MIDREX H_2 – The Road to CO2-free Direct Reduction

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INTRODUCTION

The iron and steel industry is responsible for a portion of 7-10% of the global CO2 emissions, it has to reduce its CO2 emissions drastically during the next 30 years. The EU target is a reduction of CO2 emissions by 80% until 2050, which can only be achieved by switching to different iron & steel production processes. This can be either the scrap-EAF route for certain quality grade steels or the H2 based direct reduction – EAF route for high grade steels. The use of hydrogen sources in the existing BF-BOF route can only contribute to a small reduction of CO2 emissions, but will not be sufficient to achieve the CO2 reduction targets. In order to prepare for the future, many steel producers have projected the integration of a direct reduction plant in their existing steel works in their strategy.

THE MIDREX DIRECT REDUCTION PROCESS

Currently, over 90% of iron production is through the BF route, with direct reduction having a growing share since its commercialisation in the 1970s: In 1990 DRI production made up slightly over 3% of the total iron production, rising to over 6% in 2000 and nearly 8% in 2019. Global DRI production rose by ~8% to 108 Million tonnes (Mt) in 2019 compared to 2018, representing the fourth consecutive record year for DRI production (see Figure 1). In 2020 DRI production numbers slightly declined due to the COVID-19 pandemic, but DRI processes are currently again winning strong support due to renewed interest in green technologies.

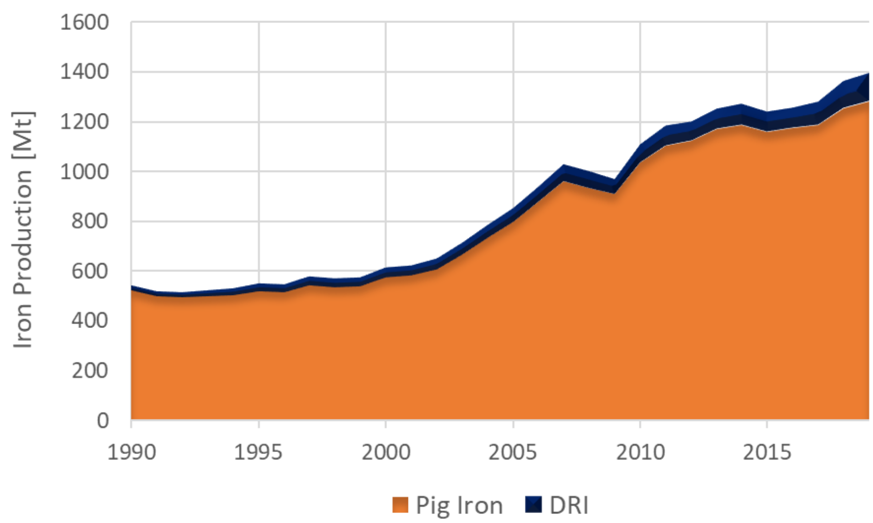


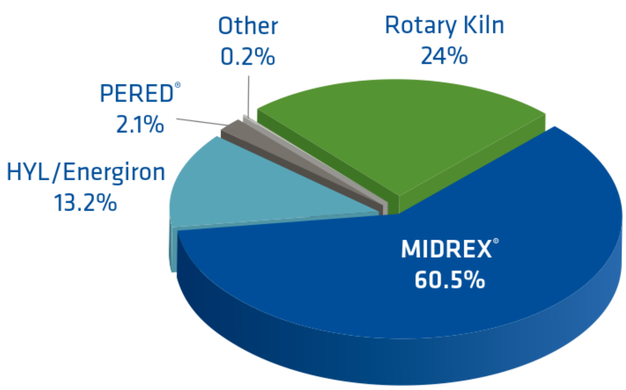
Figure 1: Worldwide iron production 1990 – 2019 [1]

Natural gas based direct reduction is a well-established technology, operating for many decades with a production rate of nearly 82 Mt in the year 2019. There are two dominant shaft based direct reduction processes, with MIDREX leading the market with an 80% market share in 2019, followed by Tenova HYL™ (see Figure 2).

The MIDREX® process is highly flexible regarding the source of energy and iron oxide feedstock. Traditionally it is operated with 100% natural gas, but it can also be operated with hydrogen in any ratio up to 100%. MIDREX® operation has been demonstrated on an industrial scale with natural gas, syngas (from coal gasification), coke oven gas, COREX® gas, and other combinations. The reducing gas ratio (H_2:CO) in a standard natural gas based plant is typically in a range of 1.5 to 1.7 (equal to H_2 content of 55% in reducing gas) while there are industrial MIDREX® plants also operating up to a H_2/CO ratio of 3.2 to 3.9 (close to 70% H_2 content in the reducing gas). The natural gas based direct reduction - EAF route can already reduce CO_2 emission by 40-60% compared to the BF - BOF route.

A MIDREX® direct reduction plant consists mainly of a reduction furnace, a top gas scrubber, a reformer, process gas compressors and a heat recovery system. The reduction gas is generated and heated in the reformer and used for reduction of iron oxide material in the reduction furnace in a counter-current flow to the solid material. Thereby, the oxygen of the oxide material is removed by hot reducing gas consisting mainly of hydrogen (H_2) and carbon monoxide (CO) and the material is metallized. The directly reduced iron is discharged in either hot or cold condition or is hot briquetted into iron briquettes (HBI).

2019 World DRI Production by Process



Total World Production: 108.1 Mt

	2017	2018(r)	2019
MIDREX®	64.8%	61.5%	60.5%
HYL/Energiron	16.9%	15.7%	13.2%
PERED®	*	2.4%	2.1%
Other	0.7%	0.2%	0.2%
Rotary Kiln	17.6%	20.2%	24.0%

* included in 'other'
(r) revised

Source: Midrex Technologies, Inc.

Figure 2: Global DRI production by process, 2019

THE TRANSFORMATION TO MIDREX H_2 PLANT

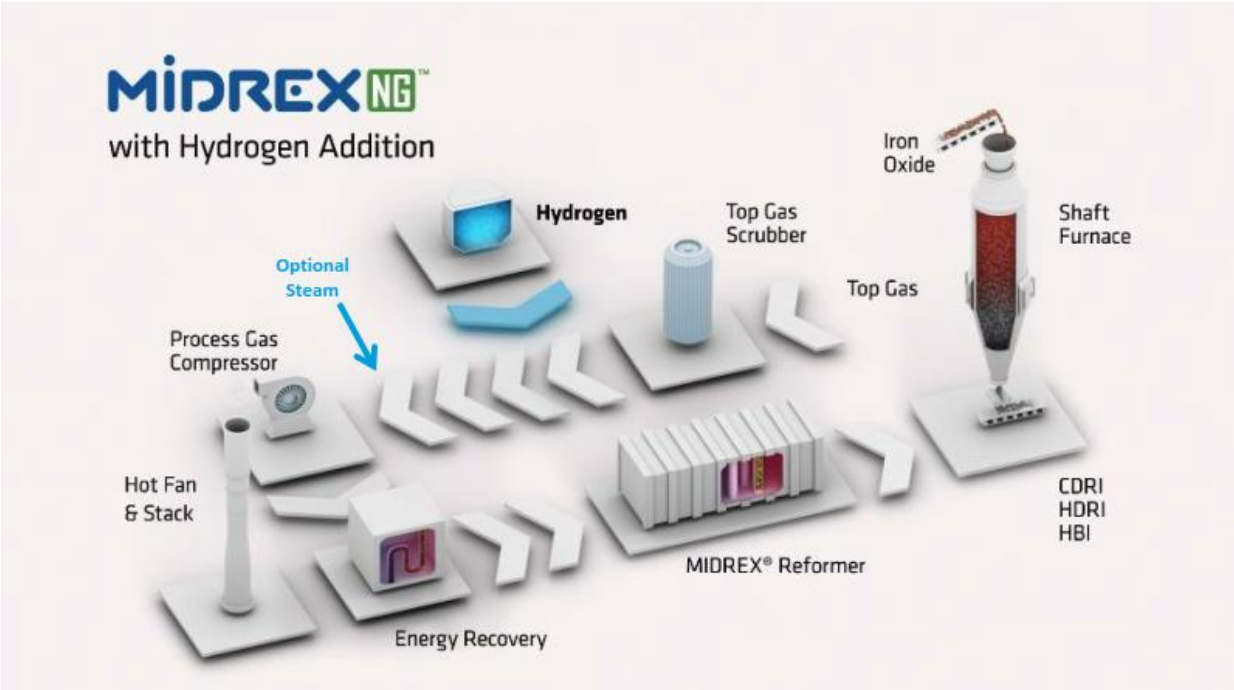


Figure 3: MIDREX® process based on hydrogen

As a highly flexible technology, a MIDREX® plant can be operated using hydrogen in a range between 0 to 100%. The MIDREX® H_2 process flow sheet for use of H_2 is shown in Figure 3. The hydrogen can be supplied ‘over-the-fence’ or can be produced on-site (e.g. via PEM electrolysis). The direct reduction process does not require high purity hydrogen, making it suitable for fossil-fuel derived hydrogen (grey), fossil-fuel derived hydrogen with CCUS (blue), or hydrogen produced from renewables via an electrolyser (green).

The natural gas MIDREX NG™ plant can be adapted in stages to a MIDREX H_2™ plant as low carbon hydrogen becomes available at a suitable cost, allowing steelmakers to reduce CO_2 emissions immediately and further reduce them in the future without major additional capital expenditure (see Figure 4). Such an approach provides steelmakers with a large degree of flexibility that can ensure new plants built today are ‘transition-ready’, minimizing stranded asset risk as policies on emissions reduction become increasingly strict.

Step 1

Build a new MIDREX NG™ plant using the most readily available energies. The product of this plant (CDRI, HDRI, or HBI) can be used in existing melting shops, including BF, BOF and EAF.

Step 2

Replace up to 30% of the natural gas used for reduction in an existing MIDREX NG plant with hydrogen as it becomes available, without the need for equipment modifications. Up to 100% hydrogen can be used with minor equipment additions to protect the reformer. The MIDREX™ process can accommodate fluctuating rates of hydrogen addition and or reduce production to take advantage of periods of excess renewable electricity

Step 3

Complete transition to MIDREX H_2™ as low carbon hydrogen becomes available and cost-effective. Some adaptions are required to accommodate plant operation for 100% hydrogen.

Figure 4: Stepwise approach to reduce CO_2 emissions via the direct reduction route

TECHNO-ECONOMIC ANALYSIS OF THE HYDROGEN DIRECT REDUCTION PROCESS

This section analyses the environmental benefits of the hydrogen based direct reduction process and its impact on operational cost based on average unit cost for a plant located in northern America (USA). Exact costs of operation will vary on the exact project details.

Definition of Calculation Basics

Basis for the subsequently presented calculations is a MIDREX direct reduction plant with an assumed capacity of 1 million tonnes per annum (MTPA) of (H)DRI/HBI production. In the comparison the iron ore will be either reduced by natural gas or by gradual addition of hydrogen to the natural gas (as described in section 3). For the comparison, the below indicated main unit costs are used for the natural gas based MIDREX® plant, which provides a 'base case' (CASE 1).

	Plant based on NG (Base Case)	Unit Rates
DRI Capacity	1 Mtpa	
Hourly DRI production:	125 t_{DRI}/h	
Consumption figures:		
- DR grade pellets	1.42 tons/t DRI	150 USD / t Oxide
- Natural gas	2.5 net Gcal	3.5 USD / mmBTU
- Electric power	120 kWh	0.036 USD / kWh
- Water (assuming cooling towers)	1.5 m³	1 USD / m³
- Manpower (including administration)	0.12 man-hours	40 USD / manhour
- Maintenance and supplies	4.00	USD 4.00 / t DRI

Table 1: Main unit cost and typical consumption figures for CASE 1 (base case)

The reduction work to produce DRI/HBI from iron oxide pellets requires conservatively estimated approximately 650 Nm³ (or 58 kg) of hydrogen per ton of DRI (see Table 2). This figure can also be lowered based on the configuration of the plant The purity of hydrogen required for this process lies at about 99.8%. It can be produced with a variety of technologies, including gas reformation and electrolysis. For reference, hydrogen for use in fuel cell electric vehicles requires a much higher purity of 99.999999% in order to avoid degradation of the fuel cell. This means that the hydrogen needed for direct reduction needs a comparably lower purity, allowing for flexible choice of the production process.

	Unit	**Value**
H_2 amount:	Nm^3/t DRI kg/t DRI	650 58
H_2 purity:	vol%	99.8
H_2 pressure (at TOP):	bar_g	min. 4.5

Table 2: Specific hydrogen consumption and requirements for direct reduction

Besides the hydrogen needed for the reduction of iron ore, energy is also required to heat the reducing gas. In the conventional direct reduction process this energy derives from a partial stream of the top gas of the Midrex shaft. Usage of the top gas from a hydrogen based Midrex plant would also be possible for heating, however, typically the hydrogen is supposed to be used for reduction and not to produce “only” energy for heating purposes. Therefore, for the presented calculations, natural gas was used as energy source for heating. This leads to CO_2 emissions and may in the future be replaced by biomass or electric heaters, but this needs to be studied in more detail.

Basis of all calculations is a Scope 1-3 approach [2,3], with a rather small Scope 3 portion of approx. 35 kg CO_2/t product.

Emission reduction potential for hydrogen-based direct reduction processes

For a comparison of hydrogen based direct reduction with the conventional route, the following cases are defined (Table 3). CASE 1 is a conventional DR plant based on natural gas (Base Case). CASE 2 and CASE 3 reflect the ‘Step 2’ and ‘Step 3’ set out in Figure 4, whereby a share of green hydrogen is blended into the gas feedstock, before then switching to 100% hydrogen. They are operated partially (CASE 2) or completely (CASE 3) with hydrogen as reducing agent. For the production of the hydrogen, the installation of a 110 MW and 350 MW Polymer Electrolyte Membrane (PEM) electrolyser plant is considered. The amount of hydrogen, the energy inputs, as well as the expected carbon content in the product are summarized in Table 3.

The results are strongly dependent on the CO_2 intensity of the grid electricity. For comparison, 4 scenarios using different CO_2 intensities of grid electricity (values varying between 417 g/kWh to 0 g/kWh) were used (Table 4). The 2030 EU target value represents an indicative intensity level that would allow the EU to achieve a net 55 % reduction in greenhouse gases by 2030, compared with 1990.

	CASE 1	CASE 2	CASE 3
	DR Plant based on NG (BASE CASE)	DR Plant with H_2 addition (30% H_2 share on reduction work)	H_2 DR Plant (100% H_2 share on reduction work)
H_2 used (Nm³/h) (kg/h)	0 0	24,000 2,200	81,250 7,300
Energy input: - Hydrogen (H_2) (mmBTU) - Natural gas (mmBTU) - Total (mmBTU) - H_2 energy/total energy	 0.0 9.9 9.9 0% H_2	 2.0 7.7 9.7 20.2 % H_2	 6.6 2.5**) 9.1 72.8 % H_2
Carbon content in DRI*)	2.5 wt%	~2 wt%	~0 wt%

*) in case required, the carbon content of the DRI for Case 1 could also be increased to > 3.5%

**) used for heating of the reducing gas

Table 3: Cases for direct reduction plant operation

Scenario	**CO_2 of grid electricity [g_{CO2}/kWh]**	**Source**
USA 2019	417	EIA's Annual Energy Outlook 2021 [4]
EU 2020	226	
EU target for 2030	76	European Environment Agency [5]
100% green H_2	0	

Table 4: CO_2 intensity of grid electricity scenarios used in the calculations

Figure 5 shows the results of the calculations for the CO_2 emissions. It depicts the emissions per ton of DRI produced for the previously described cases based on the grid factors defined in Table 4 as the electricity used for production of hydrogen is considered to come from the grid. As PEM electrolysis requires large amounts of electrical power, it can be clearly seen that the amount of CO_2 produced is strongly dependent a) on the amount of hydrogen used in the process and b) the CO_2 emission resulting from the electricity generation for hydrogen production.

Currently, no matter whether in the USA or the EU, CASE 1 (NG DR plant) has the lowest greenhouse gas emissions. Its CO_2 footprint is only slightly dependent on the CO_2 intensity of grid electricity. By the hydrogen addition the CO_2 emissions generated during hydrogen production (CASE 2 and 3) rise strongly and are highest for CASE 3 with 100% of the reduction work carried out by H_2.

As the addition of H_2 results in a stronger dependency on the CO_2 intensity of the electricity grid, there lies a large potential in CASE 2 and 3 to reduce CO_2 emissions by employing renewable energy sources to the electricity net as e.g. targeted for 2030 by the EU. At this point, CASE 1 and 2 are close to a break-even point and CASE 3 is already lower in CO_2 emissions than the other two.

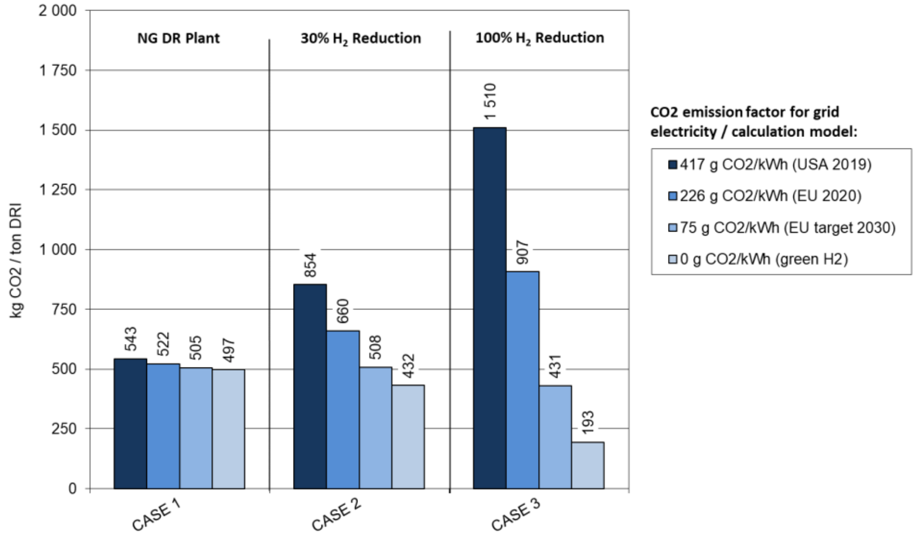


Figure 5: Comparison of CO_2 emissions for DRI production at different CO_2 intensities of grid electricity

Finally, at reducing the CO_2 emissions of the electrical energy consumed to zero, the hydrogen cases lie both clearly below the natural gas route. The largest savings and the greatest ecological benefit are being reached by 100% H_2 reduction.

Emission reduction potential of direct reduction technology compared to conventional steel-making routes

A model allows for the economic comparison of direct reduction technologies with conventional steel-making routes. To create a common basis, the final product is defined to be liquid steel. For direct reduction routes, this can be achieved by adding an EAF charged with 80% DRI and 20% scrap.

The comparative scenarios as depicted in Figure 6 are Blast Furnace + BOF, COREX + DR plant with EAF, natural gas direct reduction plants with cold or hot DRI respectively as intermediary product and the previously defined hydrogen based direct reduction Cases with an EAF.

The main result differences for the direct reduction processes compared to those in Figure 5 lies within the higher sensitivity of all EAF-based cases to CO_2 emissions resulting from high electricity consuming EAF operation. Compared to BF - BOF steelmaking, they offer great potential as environment- and greenhouse-gas-friendly technologies, even when considering actual CO_2 values for grid electricity. The COREX technology, as the second coal-based process besides the BF, can be effectively combined with a direct reduction plant based on COREX export gas. Such COREX/DR combination shows the lowest CO_2 emission for coal-based processes.

The results for the direct reduction cases are similar to those shown in Figure 5. The differences between the DR(NG)-EAF case and CASE 1 derive from direct use of hot DRI in the EAF and thereby reduce the energy-losses by DRI cooling and re-heating (see section 5). Also, the close-to-zero carbon content in the DRI in CASE 3 at high H_2 usage requires carbon addition at the EAF which increases Scope 1 emission by 82 g CO_2/ t LS. The residual amount of CO_2 (184 kg/t liquid steel) for the 100% hydrogen CASE 3 at zero electrical grid emission derives also from the natural gas used for heating and a minor portion from production of raw materials (Scope 3).

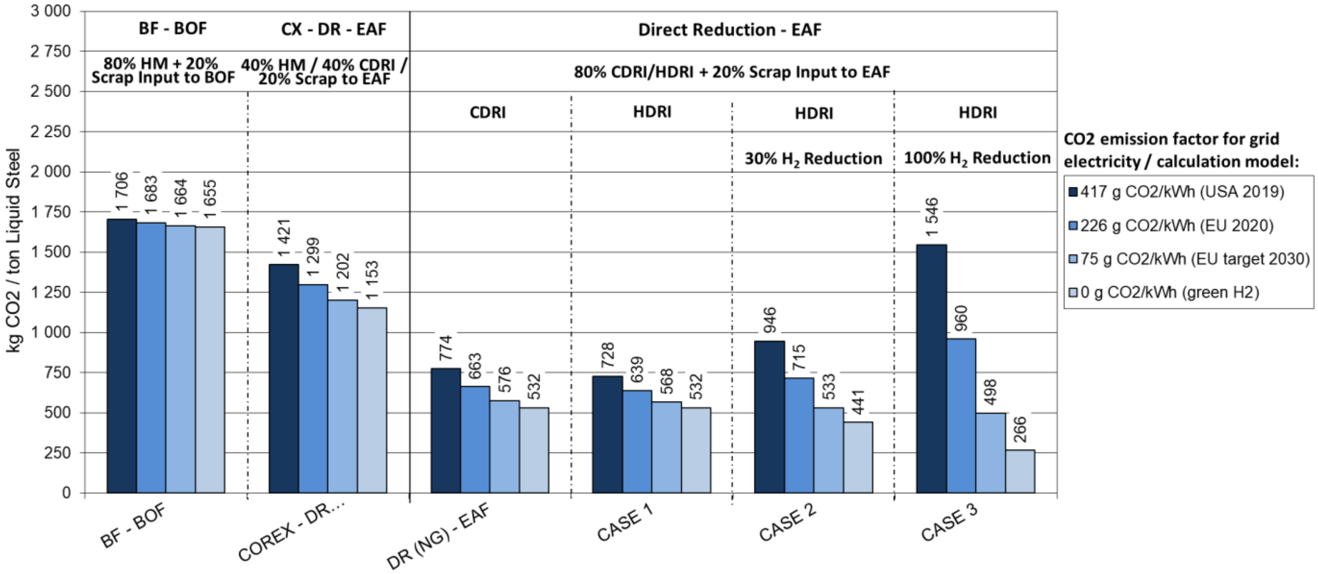


Figure 6: Comparison of steelmaking routes with regard to CO_2 emissions at different intensities of grid electricity

In Table 5, the CO_2 emissions are listed to compare the emission reduction potential of hydrogen-based DR processes for future scenarios with current operation of steel plants. It shows that the even now beneficial natural gas-based processes can be further improved to up to 86% CO_2-reduction with neutral electric energy and high hydrogen use.

Route	BF-BOF	COREX DR-EAF	NG DR-EAF	NG DR HTC EAF CASE 1	H_2 DR-EAF CASE 2	H_2 DR-EAF CASE 3	H_2 DR-EAF CASE 2	H_2 DR-EAF CASE 3
CO_2 of grid electricity (gCO_2/kWh)	417	417	417	417	75	75	0	0
Emissions (tCO_2/tls)	1943	1541	777	731	536	501	444	270
Emissions reduction versus BF-BOF	0%	-21%	-60%	-62%	-72%	-74%	-77%	-86%

Table 5: Emissions reduction potential for the different routes

Techno-economical evaluation

The calculation of operation costs (OPEX) has been carried out for a H_2 price of $1/kg and a CO_2 grid electricity intensity of 75 g/kWh. These values represent a near future basis scenario for costs of green hydrogen. As can be seen from this analysis, the natural gas price is the key value responsible for competitive production, whereas the assumed CO_2 abatement costs as shown in Figure 7, don't have a large impact on the OPEX cost and need to be high to change the result.

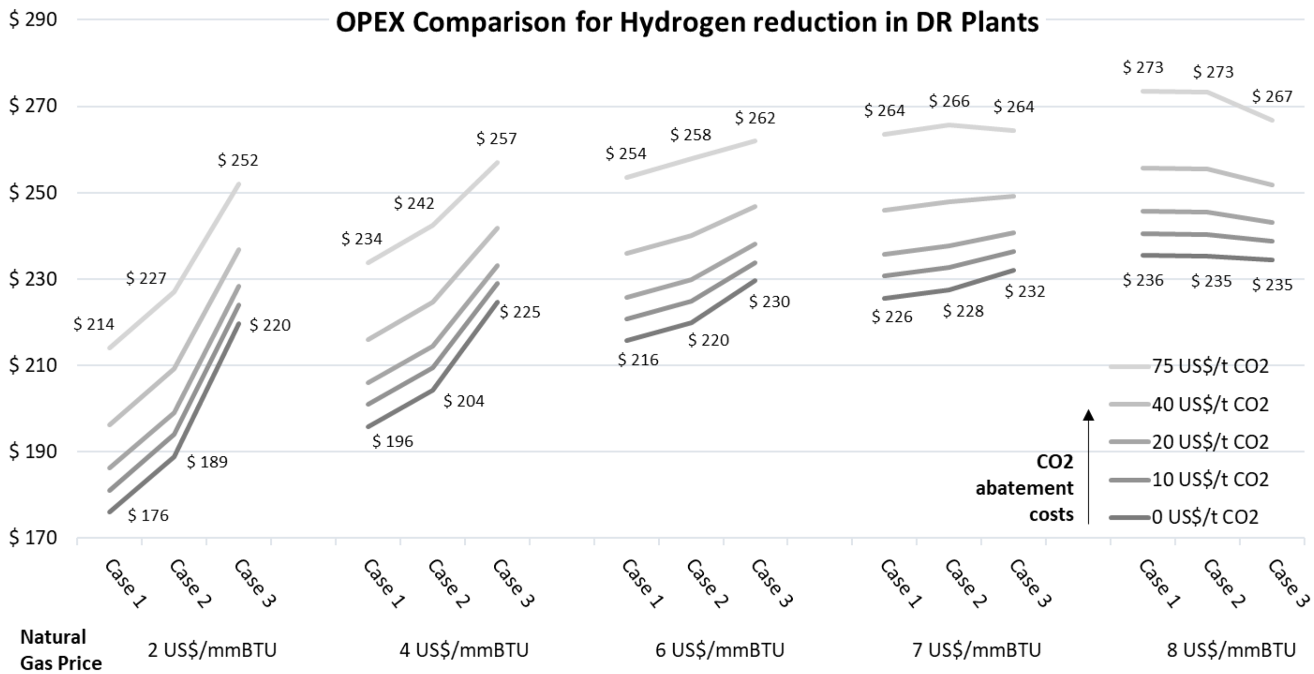


Figure 7: OPEX comparison for DRI production for CASE 1, 2 and 3

The produced DRI from the DR plant is typically used in an EAF for steelmaking. This requires additional electrical energy as well as electrodes, lime, fuel (typically natural gas), and refractory materials. Figure 8 indicates the OPEX cost for steel making considering an assumed feed mix of 80% DRI and 20% scrap to the EAF.

Again, the natural gas price plays the major role in OPEX calculations. The break-even point between the natural gas and hydrogen route, however, shifts to lower values because of the larger impact of CO_2 from grid electricity compared to total emissions.

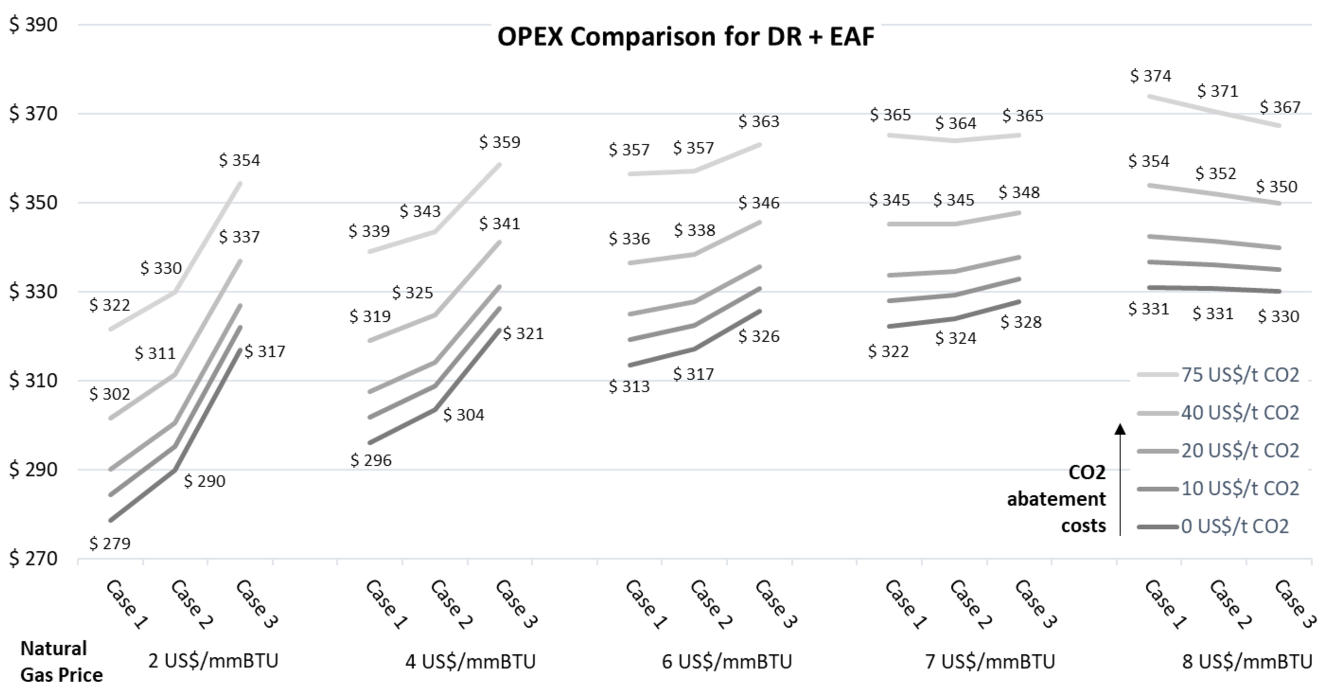


Figure 8: OPEX comparison for the DR - EAF route

Another important fact, not considered in the OPEX calculation, is that the installation of a PEM electrolyser can also be used to increase the MIDREX® plant capacity. It is possible to use the by-product oxygen from the PEM electrolyser in the direct reduction shaft, particularly for DRI production. The oxygen can be added to the bustle gas in the DR plant in order to increase the reducing gas temperature and enhance the plant productivity for HDRI plants. Alternatively, the oxygen can also be used in the EAF or for oxygen enrichment for a blast furnace, if nearby. This can provide an additional revenue for the electrolyser, reducing overall costs of operation.

USE OF DRI/HBI IN THE STEEL PLANT

Figure 9 depicts the different possibilities to use DRI/HBI in the Steel Plant.

The traditional and most common product from MIDREX plants is **Cold DRI (CDRI).** After reduction, the DRI is cooled to ambient temperature to be stored or used in a nearby EAF and passivated to prevent re-oxidation and loss of metallization. It can be transported via rail and sea but is not recommended. With lower carbon content the reactivity will even increase. In case of any transport, it should be passivated at site and inertized during transportation. Nowadays almost all MIDREX plants are hot discharge plants producing either hot DRI (HDRI) or hot briquetted iron (HBI).

For longer (sea) transport, **HBI (Hot Briquetted Iron)** is the preferred DRI product. It is made by compressing of DRI discharged from the MIDREX shaft furnace at ≥ 650°C into pillow-shaped briquettes. HBI has a density ≥ 5.0 g/cm^3, which minimizes the re-oxidation rate and minimizes yield losses from breakage. This enables HBI to be stored and transported without special precautions. It can be used in the EAF, BF and BOF.

Historically, DRI or HBI is used as a complement to scrap in the EAF, generally 10-30% of charge, but can be up to 100%. This can be batch or continuously charged, either cold or hot. HBI is used (typically up to 15%) as a cold charge to supplement scrap in a BOF. It can also be used to increase hot metal production and lower coke consumption in the BF (typically up to 20% of charge)

Hot DRI (HDRI) can be transported to an adjacent EAF at up to 650°C to take advantage of the sensible heat, which allows the steelmaker to increase productivity and reduce production cost. In EAF steelmaking, hot transport/hot charging is an effective means of lowering the cost per ton of liquid steel by reducing power and electrode consumption, as well as increasing EAF productivity – making it possible to downsize the electrical system for a greenfield EAF meltshop.

From an environmental point of view, the benefits of HDRI charging are striking: Retaining the sensible heat in the DRI rather than cooling prior to furnace discharge lowers overall emissions in two ways. First, lower electricity demand reduces power plant emissions per ton of steel produced. Second, in mills depending on charge carbon, reduced energy requirements in the EAF result in less CO_2 emission.

Nowadays, all captive DR plants (DR plants with a downstream EAF melt shop) will utilize a hot transport system to directly feed hot DRI into the EAF. Three methods for HDRI transport are possible: hot transport vessel, HOTLINK® and hot transport conveyor.

Primetals and Midrex have jointly developed the hot transport conveyor (HTC) system, using Aumund bucket conveyors to charge hot DRI into the EAF. The HTC is designed to minimize temperature loss and to prevent re-oxidation of HDRI while being transferred to an EAF meltshop up to a distance of 200 m. Hot DRI (HDRI) is discharged from the MIDREX® Shaft Furnace into a mechanical conveyor, which uses specially designed buckets to transport the HDRI to the melt shop. The proven hot transport conveyor has been used successfully with impressive results at multiple installations.

MIDREX plants can be designed to switch from one DRI form to another with no disruption of product flow – CDRI to HBI, CDRI to hot DRI (HDRI), or HBI to HDRI and vice versa. Any product can be produced simultaneously in any combination.

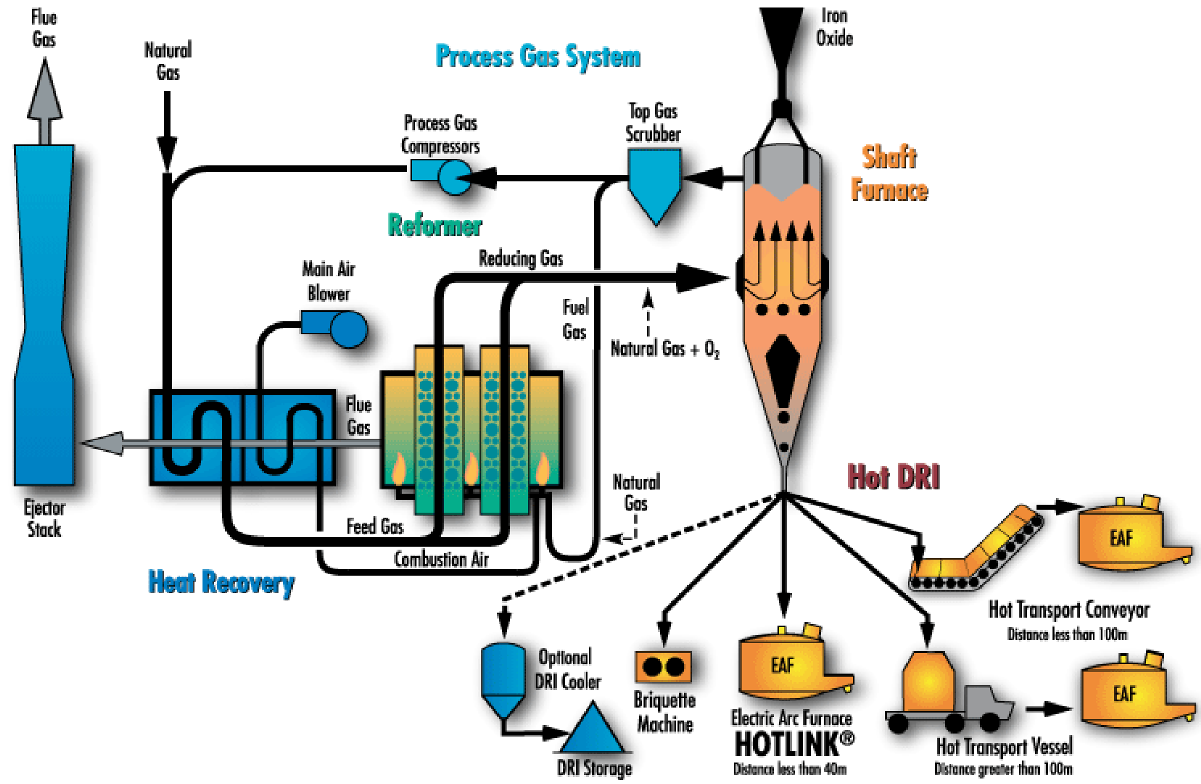


Figure 9: Use of DRI in steelmaking

ACTUAL PROJECTS FOR USE OF H_2 IN MIDREX PROCESS

ArcelorMittal Europe pursues the ambitious goal of CO_2-neutral steel production by 2050. The approaches include "Carbon Capture and Storage", "Circular Carbon" and "Clean Electricity". A major role in the company's decarbonization strategy is based on hydrogen. To ultimately reach zero CO_2 emission, this hydrogen will need to be 'green' (produced via electrolysis and powered by renewable electricity).

ArcelorMittal Europe owns Europe's only DRI-EAF facility in Hamburg, Germany, where a project is planned to use hydrogen for DRI production on an industrial scale, as well as testing of carbon-free DRI in the EAF [6]. The program includes the construction of a demonstration plant with a capacity of 100,000 t/a DRI based on pure hydrogen. The hydrogen for this demo plant is first produced out of gray hydrogen (derived from existing Midrex plant). Long-term, green H_2 is targeted.

This project will not only achieve an immediate positive environmental effect and significantly improve the current state of the art for Midrex systems with regard to CO_2 emissions, it will also create knowledge for the conversion of operation of existing systems to operation with hydrogen addition and for new plants designed for 100% "green" hydrogen.

Figure 10: Midrex® DR plant at ArcelorMittal Hamburg AG

In February 2021, Primetals Technologies and Midrex Technologies signed a contract with Mikhailovsky HBI for the world´s largest HBI plant in in Zheleznogorsk, Russia. The new plant is designed based on the principles of carbon-free metallurgy, with the prospect of fully transitioning to the use of "green" hydrogen as a reducing agent to decrease carbon emissions in the future. This project creates a strong basis for further development of “green” steelmaking and active implementation of eco technologies of steel production” [7].

CONCLUSIONS

The DRI sector in steelmaking experiences rapid growth and allows for many options in “green” steelmaking. Especially hydrogen-based reduction as used in the MIDREX H_2™ technology is winning support due to the thriving interest in green technologies.

Natural gas based Midrex plants can be converted in stages to a Midrex H_2 plant at low additional expenditure, allowing steelmakers to reduce CO_2 emissions immediately when low-carbon low-cost hydrogen becomes available. New plants are being built ‘transition-ready’, minimizing stranded asset risk as policies on emission reduction become increasingly strict.

The emission reduction potential for such hydrogen-based DR processes was analyzed by defining three cases – a natural gas base case and 2 hydrogen-based cases with 30 and 100% of the reduction work achieved by hydrogen. Due to the electricity-based hydrogen production in a PEM electrolysis plant, the CO_2 emissions of such DR plants are strongly depending on the CO_2 intensity of the electricity grid. CO_2 load numbers targeted for the near future (e.g. for 2030 in the EU) already allow for lower CO_2 emissions than the natural gas route.

A similar picture is drawn when an EAF is additionally considered to be able to compare the direct reduction routes with conventional steelmaking (BF-BOF, COREX-DR-EAF). The well-known advantages of direct reduction routes due to their lower CO_2 emissions are clearly visible and the break-even point between the natural gas and the hydrogen-based routes can be reached at even lower CO_2 emission efficiency for grid electricity.

Operational costs calculations for a near future scenario (reasonable hydrogen costs as well as CO_2 load on electricity) show a strong dependence on natural gas prices whereas CO_2 abatement costs (based on a CO_2 grid electricity intensity of 75 g/kWh) do not largely change the results. A reduced CO_2 grid electricity intensity combined with high CO_2 abatement costs would favor hydrogen usage for direct reduction.

Intelligent plant design allows for further CO_2 emission efficiency. Avoidance of energy losses is a key factor to reduce emissions. Hot DRI technologies such as the hot transport conveyor, jointly developed by Midrex and Primetals, allow to retain the sensible DRI heat, lower the EAF electricity demand and thereby reduce the overall CO_2 emissions of the plant.

Hydrogen-based plants are of world-wide interest and there are several currently ongoing projects in experimental or industrial stage. ArcelorMittal Hamburg is building a demonstration plant for DRI production based on 100% hydrogen. The newest industrial scale project is Mikhailovsky HBI's new HBI plant which is designed based on the principles of carbon-free metallurgy. The new plant is being built 'transition-ready' allowing for natural gas production with the prospect of fully transitioning to the use of "green" hydrogen. It thereby minimizes stranded asset risk for the steelmaker as policies on emissions reduction become increasingly strict.

REFERENCES

1. World Steel Association: *„Steel Statistical Yearbook" 2000 and 2020* (https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html)
2. ghgprotocol.org
3. https://en.wikipedia.org/wiki/Carbon_accounting
4. https://www.eia.gov/outlooks/aeo
5. https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111
6. https://corporate.arcelormittal.com/media/news-articles/arcelormittal-europe-to-produce-green-steel-starting-in-2020
7. https://m.metalloinvest.com/en/news/522035/