that exists to improve lives and transform the future together. One of the world's largest producers of iron ore and nickel and a major copper producer, Vale is headquartered in Brazil and operates around the world. Its operations comprise integrated logistics systems, including approximately 2,000 kilometres of railways, marine terminals and 10 ports distributed around the globe. Vale has the ambition to be recognized by society as a benchmark in safety, the best-in-class reliable operator, a talent-driven organization, a leader in sustainable mining, and a benchmark in creating and sharing value.

For more information, visit **https://vale.com**.

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Midrex and Primetals selected by Blastr

MIDREX H2™ Plant to produce 2.0 million tons of DRI per year

BLASTR Green Steel

The 2.0 million tons per year MIDREX H2™ Plant will be located in Inkoo, Finland.

Midrex Technologies, Inc. and Primetals Technologies have been selected to supply a hydrogen direct reduced iron (DRI) plant for Blastr Green Steel, one of the largest industry start-ups in the Nordic region. The 2.0 million tons per year MIDREX H2™ Plant will be located in Inkoo, Finland, that provides a strong grid connection, optimal logistics, and stable, competitively priced low CO_2 energy. The DRI plant is part of an ultra-low CO_2 emissions 2.5 million tonnes per year steelmaking facility, which will be supplied by Primetals in partnership with Blastr.

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MIDREX® Plants with 3rd Quarter Anniversaries

Midrex is known for designing, engineering, and servicing reliable direct reduction plants, as well as for making certain that these plants have long and successful operating lives. This issue of ***Direct From Midrex*** recognizes the start-up of Antara Steel Mills HBI on Labuan Island, FT, Sabah, Malaysia – 40 years; Libyan Iron and Steel Company (LISCO), Module I in Misurata, Libya – 35 years; JSW Steel (Dolvi Works) in Dolvi, Maharashta, India – 30 years; ArcelorMittal/Nippon Steel India, Module IV, in Hazira, Gujarat, India – 20 years; JSPL (Angul Works) in Angul, Odisha, India – 10 years; and JSW (Toranagallu Works) in Toranagallu, Karnataka, India – 10 years.

Antara Steel Mills HBI

STARTED **40 YEARS** AGO IN THE 3RD QUARTER

Location: Labuan Island, FT, Sabah, Malaysia

- Start-up: August 1984
- Product: HBI
- Rated Capacity: 0.65 million tons/year

The first MIDREX HBI Module was started up in August 1984 for Sabah Gas Industries, which later became part of the Lion Group as Antara Steel Mills HBI. Esteel Enterprise of Singapore completed acquisition of the HBI plant in 2022.

Antara Steel Mills HBI operated 9% over its annual rated capacity in 2023, following a record-setting year in 2022 of 20% over rated capacity. Total iron content averaged 92.63% for the year. All production was shipped by water to third parties. Cumulative HBI production through 2022 is more than 23.3 million tons.

Libyan Iron and Steel Company (LISCO) Module 1


(LISCO 1-3, from front to rear)

STARTED **35 YEARS** AGO IN THE 3RD QUARTER

Location: Misurata, Libya

- Start-up: July 1989
- Product: CDRI
- Capacities: 0.55 million tons/year

Production by LISCO's three modules increased significantly in 2023 compared to previous years. Modules 1 & 2 produce CDRI for the LISCO steel mill, while Module 3 produces HBI for export.

The three modules combined to set a multi-module production record that was last set in 2005 and eclipsed the 35 million tons milestone for cumulative production.

Read more about Libya Iron and Steel Company (LISCO) at: **https://libyansteel.com**

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MIDREX® Plants with 3rd Quarter Anniversaries

(continued)

JSW Steel (Dolvi)

STARTED **30 YEARS** AGO
IN THE 3RD QUARTER

Location: Raigad, Maharashtra, India

- Start-up: September 1994
- Product: CDRI
- Rated Capacity: 1.0 million tons/year

JSW Steel's MIDREX Module easily exceeded its rated capacity in 2023 and operated 8198 hours. Approximately 10% of the module's energy input is COG injected to the shaft furnace to reduce natural gas consumption.

JSW Steel (Dolvi) has averaged 8044 hours of operation per year since its initial start-up in 1994, and 8149 hours per year in the last 8 years. Its cumulative production through 2022 is almost 33.2 million tons.

Read more about JSW Steel and its Dolvi Works at: **https://www.jswsteel.in**

ArcelorMittal/Nippon Steel India IV

STARTED **20 YEARS** AGO
IN THE 3RD QUARTER

Location: Hazira, Gujurat, India

- Start-up: July 2004
- Product: HBI/HDRI
- Capacity: 1.0 million tons/year

Module IV established new annual productivity & electricity consumption records in 2023, as well as a new monthly production record in May.

All six modules combined have produced over 91 Mt of HDRI, HBI, and CDRI since start-up of the first two modules in 1990. Approximately 96% of the output from the four HDRI/HBI modules was in the form of HDRI, while Modules I and VI produce CDRI exclusively.

Read more about ArcelorMittal/Nippon Steel India at: **https://www.amns.in**

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MIDREX® Plants with 3rd Quarter Anniversaries

(continued)

JSPL (Angul)

STARTED **10 YEARS** AGO IN THE 3RD QUARTER

Location: Angul, Odisha, India

- Start-up: July 2014
- Product: HDRI/CDRI
- Capacity: 1.8 million tons/year

This is the first MxCol Plant using synthesis gas from coal gasifiers to produce both HDRI and CDRI for the adjacent steel shop. Through 2022, the plant had produced more than 5.3 million tons of DRI.

A hot DRI conveying system is installed from the MIDREX Plant to the melt shop. HDRI production was 54% of total production in 2023. COG was used in the DR plant throughout the year, averaging ~15% of the plant's energy requirements.

Read more about JSPL and its Angul Works at: **https://jindalshadeed.com/odisha**

JSW Steel (Toranagallu)

STARTED **10 YEARS** AGO IN THE 3RD QUARTER

Location: Toranagallu, Karnataka, India

- Start-up: August 2014
- Product: HDRI/CDRI
- Capacity: 1.2 million tons/year

JSW Steel (Toranagallu) using COREX export gas as energy input, operated over 8000 hours in 2023. Through 2022, the plant had produced almost 6.9 million tons of DRI.

A hot DRI conveying system is installed from the MIDREX Plant to the melt shop. 55% of production went to the steel shop as HDRI.

Read more about JSPL and its Toranagallu Works at: **https://www.jswsteel.in**

Lauren Lorraine: **Editor**

DIRECT FROM MIDREX is published quarterly by Midrex Technologies, Inc.,
3735 Glen Lake Drive, Suite 400, Charlotte,
North Carolina 28208 U.S.A.
Phone: (704) 373-1600 Fax: (704) 373-1611,
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