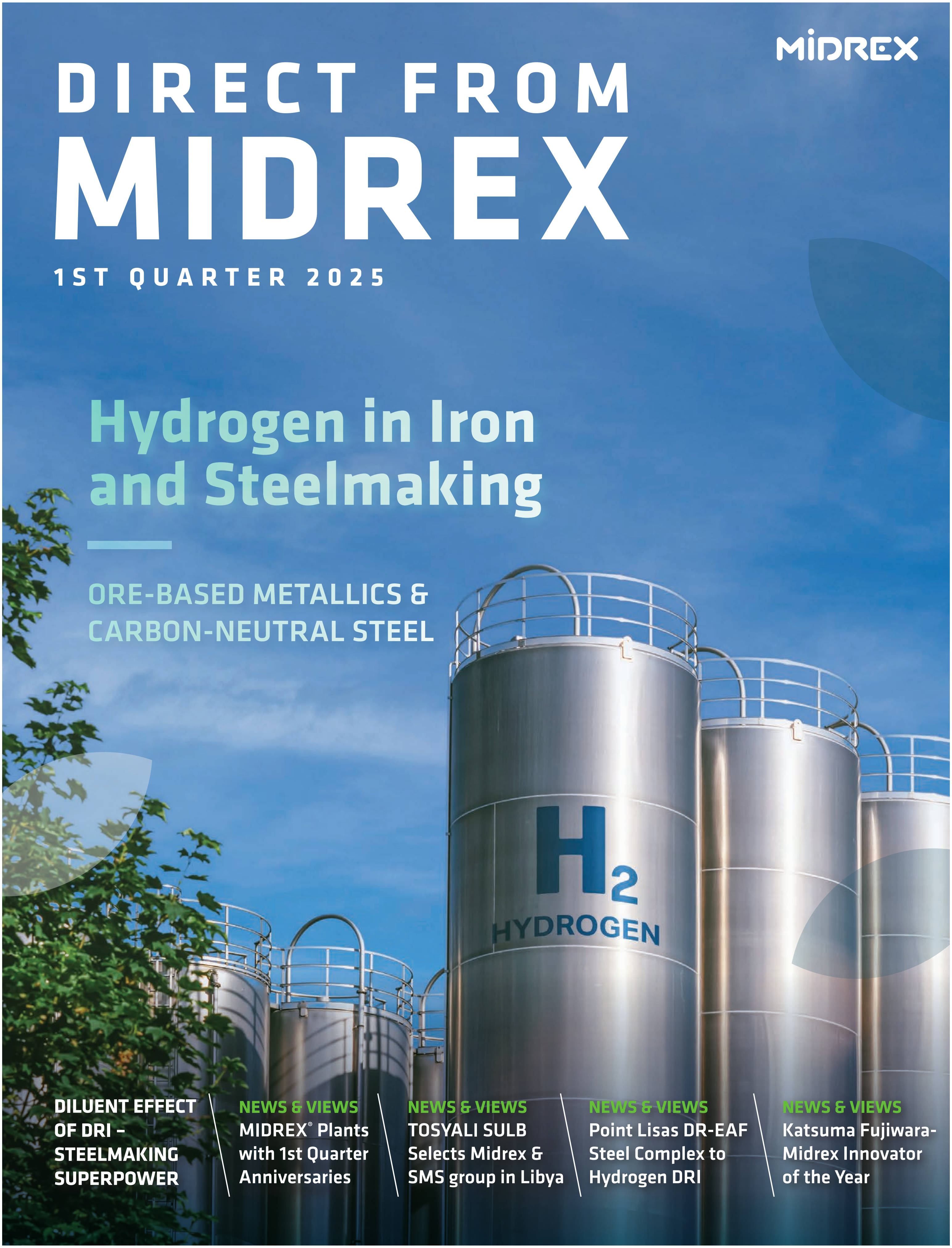
DIRECT FROM MIDREX

1ST QUARTER 2025



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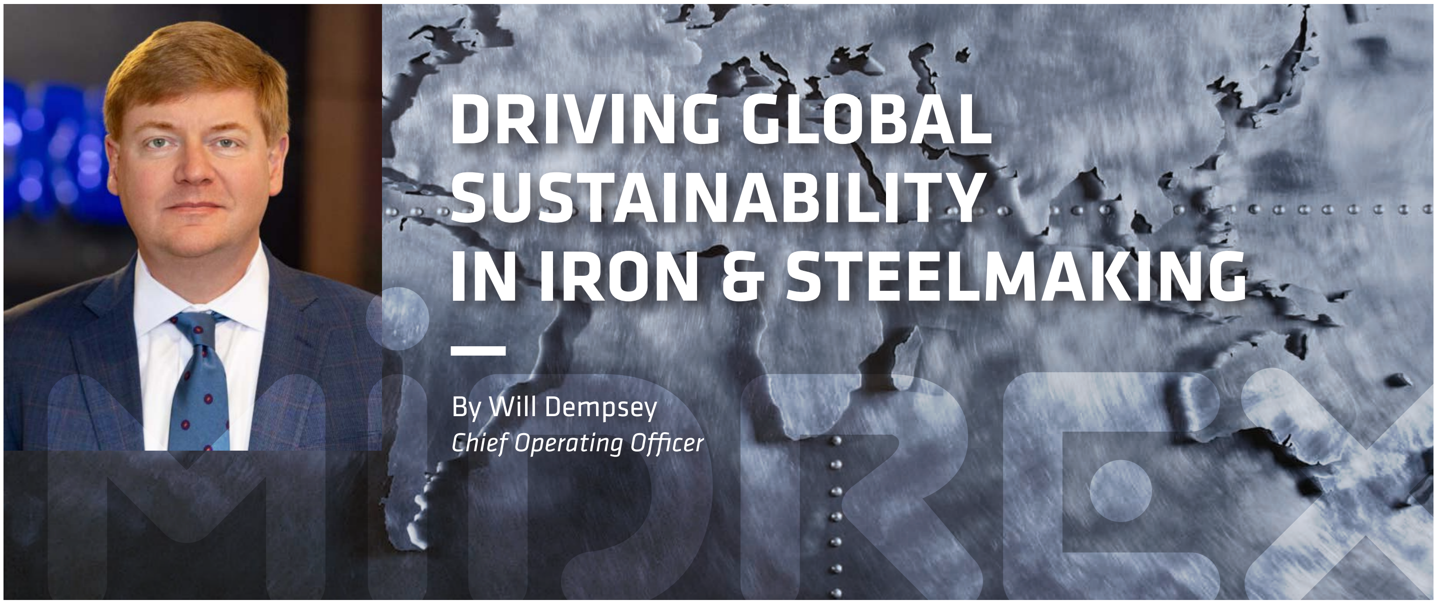

DRIVING GLOBAL SUSTAINABILITY IN IRON & STEELMAKING

By Will Dempsey
Chief Operating Officer

For over 50 years, Midrex has evolved from primarily a technology developer and research & technology development center to a global name recognized in decarbonizing iron and steel production. Originally part of the Korf Group, Midrex's early focus was on proving the technical merits of the MIDREX® Process, which included building and operating test facilities to evaluate iron ores and demonstrate how they would react in a Midrex-designed reduction furnace. Since Kobe Steel's acquisition in 1983, Midrex has not only continued as the research & development center of all direct reduction-related activities but has taken on the responsibility of managing commercial activities. This includes plant sales development, the selection and coordination of construction partners, and reciprocal relationships with MIDREX Plant operators (process licensees) around the world.

Today, Midrex operates across the globe, from its Charlotte headquarters to offices in the UK, UAE, India, and China. Our teams manage everything from engineering and plant optimization to facilitating financing for new projects. Collectively, MIDREX Plants have produced more direct reduced iron (DRI) than all other DRI plants combined.

As COO, I am proud to build on the foundation President and CEO K.C. Woody laid. My focus is on integrating operations, sales, and marketing across our global offices to enhance coordination and strengthen support for our plant operators. In 2025, through our Global Services team, we will make available advanced digitalization for operations throughout the family of MIDREX Plants.

GLOBAL REACH AND REGIONAL EXPERTISE

Midrex UK Limited

Midrex UK, established in 2009, was our first permanent office located outside the US. It has been extraordinarily successful in helping our clients access financing expertise and Export Credit Agency (ECA) resources through UK Export Finance (UKEF), which provides both sovereign guarantees for commercial bank loans and direct lending. The office provides an excellent location for meeting with potential clients and suppliers, as well as ready access to a wealth of commercial and investment banks and financial consultants.

COMMENTARY

Midrex Technologies India Private, Ltd.

With the increased interest in direct reduction as the preferred ironmaking process for decarbonizing steel production, Midrex India opened in 2011 to provide regional sales and support services as well as financial and administrative support for Midrex offices in Dubai and Shanghai. Midrex established the India Engineering Center in 2022 as a multi-discipline team of engineers and designers trained on Midrex systems and designs, thus enabling Midrex to conduct seamless project engineering around the clock. They support project estimating and proposal preparation, as well as provide site support, commissioning and start-up assistance, and plant lifecycle engineering solutions.

Midrex Technologies Gulf Services FZCO

The decision to establish a hub for Midrex Global Services support in the MENA region and Eastern Hemisphere resulted in the opening of Midrex Technologies Gulf Services FZCO in Dubai, UAE, in 2019. The office places Midrex customer support resources closer to our clients and licensees to provide faster response time and increased flexibility. Midrex Gulf Services is equipped to provide integrated plant solutions that are a tailored fit for each specific operation.

Midrex Metallurgy Technology Services (Shanghai) Ltd.

There is no doubt that China will become a major market for direct reduction processes. Since 2011, we have maintained an office in Shanghai to identify and develop opportunities for both Midrex and Kobe Steel products and technologies and ensure we are synchronized with the pace of change in the Chinese steel industry.

At Midrex, we believe the best technology solutions are ethical, elegant, practical, and completely satisfy the needs of our clients. Through the coordinated efforts of our teammates around the world, we are striving every day to deliver on that belief and ensure a more sustainable future for iron and steel production.

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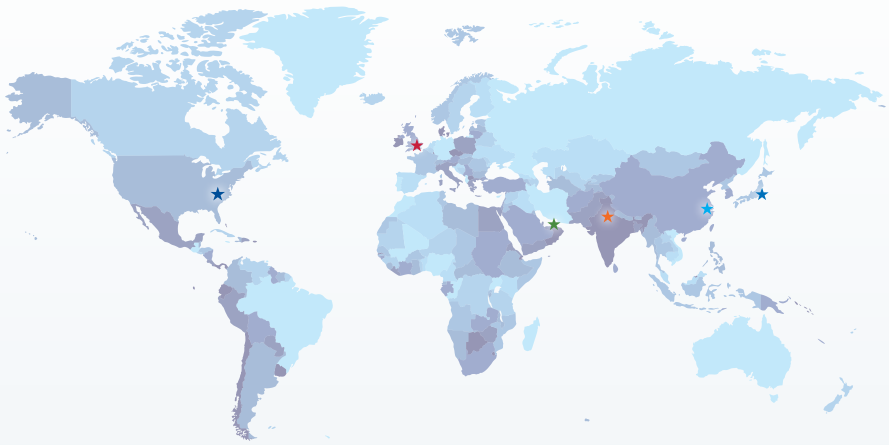
This issue of *Direct From Midrex* includes insights into hydrogen in iron and steelmaking from an International Iron Metallics Association (IIMA) white paper and a discussion of the diluent effect of DRI. News & Views celebrates MIDREX Plants with significant 1Q anniversaries, the latest Midrex contract, TTIron's plans in Trinidad and Tobago, and a Midrex achievement award and the latest patents.

MIDREX GLOBAL OFFICES



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Hydrogen in Iron and Steelmaking

Ore-Based Metallics & Carbon-Neutral Steel

This article is based on excerpts from IIMA White Paper 7: "Hydrogen in Iron & Steelmaking" by Neil Bristow, H&W Worldwide Consulting, and Chris Barrington, IIMA Chief Adviser, April 2024, reviewed and updated by Christian Boehm, Primetals Technologies Austria GmbH, and Chairman of IIMA Technical Committee.

INTRODUCTION

The global steel industry accounts for between 6-8% of carbon dioxide (CO_2) emissions. The majority of this is due to the reduction phase of iron ore in blast furnaces (BFs). While modern ironmaking systems have seen a sizeable reduction in emissions and an increase in energy efficiency in the past 20 years, to reach the targets of net zero emissions by 2050, a non-carbon, fossil-free reductant will be required. This will result in the large-scale use of hydrogen as the key reductant in ironmaking technologies.

This article outlines the different types of hydrogen, explores the costs of producing hydrogen, discusses the use of hydrogen in iron and steelmaking to replace carbon reductants, and touches on future issues and uncertainties surrounding widespread adoption of hydrogen as the primary reductant in producing iron for steelmaking applications.

INTRODUCTION TO HYDROGEN

What is Hydrogen?[1]

Hydrogen is a colourless, odourless, tasteless, and non-poisonous gas under normal ambient conditions. It exists as a diatomic molecule, meaning each molecule has two hydrogen atoms (H_2). Hydrogen is the smallest, lightest, and the most abundant element in the periodic table.

Hydrogen can be stored and consumed as liquid hydrogen or compressed gaseous hydrogen. Liquid hydrogen must be kept at -253°C at 1 bar. Compressed hydrogen must be stored at 200 – 700 bar at ambient temperature. The boiling point of hydrogen at atmospheric pressure is -253°C, which is 20°C above absolute zero and far colder than the boiling point of nitrogen (-196°C) and liquefied natural gas (-162°C). This presents major challenges in adapting existing liquified natural gas infrastructure for liquid hydrogen storage and transportation use, even in the case of hydrogen being transported in the form of methanol or ammonia carriers followed by dissociation and separation.

While hydrogen may dissipate quickly in open, well-ventilated areas, confined spaces with little or no ventilation represent a significant hazard. Combustion may occur in some scenarios depending on the flammable air temperature, gas pressure, and location of a leak. These characteristics will require corresponding electrical equipment certification for application in hazardous areas.

Hydrogen has a wide flammability range compared to other commonly handled fuels and cargoes and a maximum experimental safety gap of 0.29 mm, having an assigned 11C gas group based on the international method of area classification developed by the IEC (International Electrochemical Commission.

Although the heating value of hydrogen is the highest of all potential fuels (120-142 MJ/kg), the energy density per volume is relatively low at standard temperature and pressure. This can be increased by storing hydrogen as a compressed gas or in liquified form, but even in these forms the energy density is significantly below that of other hydrocarbons and alternate fuels; e.g., ammonia, methanol, and liquefied natural gas (LNG).

THE HYDROGEN RAINBOW

Hydrogen is given different "colours" to differentiate the various production methods ***(see Table 1)***.

Although there are many ways to produce hydrogen to reach net zero emissions, green hydrogen will need to be produced in very significant volumes. This will pose major technical and commercial challenges and will require massive government and/or private funding to enable development of the volumes of green hydrogen needed for industry and power generation.

Pink hydrogen is something of a niche product in the current market but has significant longer-term potential to add to the supply of low emission hydrogen. Nuclear energy is used to generate the heat required for high temperature steam electrolysis, without the intermittency of renewable sources of wind and solar power. Of course, nuclear power brings its own challenges: although CO_2 emission is not an issue, there are the attendant problems of long-term storage of nuclear waste, safety concerns and public acceptance. These challenges will have to be addressed if pink hydrogen is to fulfil its potential.

White hydrogen is experiencing an increased level of interest and visibility and has been referred to as "the white gold rush." There were 40 companies exploring for natural hydrogen deposits by the end of 2023, up from 10 in 2020. A key incentive driving this "gold rush" is that natural hydrogen would have a significant cost advantage over hydrogen produced from renewable energy or fossil fuels. Whereas grey hydrogen costs less than US$2/kg on average and green hydrogen currently is three times more expensive, white hydrogen could be extracted and

HYDROGEN COLOURS

GREEN	Made by the electrolysis of water by renewable energy sources. Defined as "carbon-free" hydrogen.
BLUE	Produced predominantly from natural gas via steam reforming. Heating steam and natural gas and produces carbon dioxide as a by-product, which is then captured. Defined as "low carbon" hydrogen.
GREY	Produced by methane and steam reformation but without capturing the greenhouse gases. Essentially the same as blue hydrogen but without carbon capture.
BLACK & BROWN	Using coal or lignite in the hydrogen making process. Used somewhat interchangeably this is the most carbon intensive way to make hydrogen.
PINK	Defined as hydrogen produced from nuclear energy. Also referred to as purple or red hydrogen.
TURQUOISE	Hydrogen made via methane pyrolysis at high temperatures, producing hydrogen and solid carbon. Yet to be proven commercially.
YELLOW	Hydrogen formed via electrolysis using solar power.
WHITE	Naturally occurring geological hydrogen found after fracking or from old mines. Not commercial yet, but experiencing an increasing level of interest.

NOTE: Green and blue hydrogen can generally be described as "low emission" hydrogen

TABLE 1. *The Hydrogen Rainbow*[2]

purified at a cost of about US$1/kg. There is currently only one producer, Hydroma, a Canadian company, which operates a well in Mali at an extraction cost of US$0.50/kg. Recognising that it is at an early stage of development, white hydrogen could be a gamechanger for the low emission hydrogen sector, although reserves still have to be quantified and the issues of transportation, distribution, and storage have to be addressed as for all forms of hydrogen.[3]

COSTS OF HYDROGEN

The two main routes for achieving net zero emissions by 2050 are likely to be electrolytic production of hydrogen and the addition of carbon capture, utilization, and storage (CCUS) to conventionally produced hydrogen from fossil fuels, green and blue hydrogen respectively. The key will be the production of hydrogen via the electrolysis route using ever larger and lower-cost electrolysers.

Based on existing proposed projects, low emission hydrogen could move from 0.7 Mtpa in 2021 to around 24 Mtpa by 2030. The future of many of these projects depends on improving electrolyser technology and the development of sufficient green electricity to power them. Australia is one of the leaders in the proposed use of renewable electricity-powered hydrogen production, with targets of electrolyser capacity of 50 GW by 2030. This equates to more-or-less the amount of power required to power all homes in Australia. One of the key features here is the continued reduction in the costs of renewable electricity and water, necessary to drive cost-effective hydrogen production.

Larger capacity electrolysers are currently under construction in Europe (32%), Australia (28%), and Latin America (12%)[2]. Scale is predicted to exceed 260 MW by 2025 and >1 GW by 2030. To reach these targets significant additional funding will be required, which is proving a challenge. Electrolyser capacity is being expanded to meet future demand and planned capacity. If funded, it will be more than sufficient to meet projected demand. This will be extremely important if the global steel industry moves to high hydrogen use towards and beyond 2030[4].

Costs of electrolyser capacity will be a function of size and location. To produce green hydrogen an electrolyser will need to be powered by green electricity, which will pose major challenges and difficulties (e.g., renewable power is not continuously available from solar and wind and the limited expansion potential for hydropower) and will need significant expansion of renewable power generation feeding the grid. Estimated production costs vary from around US$4/kg hydrogen to >US$9/kg, depending on location[9]. The cost of hydrogen is predicted to come down as the efficiency of electrolyser technology improves, from <70% to approximately 85%, and targets of between US$2.3 to <US$4.0 have been forecast[10]. Current costs using steam reforming generation of hydrogen are in the order of US$1.00/kg.

Electricity cost is one of the key components to the overall cost of producing hydrogen, with estimates of between 50-55 kWh required per kg of hydrogen, equating to around US$3/kg at a power cost of US$0.06/kWh[9]. Typical costs for green electricity are higher than this and vary by location but are in the order of US$0.08-0.12/kWh. Costs in developing countries are higher than in regions with advanced electricity grids and will need to see major electricity grid advances to make hydrogen costs economically viable. More recently, the cost differentials between renewable power and fossil fuels have declined[9,10] and further cost reductions are needed to continue this trend, particularly for solar and offshore wind power generation. It is expected that lower hydrogen production costs will enable large scale hydrogen generation facilities to come on stream in the next decade.

The cost of electrolysers is another major consideration. Current full costs are in the range of US$1,400 to US$1,800 per kW. Major reductions in costs of up to 70%[2] are predicted by 2030, with a target of around US$400 per kW by 2030[9] and ~<US$300 per kW by 2050, as economies of scale and technology proceed[2]. A key uncertainty will be the cost of metals; e.g., platinum and rare earths, which are critical parts of both alkaline and membrane electrolysers.

CCUS coupled to use of fossil fuels could enable hydrogen production of 3 Mtpa by 2030 in Europe, with a similar level in North America. The key here is the successful, timely development of lower cost CCUS options. Although technically CCUS can work, the major issue will be can it become commercially viable, as this will require a continued reduction in costs. A major cost driver for CCUS is the steam requirement of approx. 1 tonne of low-quality steam per tonne CO_2 captured. The total potential CCUS project pipeline is as high as 80 Mtpa CO_2.

Another issue is the cost of storage of either electricity or hydrogen to buffer intermittent green electricity generation and steady industrial demand, both daily and long term. Storage of either is expensive and not available yet at industrial scale. The cost of CCUS is highly variable and depends on the levels of CO_2 in the gas streams. Typical costs for CO_2 capture from concentrated gas streams vary from around US$15-20/t CO_2 to US$40-

120/t CO_2 for dilute gas streams. Indicative costs for CO_2 capture are shown in ***Figure 2***.[14]

To reach net zero emissions by 2050, most forecasting groups suggest that this will require the adoption of CCUS. Use of CCUS and/or green hydrogen in the steel industry is the projected route most likely to enable such low or zero emission targets by 2050 in developed regions such as the EU, North America, and north Asia.

HYDROGEN PRODUCTION

Hydrogen is not yet viable at scale. According to the IEA (International Energy Agency), green hydrogen will not be available at an industrial scale until after 2030 – currently less than 0.1% of global dedicated hydrogen production comes from water electrolysis. In the interim, blue hydrogen options are being explored. However, the main challenge will still be in producing hydrogen at scale to meet projected demands, not only from the iron and steel industry but also from the other industry sectors. Under IEA's Sustainable Development Scenario, global demand for hydrogen will increase to 287 Mtpa by 2050, which represents an increase of over 400% from 2020.[30]

The demand for hydrogen will increase strongly to 2030 and beyond. However, as yet there is no priority in the demand for hydrogen. It has not been determined which industry will receive the available green hydrogen as-and-when it becomes available. Potentially, this might come down to simple price/affordability criteria. There is a shift nowadays to favor industrial use vs. other sectors (such as transportation) that can better afford hydrogen.

Hydrogen production is nevertheless growing strongly, with numerous projects worldwide to produce the different forms of hydrogen. Production of green hydrogen is predicted to grow very strongly post 2030, as shown in ***Figure 3***, and will become the dominant form of hydrogen by 2050[14]. Blue hydrogen also will increase while grey and brown hydrogen produced from fossil fuels will decline post 2030.

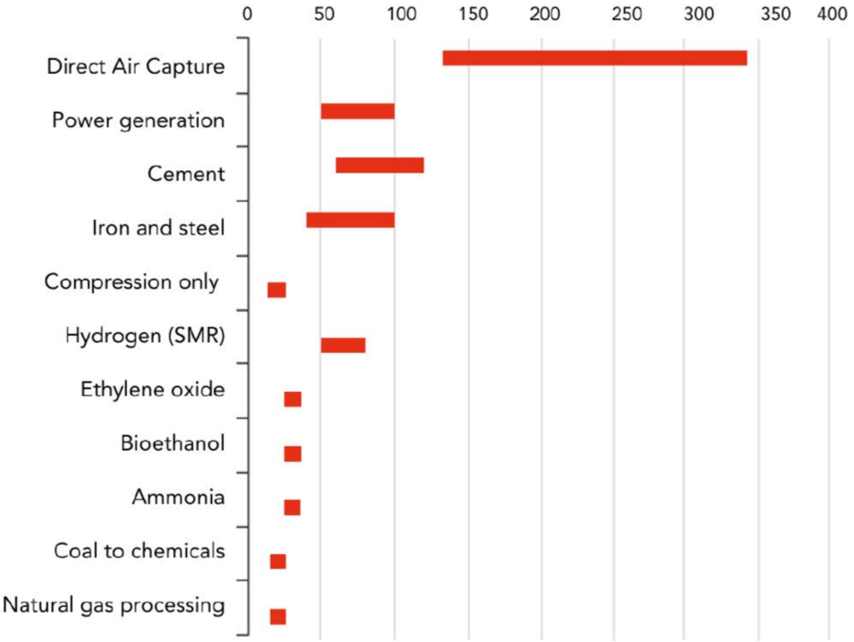


FIGURE 2. *Costs of CO_2 capture by sector (US\$ per tonne)*[14]

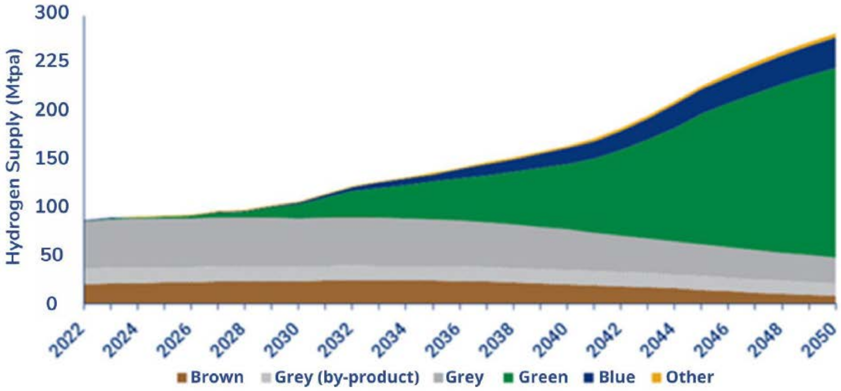


FIGURE 3. *Global hydrogen production by colour: 2022 to 2050 (Mtpa)*[15]

HYDROGEN IN IRON & STEELMAKING

The conventional route currently used in the production of steel is ~72% via the cokemaking/blast furnace/basic oxygen furnace (CO/BF/BOF) route and ~29% via the scrap/DRI/electric arc furnace (EAF) route, worldwide. The blast furnace route emits up to four times more CO_2 than the EAF route. The major source of the CO_2 via the blast furnace route is the sintering and iron ore reduction/smelting processes ***(see Figure 4[8])***.

The direct use of hydrogen for iron and steelmaking is for heating purposes and for the reduction of iron ore oxide. Three main application fields for the utilization of hydrogen within the iron and steelmaking exist:

- **Hydrogen injection in blast furnaces:** here a partial replacement of coke or pulverized coal as PCI and/or the replacement of natural gas or other reductants with hydrogen is possible but limited. As hydrogen reduction is endothermic, it absorbs heat and results in a cooling effect in the blast furnace raceway, which needs to be compensated with additional heat added to the reduction and melting process inside the blast furnace. This reduces carbon emissions but does not eliminate them entirely.
- **Hydrogen Plasma Smelting Reduction (HPSR):** This is a process that uses hydrogen plasma to reduce iron ore, which is still in experimental stages but has certain potentials.
- **Hydrogen-based Direct Reduced Iron (H2-DRI):** Instead of using natural gas or coal, hydrogen can serve as a reductant to remove oxygen from iron ore. This process produces water (H_2O) instead of CO_2, making it more environmentally friendly.

Most major steel companies have published emission reduction targets, with the majority seeking to achieve 25-30% or more by 2030, while aiming for net zero emissions by 2050. As part of these ambitions to decarbonise the steelmaking process, the widespread use of hydrogen has been planned. This will be focused on technology seeking to replace natural gas with hydrogen in direct reduction processes and partially replacing pulverised coal injection (PCI) with hydrogen in the blast furnace. This will be undertaken in staged processes.

For hydrogen to be used in combination with CO in direct reduction shafts, significant planning has been done on moving to increased levels of hydrogen and then to full 100% hydrogen reduction. Where there is the practical option to store CO_2 geologically, carbon capture and storage also can be added to the process to reduce the carbon footprint for existing direct reduction plants and/or blast furnaces. Partial use of captured CO_2 already occurs in Mexico and Abu Dhabi, for example[17]. Most major European steelmakers have plans to add DRI capacity to their steel plants by or soon after 2030.

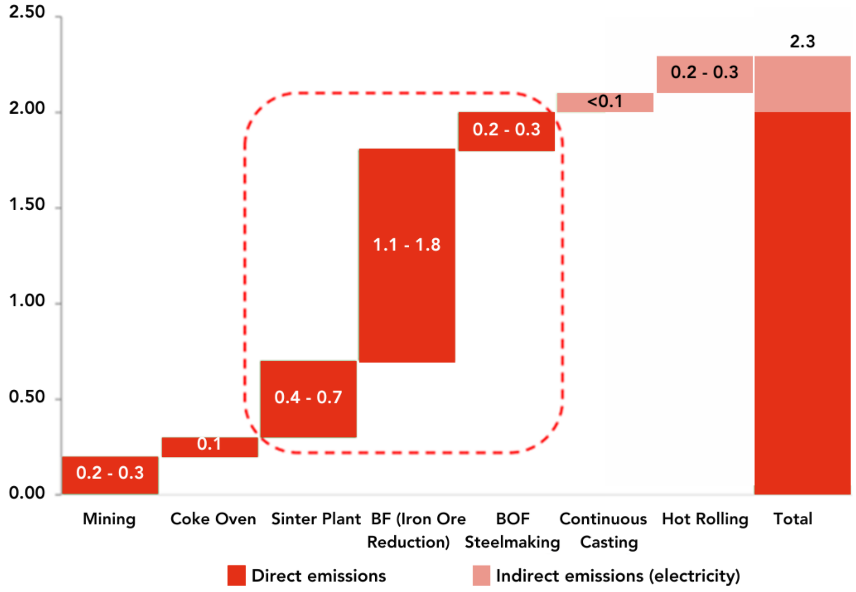


FIGURE 4. *CO_2 emissions during CO/BF/BOF steelmaking by stage (T CO_2/T HRC)*[8]

It is worth noting that HBI could also be seen as a form of energy transport. HBI manufactured in green or low emission hubs, for example in the USA, Middle East, Australia, etc. and shipped to countries with high energy cost and/or limited potential for renewable energy, would be a much simpler and lower cost solution than transportation of hydrogen as liquid, gas, or ammonia.

Hydrogen-based Direct Reduction

Flowsheets for 100% hydrogen-based reduction have been developed for both the MIDREX® and ENERGIRON® processes. In addition to the established direct reduction processes, emerging direct reduction technologies, such as Primetals' Hyfor™ fluidised bed process and the POSCO/Primetals HyREX fluidised bed process combined with a smelter will be hydrogen-based. Metso's re-emerging Circored™ fluidised bed process is also hydrogen-based.

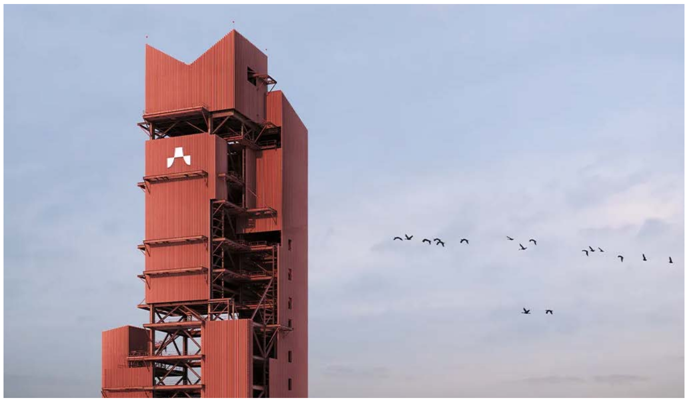
Plans are also well advanced, especially by integrated steel companies in Europe (including SSAB, thyssenkrupp, Tata Steel Ijmuiden, voestalpine, Salzgitter and Saarstahl) for the transition from blast furnace-based to direct reduction-based iron production with the resultant DRI to be used to complement recycled steel in EAF steelmaking or, via an electric smelting step, as BOF feedstock. Similar plans are also underway in the Asia Pacific region, for example in Australia for replacing the blast furnace at Port Kembla works. There are also hydrogen-based direct reduction plants in China, albeit so far with hydrogen derived from coke oven gas.

H2FUTURE[16,24] is a European flagship project for the generation of green hydrogen using electricity from renewable energy sources. Under the coordination of the utility VERBUND, steel manufacturer voestalpine, and proton exchange membrane (PEM) electrolyser manufacturer Siemens Energy, a large-scale 6 MW PEM electrolysis system is in operation at the voestalpine Linz steel plant in Austria.

In the near- to medium-term, most of the new direct reduction plants will be based on natural gas with a progressive shift to low emission hydrogen as it becomes economically available. Both the MIDREX and ENERGIRON processes have flexibility in the proportion of hydrogen in the reducing gas, as well as the ability to include carbon capture technology. However, using hydrogen produced from natural gas for DRI production emits more CO$_2$ than using the natural gas directly.

A front runner in hydrogen-based direct reduction is HYBRIT (Hydrogen Breakthrough Ironmaking Technology) in Sweden, a joint venture of SSAB, LKAB, and Vattenfall[25,26]. Having successfully demonstrated the process at a pilot plant in Luleå, the next step is a demonstration plant to be built by LKAB and located at Gällivare, using green pellets from LKAB and green hydrogen based on green electricity from the Swedish grid. SSAB will utilise the green DRI to produce green steel at its Oxelosund works and eventually at its Luleå works, which will be converted to EAF steelmaking.

In Boden, Sweden, Stegra (formerly H2 Green Steel) is advancing toward a 2026 start-up of the world's first commercial-scale green steel mill powered by renewable energy and based on 100% hydrogen DRI. The state-of-the-art steel mill will have an initial production capacity of 2.5 mtpy fed by a MIDREX H2™ Plant supplied by Midrex and Paul Wurth, with an production capacity of 2.1 mtpy of hot DRI (HDRI) and hot briquetted iron (HBI). SMS group will provide the rest of the steel mill for the production of a broad product mix including advanced high strength steel and automotive steel grades.



Our journey towards 5 million tonnes of green steel

June 2023: Full environmental permit approved - in record time

Beginning 2026: Production start

2026-2028: Ramp-up to full production of 2.5mt hot- and cold-rolled steel

2028: Expansion - ramp up to full 5mt capacity

2030 (earliest 2): Yearly production of 5mt green steel

Stegra is pursuing a 5-step development plan for its lighthouse project, with the goal of producing 5 mtpy of "green" steel:

STEP 1: Giga-scale Electrolysis – using renewable electricity to decompose water into hydrogen and produce enough hydrogen to make 5 million tonnes of high-quality steel annually by 2030.

STEP 2: Hydrogen-based Direct Reduction – using green hydrogen instead of coal or natural gas to react with oxygen in iron oxide pellets to produce highly metallized direct reduced iron (DRI) for steelmaking with steam as the residual, thus reducing CO_2 emissions by up to 95%.

STEP 3: Electric arc furnace (EAF) Steelmaking – using renewable electricity to heat DRI and steel scrap to create liquid steel, with contained carbon in the slag playing an important role in lowering electricity consumption and enabling the transformation of iron to steel.

STEP 4: Continuous Casting and Rolling – allowing energy consumption to be reduced 70% and replacing natural gas in the traditional process.

STEP 5: Downstream Finishing Lines – cold rolling, annealing, and hot-dip galvanizing for adjusting steel thickness, creating desired mechanical properties, and protecting against corrosion, respectively.

FUTURE ISSUES & UNCERTAINTIES

There are issues and challenges with respect to adoption and use of hydrogen as a carbon replacement in the steel industry. These include:

1. **Rate of production of green hydrogen:** there are numerous projects in the pipeline to produce green hydrogen, but these are wholly insufficient to meet the requirements, commitments, and targets of European steel companies. Tracking the development of such projects will provide a good indication of the feasibility and timeline for the steel companies to meet their stated targets. A key requirement to monitor will be the development of large-scale green power facilities and electrolysers capable of producing large volumes of green hydrogen at commercially viable costs.
2. **Cost reduction of hydrogen production:** aggressive hydrogen cost reduction targets are forecast to 2030. The progress and realisation of these targets will provide good indications of the economic feasibility of reaching net zero emission by 2050.
3. **Technical achievement of successful hydrogen use in steelmaking and DRI production:** monitoring of the progress of large-scale hydrogen injection into large blast furnaces and the construction of hydrogen-based DRI facilities, for example, the HYBRIT demonstration plant and the Stegra industrial-scale plant due to start in 2026, will be a good guide as to the likelihood of European steel companies reaching their 2030 targets for emission reduction.
4. **Development of ranking industries for hydrogen adoption:** no such list is currently available. The assessment of industries for available hydrogen when available will allow steel companies to assess their place in the queue and plan accordingly.
5. **Evolution of public opinion:** current public opinion is strongly in favour of net zero emissions by 2050. However, the economic viability of achieving this target is being increasingly questioned. Many developing countries will not be able to do so. India and China are targeting 2060 and 2070, respectively, and countries in Africa with growing populations do not have targets. In some European countries there already have been some policy-driven slowdowns in the rate of progress towards achievement of key milestones along the pathway to net zero, even as they maintain their 2050 net zero emission goals. Monitoring progress in achievement of intermediate targets; e.g., in 2030, and any changes in public sentiment will assist in determining the rate of adoption of hydrogen use in the steel industry.

Use of hydrogen in shaft furnace-based direct reduction processes will require some technical and operational changes including:

- **Energetics and cooling effect:** direct reduction based on hydrogen is different to that based on natural gas as the thermodynamics result in an endothermic reaction delivering a cooling effect inside the reduction shaft. For the case of hydrogen use, some adjustments of temperature and/or gas flow can overcome the cooling effect.
- **Condensation of water:** hydrogen reduction forms water. However, this is more of a problem for the blast furnace.

Concerning direct reduction plants, if not properly designed and operated, there is the potential for water condensation in the upper regions of the reactor.

A further issue is that a solely hydrogen-based direct reduction plant will produce DRI without carbon, an issue addressed in IIMA White Paper #2[19] and the article by Dr. Sara Hornby and Professor Geoff Brooks published in ***4Q2024 Direct From Midrex***, titled "Future Processing Options For Hydrogen DRI."

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DILUENT EFFECT OF DRI – STEELMAKING SUPERPOWER

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DR. VINCENT CHEVRIER

Compiled from articles previously published in *Direct From Midrex* and information prepared by HBI Association by **Frank Griscom**, Griscom Consulting, Charlotte, NC, and edited by **Dr. Sara Hornby**, Global Strategic Solutions, Charlotte, NC, and **Dr. Vincent Chevrier**, General Manager-Technical Sales and Marketing, Midrex Technologies, Inc.

INTRODUCTION

Quality of ferrous scrap is primarily measured by melting yield, density, physical size, and chemistry. While the first three features have significant economic and operational implications, chemistry – and particularly, residual element/material content – has the greatest effect on final steel quality.

With each improvement in steel production technology and know-how, the supply of high quality revert scrap declines. Although the number of automobiles scrapped is much greater today, the use of plastics, alloys, and other contaminating materials is increasing. Likewise, supplies of industrial scrap, such as clippings, trimming, and turnings are declining as metalworking becomes ever more sophisticated.

Scrap quality is never guaranteed and can vary from region-to-region, type-to-type, and even lot-to-lot. But DRI brings out the best in a scrap charge because it offsets many of the shortcomings of scrap, as shown in the ***Figure 1*** comparison.

SCRAP

- From various steel products (source not always known)
- Limited collection season
- Waste product (inclusions)
- Dissimilar, diverse chemistry
- Heterogeneous composition

DRI

- From natural iron ore (mine to production plant)
- Year-round manufactured product
- Original product (low residuals)
- Known, consistent chemistry
- Homogeneous composition

FIGURE 1. *Comparison of scrap and DRI*

The value of direct reduced iron (DRI) as a diluent to scrap cannot be overstated nor should it be overlooked or discounted when compared to some of its other attributes: melt consistency, predictable chemistry and heat & mass balance, nitrogen control, productivity, and power benefits when DRI is continuously hot charged at much higher temperatures than scrap. The diluent effect of DRI is a feature that can benefit all electric arc furnace (EAF) operators regardless of the steel grade they produce.

CARBON STEEL QUALITY

EAF steelmaking has come a long way in a relatively short time, and the driving force has been "higher quality." There have been major strides in equipment, techniques, and practices since the EAF made its debut as a way to make small quantities of basic steel grades from obsolete, discarded steel products. Today, major steel companies throughout the world are using EAFs to produce everything from high-strength rebars to steel sheets for automobile body panels and electrical steels.

Of the four steel types or groups – carbon, alloy, stainless, and tool – carbon steel accounts for 90% of production. Carbon steels only contain trace amounts of elements besides carbon and iron. The key factor distinguishing low/mild, medium, and high carbon steel is the percentage content of carbon in the steel: mild (0.4-0.3%), medium (0.3-0.6%), and high (0.6-1.5%).

Low (Mild) Carbon Steel

Due to its low strength, softness, and ductility, it is easily shaped and machined. Low carbon steel, often called mild steel, includes most carbon steel, as well as high-quality carbon steel used for engineering structural parts. Low carbon steel is generally not heat treated before use and is generally rolled into angle steel, channel steel, I-beam, steel pipe, steel strip or steel plate for making various building components, containers, boxes, furnace bodies, and agricultural machinery. High-quality low carbon steel is rolled into thin plate to make deep-drawn products, such as automobile cabs and engine covers. It also can be rolled into bars for the production of mechanical parts with low strength requirements.

Medium Carbon Steel

Medium carbon steel is a balanced combination of strength, ductility, and toughness. It includes most of high-quality carbon steel and a portion of plain carbon steel. It has good thermal processing and cutting performance but its welding performance is poor, so preheating is required before welding. Cold-rolled or cold-drawn material can be used with or without heat treatment. Medium carbon steel is mainly used to manufacture high-strength moving parts, such as air compressors; pump pistons; steam turbine impellers; heavy machinery shafts, worms, gears, etc.; surface wear parts; crankshafts; machine tool spindles and rollers; bench tools; and more.

High Carbon Steel

High carbon steel has high strength and hardness, is wear resistant but has lower ductility, which renders it harder to shape. It can be quenched and tempered; however, cracks are easily generated during water quenching due to its high carbon content so two-liquid quenching is often used, as well as oil-hardening for small-section parts. High carbon steel is mainly used in the manufacture of springs, wear parts, and high-hardness tools.

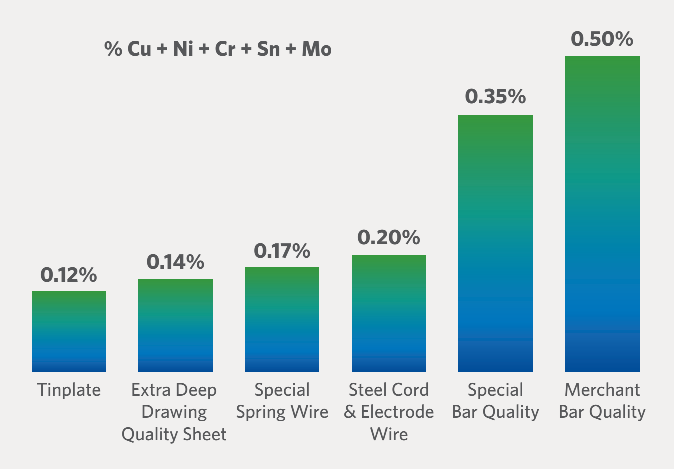

FIGURE 2. *Typical residual limits in carbon steel products*

THOSE TROUBELSOME RESIDUAL ELEMENTS

While melting yield, charge density, and the physical size of scrap have significant economic and practical implications for EAF steelmakers, chemistry – and particularly residual element content – has the greatest impact ***(see Figure 2)***. The control of these elements is probably the most persistent challenge to EAF steelmakers (Note: The term "residual elements" in this article refers to those elements not intentionally added to the steel that are difficult, if not impossible, to remove from the bath during the steelmaking process. For this reason, they are also called "tramp elements").

Table 1 lists the various residual elements and materials commonly found in and on scrap, how they are removed in steelmaking (if possible), and how they affect steel products. Those not preferentially oxidized versus Fe tend to stay in the steel.

The following briefly describes the effects of some of these elements on EAF operations *(also, see Table 2)*:

- Cu, Ni, Mo, Co, Sn, As, and Sb – tend to harden the steel and make it more difficult to roll.
- Si, P, Cr, and Al – lower the basicity of the slag and make it more difficult to remove sulfur and phosphorus in the heat.
- Zn and Pb – volatilize and affect refractories, fume collection equipment, and effluent water.
- S – exerts negative influence on steel properties and is difficult to remove, which results in lower productivity.
- Oil, grease, paint, plastic, rubber, and organic fibers – reduce liquid steel yield, produce heavy fumes, introduce sulfur into the melt, and affect melt chemistry control.
- Dirt, sand, glass, clay, and concrete – contribute to larger slag volume, which results in lower liquid steel yield.

Light scrap, used as a "cushion" for larger, heavier scrap layers in the EAF, can be detrimental also. It oxidizes rapidly resulting in increased furnace lining wear, poor melt chemistry control, lower liquid steel yield, and decreased productivity.

Because most of "the big five" residual elements (copper, nickel, chromium, tin, and molybdenum) are not oxidized during the steelmaking process, they tend to concentrate and harden the steel. Equally disturbing is variability in the chemistry of the liquid steel from melt-to-melt, especially the level of residual elements. These can cause hot shortness (embrittlement of steel during hot working) and surface hot shortness (formation and concentration of low melting

Element/ Material	REMOVED IN STEELMAKING				DETRIMENTAL TO	
	No	Partly	Yes	Melting Furnace	Productivity	Steel Quality
Cu	🟩				🟩	🟩
Sn	🟩				🟩	🟩
Ni	🟩					🟩
Mo	🟩					🟩
As	🟩					🟩
Co	🟩					🟩
Sb		🟩				🟩
Cr		🟩				🟩
S		🟩		🟩	🟩	🟩
P		🟩		🟩	🟩	🟩
Si			🟩	🟩	🟩	🟩
Al			🟩	🟩	🟩	
Pb			🟩	🟩		
Zn			🟩	🟩		
Mg			🟩			
Nb			🟩			
V			🟩			
Zr			🟩			
Dirt			🟩	🟩	🟩	
Oil			🟩	🟩	🟩	
Plastic			🟩	🟩	🟩	
Rust			🟩	🟩	🟩	

TABLE 1. *Common constituents in/on scrap and their effect on steelmaking*

Property	ELEMENT					
	Cu	Ni	Cr	Mo	Sn	Sb
Strength and Hardness	+	+	+, -	+	+	+
Ductility	-	+, -	+, -	-	-	
Strain Hardening	+, -	0	0, -	-	-	
Strain Ratio	+, -	0	0, -		0	
Impact Resistance	+	+	0	-	0, -	
Hardenability	+	+	+	+	+, 0	+, 0
Weldability	-	-	-	0-		
Corrosion Resistance	+	+	+	+	+	
Temper Embrittlement					+	+

\+ increases - decreases 0- no effect

TABLE 2. *Effect of Increases of Residual Elements on Various Steel Properties*

temperature compounds along grain boundaries), which affects surface quality.

Thus far, no one has found an economically feasible way to remove the most troublesome residual elements (copper, tin, nickel, molybdenum, arsenic, and cobalt) from liquid steel. Vacuum treatment can be used to remove some of the more volatile residual elements, but the removal rate is too slow for most of them.

Chlorine-based reagents have been considered for tin removal, but large iron losses associated with this treatment preclude its practical application. Similarly, calcium can remove some arsenic, antimony, tin, and nickel but the efficiency is far too low to justify the use of this expensive reagent.

Sodium sulfide has been studied for the removal of copper and tin; however, this treatment requires high carbon and low temperature, as opposed to low carbon and high temperature associated with liquid steel.

UNTIL THE DAY COMES WHEN EACH PIECE OF SCRAP IS INDIVIDUALLY ANALYZED AND SORTED, THE DIFFICULTY IN IDENTIFYING TRAMP ELEMENTS IN OBSOLETE SCRAP WILL CONTINUE TO FRUSTRATE USERS AND SELLERS ALIKE.

DRI TO THE RESCUE

EAF steelmakers are well aware of the increasing contamination of scrap. The immediate solution sounds simple: improve scrap segregation to separate "clean" scrap from the undesirable materials. While this solution is logical and seems practical, the realities of scrap collection, processing, and brokering prove to the contrary. And it does not take care of the in-situ tramp elements.

The scrap industry is highly competitive and cost-conscious. While steelmakers want better scrap segregation, they still expect the lowest price, which does not support investment in better equipment and facilities and the manpower to operate them. This is the primary reason a growing number of steel producers are investing in scrap collection and processing.

DRI has none of the vagaries that surround scrap collection and processing because it is manufactured from natural iron ore, having known chemical content, without melting. As a result, the DRI contains only iron, gangue (silica and alumina), carbon (typically 1-2%), and a small amount of unreduced iron oxide. The gangue constituents are removed in the EAF slag and the carbon reacts exothermically with the unreduced iron oxide in the DRI, thus generating carbon monoxide, which is not only useful in foaming the EAF slag but also helps purge nitrogen and hydrogen from the metal bath. Any excess carbon in the DRI post-reduction reacts with oxygen or oxides in the bath augmenting the carbon effect.

The advantage of DRI for controlling residual elements is evident when comparing the residual levels in DRI (traces to < 0.1%) with various grades of scrap (0.1-0.6%). DRI is even "cleaner" than blast furnace pig iron, which is contaminated by coke, sulfur, and fluxes.

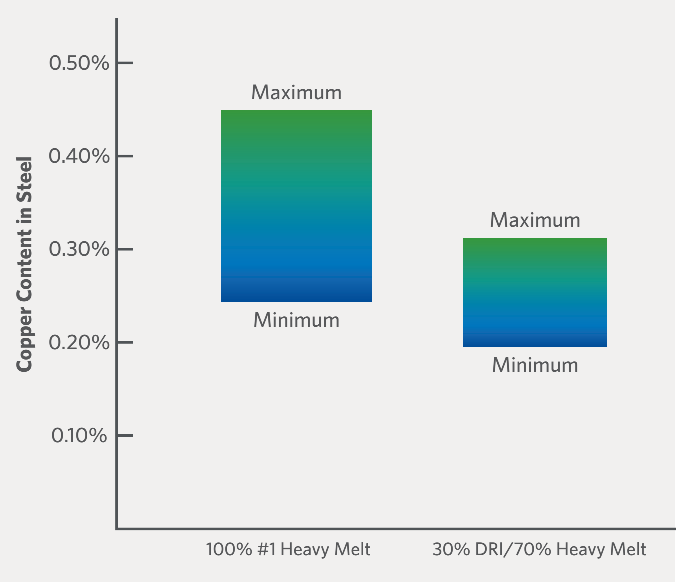

FIGURE 3. *Influence of DRI on copper variability*

The impact of DRI on final steel chemistry can be seen in a comparison of copper levels in steel produced from 100% #1 HMS and a charge mix of 30% DRI-70% #1 HMS ***(Figure 3)***. The copper range in the 100% #1 HMS steel is 0.25-0.45%, while the copper range in the 30% DRI-70% #1 HMS is slightly more than 0.20-0.30%.

It should be noted that the variability of the copper level as well as the amount of copper is reduced, which is equally important in determining the quality and value of the final steel product.

In addition to the control of residual elements, the use of DRI in the EAF limits the amount of sulfur, phosphorus, and nitrogen in the liquid steel and provides for more consistent product quality. Benefits include: lower yield strength (improved malleability, more elasticity) due to less residuals and nitrogen content, improved surface quality from less free oxygen in the bath, greater predictability of mechanical properties after heat treating, and more resistance to strain aging.

CONCLUSION

When DRI made its first appearance in modern steelmaking, it was somewhat jokingly called "sponge iron" due to its porous nature. Early on, it was used primarily in scrap-deficient regions and became known as a scrap substitute. When DRI started to turn heads in more established steel producing economies, such as the US, it was at first considered a scrap alternative and seen primarily as a means to affect the price of steel scrap. Today, DRI is rightfully known as a scrap supplement for EAF operations and as a burden enrichment for blast furnace hot metal production. For the future, it will be regarded as the preferred source of ore-based iron units for low carbon emissions, hydrogen-based steelmaking, according to the International Energy Agency (IEA) Iron & Steel Technology Roadmap.

If the steel industry ever needed a superpower, it's now. Regardless of what it is called, DRI will continue to grow in importance as steel producers strive to meet stricter CO_2 emission standards while sustaining profitable operations.

For further insights into hydrogen-based DRI and its role in green steelmaking, see the following:

- "Impact of Hydrogen DRI on EAF Steelmaking," by Dr. Sara Hornby, Global Strategic Solutions, Charlotte, N.C. USA, and Prof. Geoff Brooks, Swinburne University of Technology, Melbourne, Victoria, Australia; 2Q2021 DFM.
- "Future Processing Options for Hydrogen DRI," by Dr. Sara Hornby, Global Strategic Solutions, Charlotte, N.C. USA, and Prof. Geoff Brooks, Swinburne University of Technology, Melbourne, Victoria, Australia; 4Q2024 DFM.
- IEA paper referencing hydrogen DRI associated with CCUS in the future of steelmaking – **www.iea.org/energy-system/industry/steel**.

Midrex News & Views

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

MIDREX® Plants with 1st Quarter Anniversaries

We are proud to celebrate these remarkable milestones with our customers— 35 years since start-up for ArcelorMittal Nippon Steel India and 25 years for EZDK!

35 YEARS

ArcelorMittal Nippon Steel India (AM/NS India) Module I

Location: Hazira, Gujurat, India
DR Plant: 1st of 6 MIDREX® Modules

- **Start-up:** March 1990
- **Product:** CDRI
- **Rated Capacity:** 0.44 Mt/y

Module I was one of two MIDREX Modules acquired from Nordeutsche Ferrowerke in Emden, Germany, disassembled, and relocated to India by Essar Steel India Limited (ESIL). AM/NS India acquired the assets of ESIL in December 2019.

Module I was converted to hot discharge/hot transport to the melt shop in 2000 and reconfigured for CDRI discharge in 2017.

In 2024, Module I produced 615,007 metric tons (tonnes) of CDRI and all six modules combined have produced over 96 Mt of HDRI, HBI, and CDRI since start-up of modules I and II in 1990.

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

25 YEARS

Al Ezz Dekheila Steel Company - Alexandria (EZDK) Module III

Location: El Dikheila, Egypt
DR Plant: 3rd of 3 MIDREX® Modules

- **Start-up:** February 2000
- **Product:** CDRI
- **Rated Capacity:** 0.8 M t/y

The direct reduction/electric arc furnace (DR/EAF) steelworks located west of Alexandria, Egypt in El Dikheila is the largest steel manufacturing facility in Egypt, with a total annual capacity of 3.2 million tons of finished steel products comprising 2.1 million t/y of long products (rebar and wire rod) and 1.1 million t/y of hot rolled coil.

Al Ezz Dekheila Steel Company - Alexandria (EZDK) began life as Alexandria National Iron & Steel Company (ANSDK) in 1982, and operates three MIDREX Modules, which supply the melt shop with 80% of its metallic charge, with high-grade scrap making up the remainder.

Through 2024, Module III has produced more than 22.2 million tons of DRI, which is a yearly average well above its annual capacity rating of 0.8 million tons

Read more about Al Ezz Dekheila Steel Company at https://www.ezzsteel.com

Midrex News & Views

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

TOSYALI SULB Selects Midrex and SMS group for DRI Complex in Libya

Libya intends to become a supplier of direct reduced iron (DRI) in the Mediterranean basin and beyond with the announcement of a DRI complex based on MIDREX Flex® technology to be built in the Benghazi region. TOSYALI SULB Steel Industries, which was formed by TOSYALI and Libya United Steel Company for Iron & Steel Industry (SULB) to lead the development of the iron and steel sector in Libya, will immediately commence the first phase with construction of a 2.5 million ton cold DRI (CDRI) plant.

TOSYALI SULB will utilize MIDREX® technology similar to what equips the two DRI plants owned and operated by TOSYALI Algerie in Bethioua (Oran), Algeria. With MIDREX Flex, the plants can operate initially with natural gas and transition to using hydrogen, as it becomes available, making them leading contributors to green steel production. The Libyan plant will supply CDRI to meet the needs of the nearby region.

TOSYALI SULB Contract Signing Pictured (left to right): Guido Bonelli, Paul Wurth Italia; Fuat Tosyali, TOSYALI Holding; K.C. Woody, Midrex

When this investment is completed, TOSYALI SULB will be one of the key suppliers of DRI in the world.

Point Lisas DR-EAF Steel Complex
Plans to Transition to Hydrogen DRI

TT Iron Steel Company (TT Iron) has purchased one of the largest steel mills in the Americas located in the Point Lisas Industrial Estate, Couva, Trinidad and Tobago, and intends to produce low carbon emissions "green" steel using scrap and direct reduced iron (DRI) from a trio of MIDREX® Plants. The DRI-Electric Arc Furnace (EAF) based iron and steel complex was originally constructed for ISCOTT – the Iron and Steel Company of Trinidad and Tobago and was most recently owned and operated by ArcelorMittal Point Lisas Ltd.

→ Honoring Outstanding Achievements at Midrex

Midrex Research Engineer **Katsuma Fujiwara** is the first recipient of the 2024 Innovator of the Year award. **Katsuma** was cited for his deep understanding of thermodynamics and chemical processes that have made him a key contributor in solving complex technological challenges at the Midrex Research and Development Technology Center.

Link to story can be found **here.**

In the dynamic environment of Midrex, certain individuals stand out as beacons of excellence. One such individual is **Dawn Craft**, our Senior Executive Administrative Assistant and the recipient of the 2024 Iditarod Award. This award, presented annually during our first-quarter company meeting, honors a teammate who exemplifies the qualities of integrity, dependability, initiative, teamwork, accountability, respectfulness, organization, and decisiveness—the very essence of the Iditarod spirit. Link to story can be found **here.**

Katsuma Fujiwara (right), wins
2024 Innovator of the Year Award

Dawn Craft (center), wins
2024 Iditarod Award

Also, five patents were awarded to Midrex engineers in 2024:

- Oxygen injection for reformer feed gas for direct reduction process **(Mickie Michishita)**
- Direct reduction process utilizing hydrogen **(Keith Bastow and Greg Hughes)**
- Method and system for heating direct reduced iron between a DRI source and processing equipment for the DRI **(Todd Astoria and Jim Lewis)**
- System and method for the production of hot briquetted iron containing flux and/or carbonaceous material at a direct reduction plant **(Mickie Michishita and Todd Astoria)**
- Methods and systems for increasing the carbon content of DRI in a reduction furnace **(Keith Bastow, Todd Astoria, and Greg Hughes)**

Lauren Lorraine: **Editor**

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