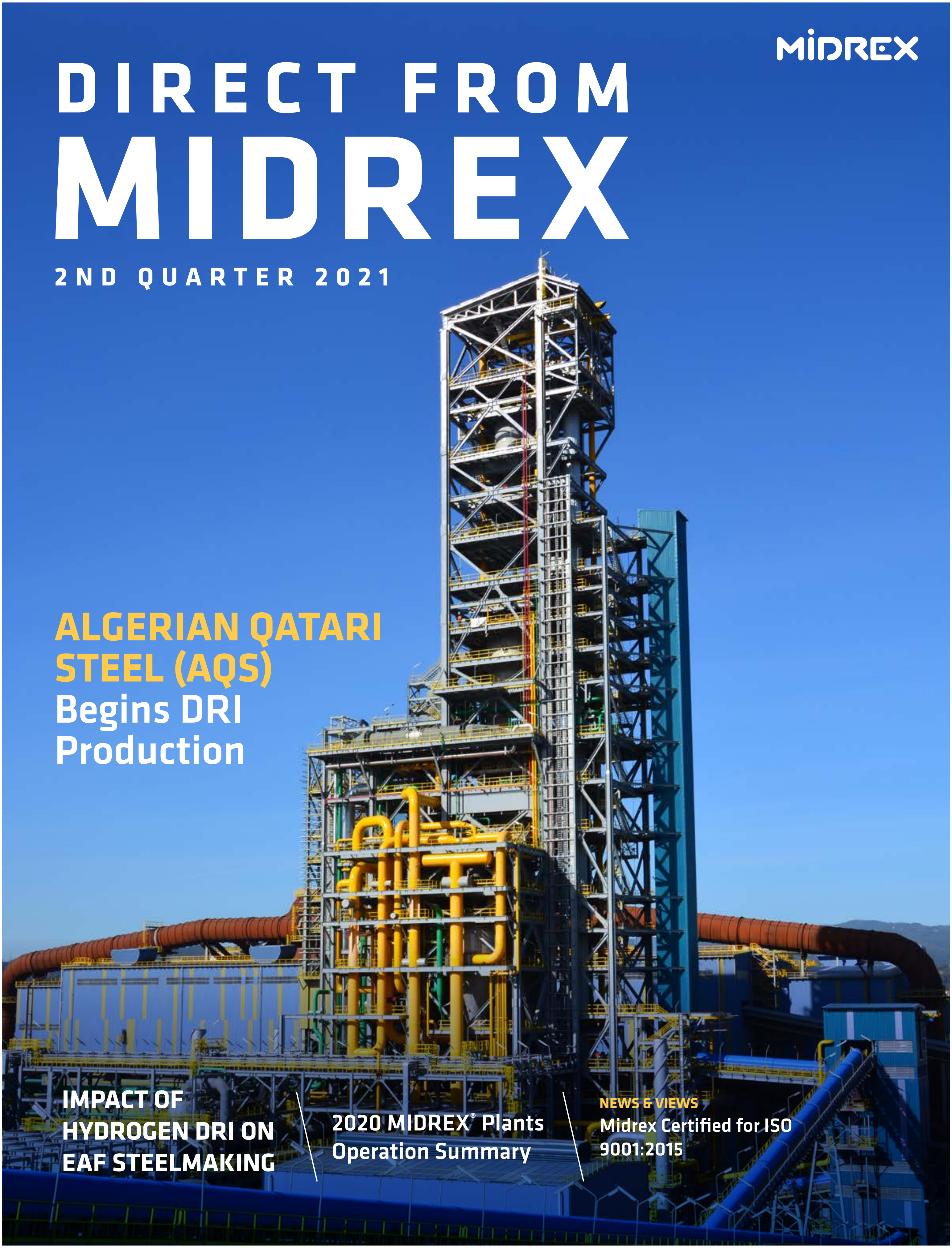

DIRECT FROM MIDREX

2ND QUARTER 2021

ALGERIAN QATARI STEEL (AQS) Begins DRI Production

IMPACT OF HYDROGEN DRI ON EAF STEELMAKING

2020 MIDREX® Plants Operation Summary

NEWS & VIEWS
Midrex Certified for ISO 9001:2015

COMMENTARY

PERSEVERANCE AND TEAMWORK – THE HALLMARKS OF SUCCESS

By Chris Hayes
Vice President – Operations

Despite the unprecedented challenges of the last 18 months – not to mention the normal rigors of working outdoors in all types of climates and weather – the men and woman who build, start-up and commission, and operate MIDREX® Plants have persevered. For example, Tosyali Algérie set a new world record for direct reduced iron (DRI) production in only the second year of operation, and the plants of Algerian Qatari Steel (AQS) and Cleveland-Cliffs Toledo HBI were completed and put into operation.

In 2020, 69 MIDREX Plants comprised of 77 modules* were in operation in 21 countries around the world producing cold DRI (CDRI), hot DRI (HDRI), hot briquetted iron (HBI), or a combination of the DRI forms. Except for those idled by non-process factors, 99% of all MIDREX Modules ever constructed are capable of operating today.

Plants based on MIDREX Technology each year produce more than 60% of the entire world's supply of DRI and more than 80% of DRI produced by shaft furnace technologies. We expect similar results when the World Direct Reduction Statistics for 2020 are published later this year.

We are very proud of the reputation for reliability, flexibility, and performance that has been earned by MIDREX DR Technology. It is a reputation that reflects our core values:

- **Integrity** – Act honestly and fairly for the good of all
- **Commitment** – Be dedicated to the success of customers, the well-being of teammates, and the growth of Midrex
- **Teamwork** – Be actively engaged, respect and trust others, accept responsibility, learn from mistakes, and share credit for achievements
- **Quality** – Do your best in every situation and produce a quality of work that sets a high standard for the Industry
- **Innovation** – Be a pioneer in the Industry and think creatively toward our future

More than 50 years ago a creative idea for making use of existing knowledge and expertise in an exciting new way launched the MIDREX Process. Through the years, hundreds of Midrex men and women have built upon that innovative spark to mold a culture of cooperation, progress, and caring for others that inspires all we do. Together with our construction and equipment partners, corporate customers, and the direct reduction industry's best and brightest plant operators we will continue to strive for excellence in delivering sustainable solutions for our customers and furthering the effort to decarbonize steelmaking.

I would be remiss to not mention the outstanding efforts of all Midrex Group teammates in achieving ISO 9001:2015 recertification. This year Midrex Technologies Gulf Services FZCO and the Midrex Research & Development Technology Center were added to the Midrex ISO certification first achieved in 1998. Midrex Technologies India Private, Ltd. and Midrex UK Ltd. were originally registered under ISO 9001:2008 and were recently recertified.

As Midrex President & CEO Stephen Montague said in his recently published interviews in Metal Market Magazine and Business Focus Magazine, "It's all about people."

**A MIDREX Plant can include one or more modules*

↓

In addition to an article that summarizes the operation and achievements of MIDREX Plants in 2020, this issue of *Direct From Midrex* includes an in-depth article that discusses the benefits and challenges of melting hydrogen-based DRI. In addition, the News & Views section contains noteworthy Midrex-related events occurring during 2Q2021.

Impact of Hydrogen DRI on EAF Steelmaking

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INTRODUCTION

The world steel industry constitutes 8% of the overall energy demand whilst contributing 7% of the total carbon dioxide (CO_2) generated by humanity (2.6 GTonne [GTe] CO_2 2020; 2.8 GTe CO_2 2015) [1, 2], ***Figure 1***]. The great majority of this CO_2 generation is due to coal, constituting 75% of the energy used in the steel industry, predominantly in the ironmaking process, where carbon is used chemically to reduce iron oxide and provide fuel for the process. In the case of the Iron Blast Furnace, carbon (in the form of coke) also plays a vital role by providing structure and mechanical support to the bed of materials in the reactor shaft.

Figure 1 (next page) summarizes the generation and required CO_2 reductions, the anticipated increase in steel demand, and the required change in carbon intensity between 2015 and 2050[3]. The massive potential generation of CO_2 from industrial processes and transportation is the motivation behind the desire to decarburize and become a Hydrogen Economy (using H_2 as a fuel source). This, of course, assumes cheaper and 'greener' methods of H_2 production become reality.

In the case of shaft furnace-based direct reduction (DR) processes, such as MIDREX®, a reducing gas mixture of carbon monoxide (CO) and H_2 is produced from the decomposition of natural gas. Carbon does not play a key role in the process; however, increasing the H_2-to-CO ratio does have a significant effect on the process heat balance. In fact, there is substantial evidence that carbon can be removed from the process and replaced by H_2, as was discussed in the first quarter 2020 issue of *Direct from Midrex* [4].

WHAT IS MEANT BY GREY, BLUE, AND GREEN HYDROGEN?

Hydrogen is labelled according to the source of underlying energy carrier used to produce the H_2 and whether carbon capture and storage (CCS) is employed:

- **Grey hydrogen** – fossil fuel source with no CCS to remove, store, and stabilize CO_2
- **Blue hydrogen** – fossil fuel source with CCS or electrolysis using non-renewable electricity but at great capital cost for commercially available CCS and H_2 generation equipment
- **Green hydrogen** – water electrolysis using renewable electricity coupled with renewably-sourced electrical energy, which is challenged by the cost and scale of current commercial plants

(Source: *CRU Steel Metallics Monitor - 2020 Macro Trends*, 14 Oct 2020, "How higher CO_2 prices could shift the EU to low-carbon steelmaking")

There are significant issues to overcome before the Hydrogen Economy is a reality for steel and other industries; the main one being the economical supply of 'green' hydrogen and electricity[4,5]. There are also significant operational issues: for example, the endothermic nature of the H_2 reduction reactions of shaft furnace-based DR processes means the heat balance will be quite different than for a conventional natural gas-based configuration and likely would present operating challenges. Also, the production of 0% carbon direct reduced iron (DRI) would have major repercussions on the subsequent EAF steelmaking step, the impact of which is the prime topic for this article.

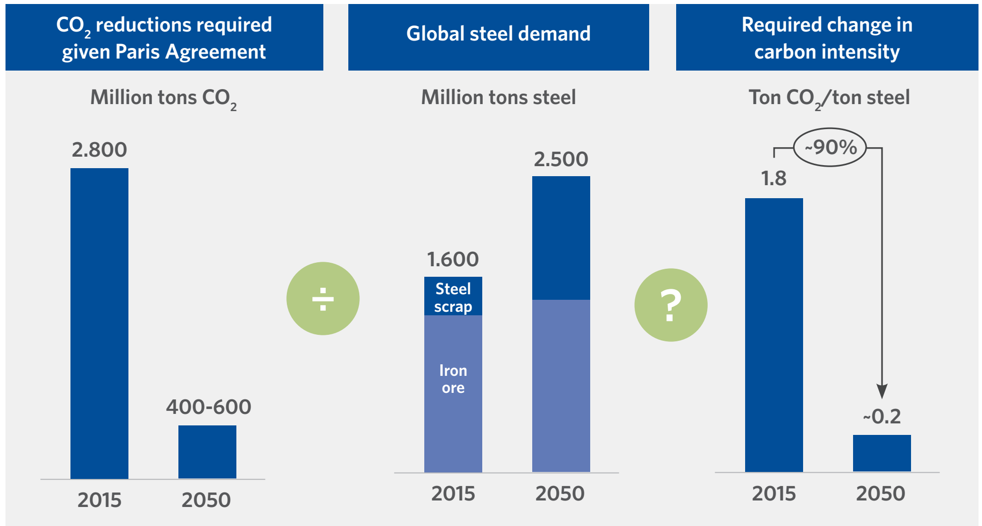


FIGURE 1. *Required Change in Carbon Intensity 2015 to 2050* [3]

Technology	Parameter	Units	Today	2030	Long term
Water electrolysis	CAPEX	USD/kW_e	900	700	450
	Efficiency (LHV)	%	64	69	74
	Annual OPEX	% of CAPEX	1.5	1.5	1.5
	Stack lifetime (operating hours)	hours	95,000	95,000	100,000
Natural gas reforming	CAPEX	USD/kW_{H2}	910	910	910
	Efficiency (LHV)	%	76	76	76
	Annual OPEX	% of CAPEX	4.7	4.7	4.7
	Emission factor	$kgCO_2/kgH_2$	8.9	8.9	8.9
Natural gas reforming with carbon capture	CAPEX	USD/kW_{H2}	1,680	1,360	1,280
	Efficiency (LHV)	%	69	69	69
	Annual OPEX	% of CAPEX	3	3	3
	CO_2 capture rate	%	90	90	90
	Emission factor	$kgCO_2/kgH_2$	1.0	1.0	1.0
Coal gasification	CAPEX	USD/kW_{H2}	2,670	2,670	2,670
	Efficiency (LHV)	%	60	60	60
	Annual OPEX	% of CAPEX	5	5	5
	Emission factor	$kgCO_2/kgH_2$	20.2	20.2	20.2
Coal gasification with carbon capture	CAPEX	USD/kW_{H2}	2,780	2,780	2,780
	Efficiency (LHV)	%	58	58	58
	Annual OPEX	% of CAPEX	5	5	5
	CO_2 capture rate	%	90	90	90
	Emission factor	$kgCO_2/kgH_2$	2.1	2.1	2.1

Notes: 25-year lifetime and a 95% availability factor assumed for hydrogen production from natural gas and coal. Availability factors for electrolysis are based on the full load hours of electricity shown in following table. For water electrolysis, possible revenues from oxygen sales have not been considered in the cost analysis.

Sources: References in Table 1 of Chapter 2 for electrolysis IEAGHG (2014), "CO_2 capture at coal based power and hydrogen plants", IEAGHG (2017), "Techno-economic evaluation of SMR based standalone (merchant) hydrogen plant with CCS".

TABLE I. *Comparison of Capex, Opex, Efficiency and CO_2 Impact of Hydrogen Production Routes* [1]

A summary of estimated capital and production costs, process efficiency, and environmental impact for different hydrogen generation technologies is provided in *Table I (previous page)*[1].

The complex issues involved with the manufacture, storage, transportation, and use of 'blue' and 'green' hydrogen are magnified by the political and social issues involved in using CCS technology and concerns for the safety and sustainability of this technology. These issues are beyond the scope of this article but are important to appreciate when critically analyzing the commercialization potential of hydrogen-based ironmaking technology.

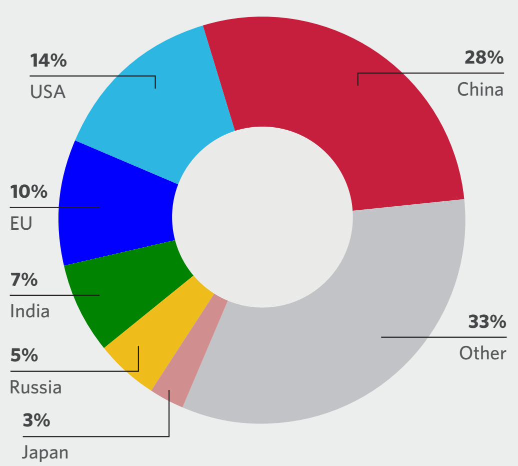
EAF CO_2 GENERATION

Electric Arc Furnace (EAF) based mini mills (MMs) produce 28% of world steel, though they account for only 8% of the CO_2 generated by the steel industry. On the other hand, conventional integrated mills (blast furnace/basic oxygen furnace [BF/BOF] route) produce 72% of world steel with a higher CO_2 generation rate (92%), as shown in *Table II* [1, 7].

The volume of CO_2 can be diminished significantly from that of the BF/BOF route with the incorporation of H_2, renewables, and scrap, as shown in *Figure 2a* [5, 8]. *Figure 2b* shows CO_2 emissions intensity by country.

FIGURE 2b.

CO_2 Generation by Country [7]



Global CO_2 Emissions

	MTe Steel	%	MTe CO_2	%	Te CO_2/Te$_{Steel}$
TOTAL	1,869.0		3,170.2		1.6962
EAF	523.0	28	209.0	8	0.3996
BF/BOF	1,346.0	72	2,961.2	92	2.2000

TABLE II. *CO_2 Generation by Steel Mill Type* [1, 7]

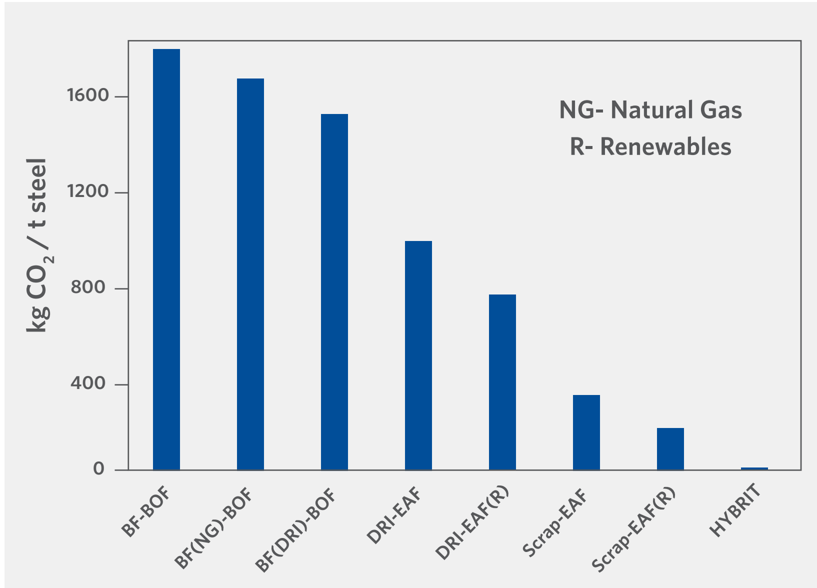


FIGURE 2a. *CO_2 Generation by Steel Route* [5, 8]

	CO_2 kg per Area Summary			
RAW MATERIALS	PRODUCTION	TRANSPORT	MELTING	TOTAL
Scrap/OBMs	156,423	4,028	19,053	179,504
Oxygen	1,263			1,263
Natural Gas	94	126	2,946	3,166
Electricity (kWh)	35,720			35,702
Fluxes	20,109	115		20,224
Coal		9	4,895	4,904
TOTAL CO_2 (kg)	213,609	4,277	26,895	244,781
TOTAL CO_2 (kg/Te $_{liquid\ steel}$)	777	16	98	890

TABLE III. *CO_2 Sources in EAF Steelmaking* [9]

Table III identifies some EAF CO_2 sources[9], from power generation (50-70% energy input to the EAF *[see Figure 7]*) to combustion of C from the bath, dirt on scrap, in-situ C (liquid steel, scrap, PI, DRI, HBI, MagCarbon bricks, electrodes, charge C, injection C), and lime production.

CO_2 remediation is focused on the EAF route, despite the smaller impact it presents, because the EAF route is regarded as the easiest, most economical conversion option. The EAF route has lower reliance on diminishing quality iron ore sources (i.e., predominantly scrap-based), has a current global recycle rate of 80-90%, and uses only 1/8th of the energy compared to conventional integrated mills.

Scrap-based EAF operations present the most CO_2 friendly route ***(Figure 3)*** even when including electricity contributions (assuming 65 kg CO_2/Te DRI and about a 15% scrap charge in the BOF). However, the beneficial continuous recycling in the EAF will render prime scrap sources few-and-far-between long term ***(Figure 4)***, necessitating greater use of Ore Based Metallics (OBMs – DRI/HBI and Pig Iron) and Hot Metal. This need will be greater for high quality steel mills with stringent residuals requirements. ***Figure 5*** shows the residual levels (and yield) of various metallics and specific steel quality needs. Significant variation in C (0.08% in sheet to 0.4% in rebar) and detrimental copper (Cu – 0.33% in structural to 0.04% to 0.1% in sheet) between scrap grades means that to produce a 0.08% Cu steel today (with USA scrap currently containing 0.25-0.3% Cu), a 70% OBM charge is needed.

Whilst there will be plenty of obsolete scrap moving forward, meeting quality steel chemistry constraints will require the industry to demand changes in scrap handling, such as a global agreement on an international standard scrap nomenclature and specification and better segregation. Cost premiums for guaranteed prime quality scrap will undoubtedly result.

Since the EAF charge constitutes 76-89% of the cost of a tonne of liquid steel (Te_{ls}) a stringent value in use (VIU) model will be required to maximize EAF steelmaking profitability by minimizing liquid steel costs. This will need to be an all-encompassing VIU charge model [11] reflecting value not only for composition (low residuals, C content, and gangue) but also physical properties of raw materials,

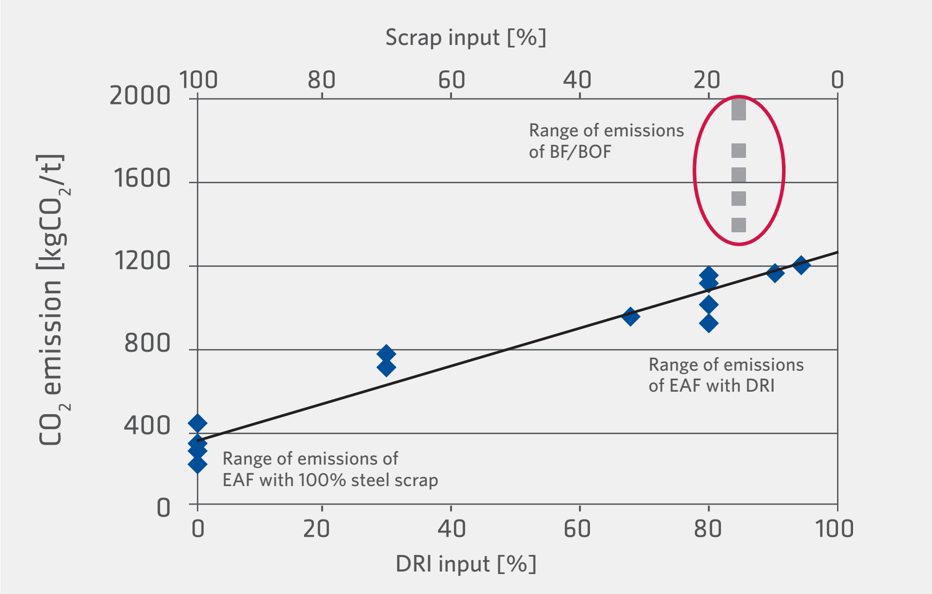


FIGURE 3. *Impact of DRI on steelmaking CO_2 emissions* [10]

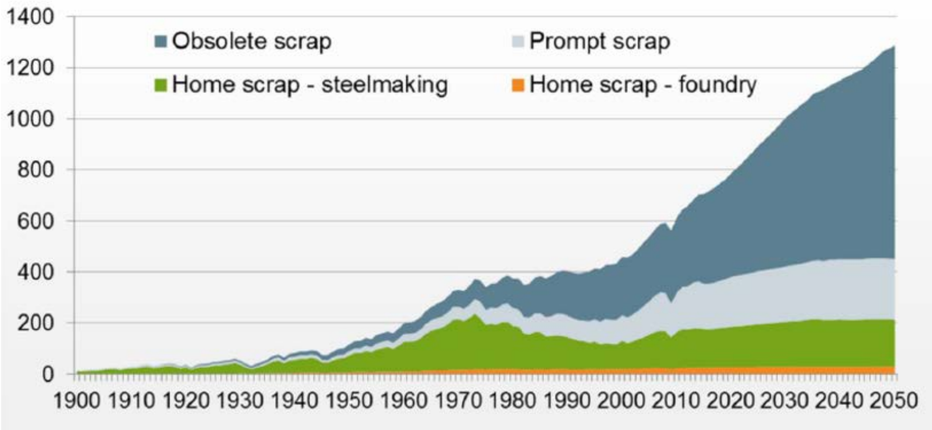


FIGURE 4. *Global Scrap Availability (Million Tonnes)*

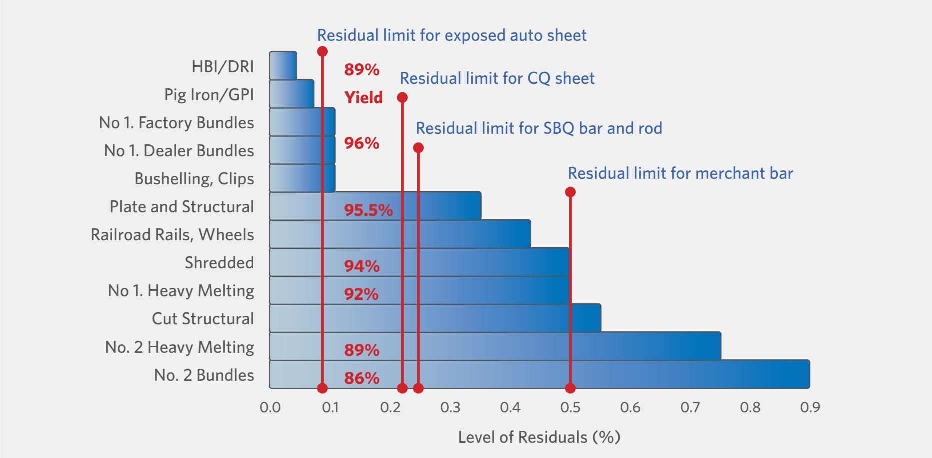


FIGURE 5. *Residuals Level and Yield by Metallics Type* [11]

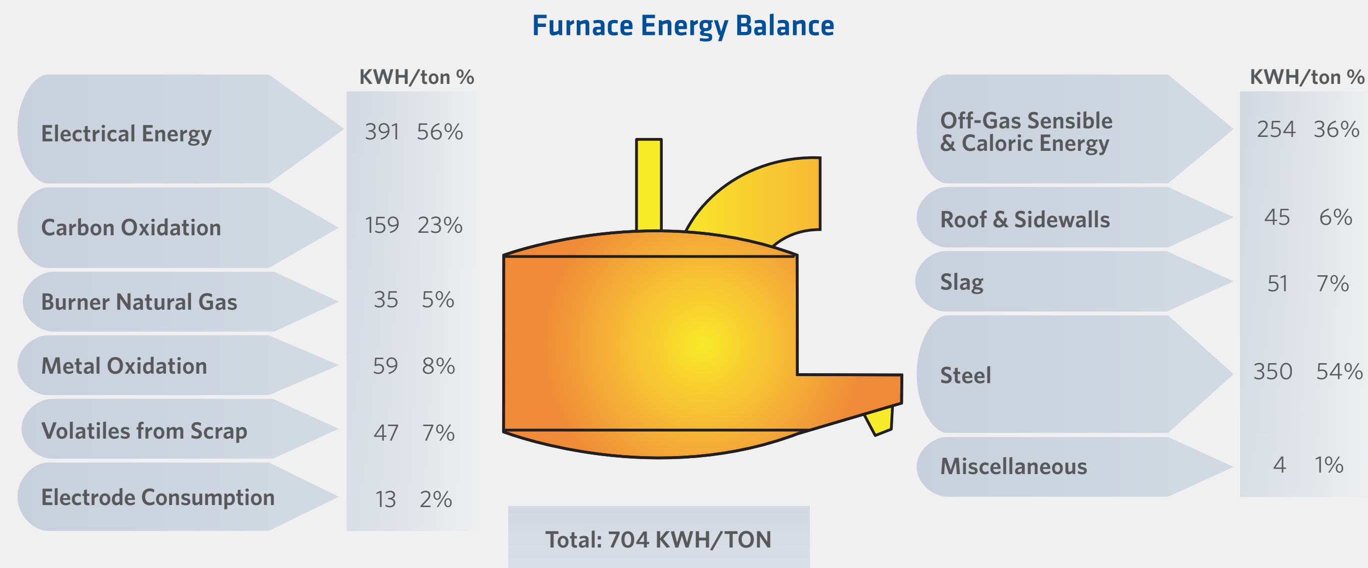


FIGURE 6. *EAF Energy Balance* [12]

benefits and potential operational impacts [11], an environmental impact minimization algorithm, and if large scale H_2 DRI production capacity becomes a reality, 0% C_{DRI} and its impact on slag volumes and chemical energy. How will they impact productivity, yield and operational costs?

BENEFITS OF CARBON IN EAF OPERATIONS

Steel is an alloy of iron (Fe) and carbon (C); therefore, 'zero carbon steelmaking' is a contradiction. The term 'carbon neutral steelmaking' is a more accurate descriptor. Accepting that large amounts of H_2 can be incorporated into the MIDREX Shaft Furnace, and that the reaction between H_2 and iron oxide will proceed similarly as with the mixture of CO/H_2 produced from natural gas (NG) and iron oxide (FeO), the absence of CO will result in an endothermic reaction (requiring heat balance adjustment) and no DRI carburization. This resultant zero carbon DRI (0% C_{DRI}) will create most of the issues when considering EAF melting.

EAF melting has changed dramatically since 1965 [12], predominantly through a significant increase in chemical energy use, now 35-50% of melt energy ***(Figure 6)***. This chemical energy is derived from O_2 (sourced from O_2 injection, excess O_2 from oxy-fuel burners, or bath reduction) combusting with a fuel (NG, etc.), C in the charge or bath, and other elements in the bath (Fe, Si, Al, etc.). This high chemical energy input has required process optimization for energy, charge materials, and carbon sources.[11, 12]

Historically, C was added as charge C. This was followed by C injection and in-situ carbon from OBMs (PI, HM and low-to-high C HBI/DRI). In the early 90s, DRI C was between 1.6% and 1.8%C because most mills lacked O_2 tools/supply to decarburize the melt, leading to longer tap-to-tap times, reduced productivity, and higher steel costs since productivity value was at a premium versus reduced energy costs. Interest in 'high % C DRI' rose with improved O_2 tools, larger off-gas systems (OGS), and knowledge and acceptance of the VIU of in-situ C_{DRI}.

Today, CDRI can range from 1% (HBI) to 4.5% (DRI), process and reductant dependent[13], though most mills operate between 1.5% and 3.5%. The optimal % C is controversial, even changing plant-to-plant within the same steel group.[14]

At 100% efficiency, C will combust to produce 9.09 kWh/kg C. In-situ CDRI efficiency is > 95% (versus 24% to 76% for charged or injected C [7, 11, 12]). ***Tables IV*** [9] ***and V*** [7] and ***Figure 7 (next page)*** show the potential C contribution to EAF energy, power, productivity, yield, and electrode wear [14]. The impact of EAF C_{DRI} benefits versus lost DRI plant productivity and costs in a captive DRI/EAF plant are site specific, even within companies – ArcelorMittal (AM) East Montreal runs 2.0-2.2% C whilst other AM plants run at 2.2-2.7%C. [14]

The benefits of DRI in-situ C are many. Unlike charge C, C in DRI contains no ash, sulfur, or volatiles, which are detrimental to the melt process and/or steel quality. The combustion efficiency is much higher and, after C has reduced the FeO in the DRI (FeO_{DRI}), the excess C is available for chemical energy input (see a typical energy balance shown in ***Tables IV and V***). For example, at 95% met and 93% Fe_{Total}, 1.4% C reduces 67% FeO_{DRI} and 0.75%-1.75% excess C is available for combustion depending on % CDRI (1.8%-2.0% C in this example).

ENERGY SOURCE	% TOTAL
Electrical Energy	50%
CO Formation	10%
CO_2 Formation	24%
Fe_3C Disassociation	3%
CH_4 Combustion	9%
Iron Oxidation	1%
Silicon Oxidation	3%
TOTAL	696kWh/t_{ls}

TABLE IV. *EAF Energy Sources Today* [9]

DRI %C	%FeO	92.5% Met	95% Met
1.8%		0.30% C_E	0.75% C_E
2.4%		0.95% C_E	1.45% C_E
2.0%	20%	0.90% C_E	1.45% C_E
2.0%	35%	1.25% C_E	1.75% C_E

TABLE V. *Excess Carbon by DRI %C & %Met* [7]

The reduction of the FeO_{DRI} by the CDRI completes the metallization. The chemical energy generated from the excess C_{DRI} reduces the kWh/Te, power-on time, and tap-to-tap, and thus increases productivity. The CO generated from the combustion foams the slag creating a foamy slag, increasing the slag's surface area, improving removal of undesirable elements from the steel (including N, H, S, and P), and 'refining' it. As the foamy slag buries the electrodes, heat transfer/thermal efficiency is improved (> 93%), further shortening power-on time (POT), tap-to-tap time (TTT), and reducing kWh/Te. ***Figure 8*** shows some of the EAF reactions.[15] Increased C_{DRI} compensates somewhat for increased kWh/t required to melt DRI (presence of gangue) versus scrap and, because $(FeO)_{slag}$ is decreased, refractory life increases.

With high chemical energy input to the EAF, OGS losses (as high as 36%) must be minimized

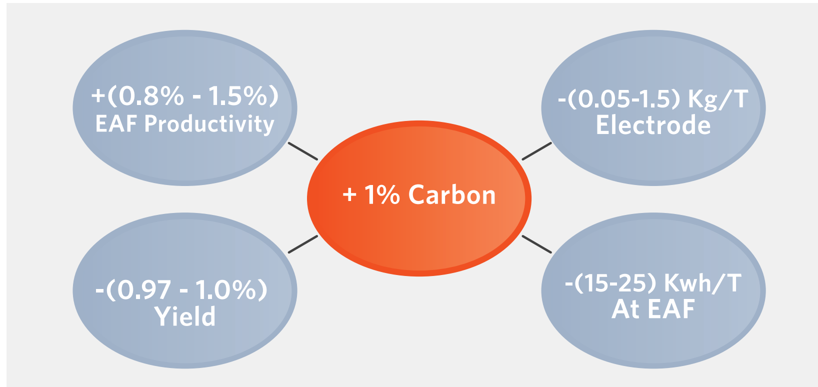


FIGURE 7. *Effect of 1% C_{DRI} on EAF Operations* [14]

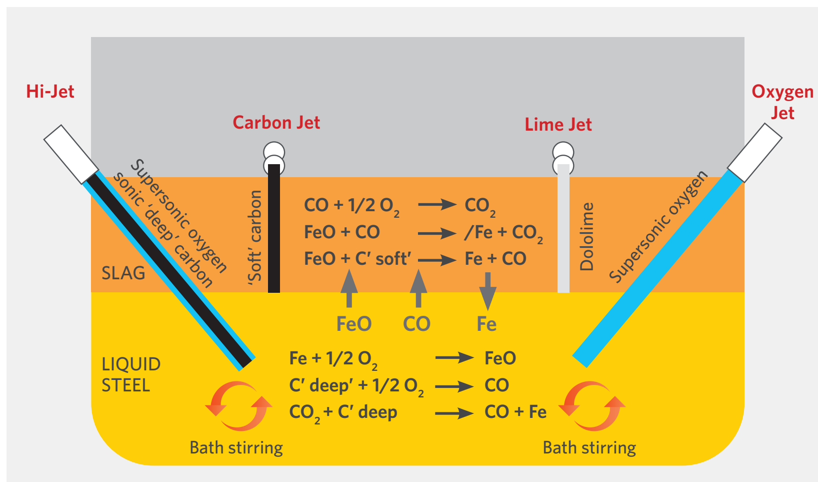


FIGURE 8. *Basic EAF Bath Reactions* [15]

(Figure 6 and 7, Table IV). Energy optimization, using off-gas analysis, identifies sources of non-combusted 'fuels' exiting the EAF (CO, O_2, H_2, C) and allows adjustment of C, O_2, oxy-fuel burners, volumes and injection angles. [12] Process optimization and OGA has highlighted the need for efficient C sourcing, optimal O_2 solutions, as well as good foamy slag practice and optimum raw materials to lower kWh/Te, TTT/POT and electrode wear, and increase yield and productivity whilst producing quality steel.

USE OF DRI/HBI IN THE EAF

One of the main reasons for using DRI/HBI is the consistently low residual content which provides predictable chemistry control of the liquid steel. Blending DRI/HBI with low cost-lower quality obsolete scrap can improve the overall cost of producing quality steel. Where scrap supply is poor or non-existent, captive DRI plants can all but alleviate metallics sourcing issues.

If standard operating procedures (SOPs) are optimized to take advantage of the unique chemical, thermal, and continuous charging properties of DRI, major benefits are available, perceived disadvantages such as excess consumables and slag (primarily attributed to gangue content) can be negated whilst operations and costs can be improved[7, 11, 20] with educated use and process optimization. In-situ C_{DRI} (or CPI) with >95% efficiency (assuming the C is aligned with the available O_2 tools and OGS size) can reduce the kWh/Te, despite the gangue content. [8, 17, 20] Nucor AK found melting 50% DRI could be done with lower kWh/ton and TTT than 100% scrap heat (see ***Table VI*** and [16]).

Some of the cost benefits have been quantified:

- Continuous feeding DRI can save $29.50/Te (no roof swings)
  - Exceeding the optimal feed rate can cause 'icebergs' (more so with HBI than DRI)
- Hot DRI (HDRI) charging saves 20-30 kWh/100° C or $5-10/$Te_{ls}$ [8, 11, 20]
  - Slower initial feeding without O_2 to a colder bath is required to prevent excessive C boils
- Optimization is a must to avoid greater off-gas volume and energy loss with high % C and HDRI

A cost benefit has not been assigned to the reduced N, H, and inclusions resulting from flushing by CO generated from the in-situ $C_{DRI,}$ nor the benefits of a faster and earlier formed foamy slag (improved arc stability, energy transfer; lower electrode wear, kWh/Te, noise). BHP [17] reported 100% DRI reduced $[N]_{melt}$ from 80 ppm to 10 ppm and $[N]_{billet}$ from 115 ppm to 28 ppm versus 100% scrap and increased refractory life and yield, as FeO recovery was improved.

Educated use has meant high quality steel producers, who sought less variable chemistry and downstream optimization, are no longer the sole DRI users.

IMPLICATIONS OF 0%C DRI/HBI

Over 300,000 Te of 0% carbon H_2 DRI were produced on an industrial scale at the Circored Plant in Trinidad, using a two-stage fluidized bed process [15]. A melting trial of some of the 95% met, 0% C Circal™

%DRI	100% scrap	25%	30%	35%	40%	45%	50%
KWh/ton	421	375	377	380	393	399	408
TTT (mins)	61	52	53	54	55	57	59

TABLE VI. *Nucor AK Results using DRI* [16]

	Cost in US$/Tonne HBI Added to the EAF				
Gangue	+ Fluxes	+ Additions	Yield Loss	Slag Cost	Total
SiO_2 / 0.1%	0.156	0.062	0.135	0.015	0.368
Al_2O_3 / 0.1%	0.114	0.062	0.135	0.015	0.326
CaO / 0.1%	(0.075)	0.030	0.135	0.001	0.091
MgO / 0.1%	(0.071)	0.028	0.135	0.001	0.093

TABLE VII. *Impact of gangue in Asian mills* [17]

AM MX	Total Fe	%FeO	%C	%Gangue
DRI	90.80	6.77	2.08	4.47
SCRAP	93.85	1.80	0.47	4.25
DELTA	+3.05	-5.03	-1.61	-0.22

TABLE VIII. *AM MX Gangue Comparison* [7, 20]

HBI was conducted at North Star Steel Texas, with the melting results being published in 2001 [18].

The results of the initial melting trial determined:

- Melt shop SOP required modifying
- Injection of C to the slag was required to control FeO (28%-35%)
- C and O_2 injection were needed to stir the bath, reduce the FeO, and assist in creating a foamy slag
- Feeding high % DRI with scrap continuously into large heels produced the best results and avoided forming icebergs if the feed rate was properly matched to the heat input
- Significant decrease in residual levels was obtained, as expected
- Fe recovery from the FeO_{DRI} was achieved if sufficient alternative C was added to the furnace
- No clumping or icebergs occurred when 18.2 Te of HBI were charged as a single bucket layer
- Charge densification resulted in a reduction in POT
- No mechanical issues (shipping, transfer, and charging) were experienced
- Phosphorous removal was good and sulfur behavior was normal
- The increase in FeO_{slag} attributable to HBI was minimal, but there were problems achieving the low nitrogen specifications and maintaining a good foamy slag due to lack of CO boil

In a subsequent trial, significant changes were made to the melt shop SOP:

- O_2 injection was delayed resulting in higher electrical energy use
- Foamy slag was improved using a high pig iron charge and more injectable C to meet nitrogen specifications assist in creating a foamy slag
- Low residual levels were met using a large amount of pig iron
- HBI could only ever partially replace PI (22Te HBI charged)

This plant experience processing the 0%C Circal HBI suggests more energy will be required to melt 0% C DRI. This will create more CO_2 emissions from power generation unless 'green' energy is available (0.295kg-1.005kg CO_2/kWh – World Steel Association states 9.8GJ Fuel/MWh electricity) – as well as a need for alternative C sources unless pig iron is used, which then involves BF CO_2 emissions.

The projected future dearth of DR-grade iron ore (67% Fe or greater) will compound the increased EAF energy requirement because lower Fe ores, similar to what is currently processed in blast furnaces, would need to be used in DRI facilities. There would be no C_{DRI} to reduce the FeO_{DRI} and complete the metallization. Incomplete metallization and missing C_{DRI} will increase the amount of gangue in the system, FeO_{slag}, and contribute to yield loss unless substantial C is added to the EAF (per current operating guidelines). Therefore, 0% carbon hydrogen-based DRI, coupled with poor ores, would negate the benefit of using hydrogen unless the energy used in the EAF was clearly 'green.' If not, the overall carbon footprint will not be lowered.

There is a clear need for a thorough analysis of all the issues. Developing sufficient renewable energy capacity for EAF steel production is a significant issue itself with immense additional challenges of finding affordable 'green' H_2 production routes. All opportunities depend upon 'green' power and H_2 supply volumes reaching required levels at acceptable prices – both extremely challenging. H_2 is currently cost-prohibitive (requiring 800MW/Te DRI), especially when compared to the much cheaper current C tax for steelmaking (25EU/Te CO_2 versus \$350-\$450/Te CO_2 mitigation). [4, 5]

Other important effects to consider when assessing the value vs. environmental impact of replacing natural gas with hydrogen in the DRI process include:

- The temperature at which steel melts increases with decreasing % C, requiring more energy.
- Thermodynamically, low carbon steels are associated with high FeO content slags, so there would be potentially lower yields unless the FeO_{slag} is reduced after the initial melting stage.
- There will be less available in-situ chemical energy in the DRI.
- Other C sources will be needed for FeO_{DRI} reduction, foamy slag production, bath stirring, chemical energy, flushing of nitrogen, hydrogen, and other undesirable elements. Unless the alternatives are 'green,' they will have their own CO_2 emissions issues. Additionally, twice as much carbon is likely to be required if not in-situ, adding more CO_2.
- Bath stirring will be required: carbon injection or bottom porous plug or tuyeres using nitrogen, argon or CO_2 (or even O_2 with natural gas). Industrial gas production requires more power. It could be possible to capture CO_2 and use it for stirring [19] but there will be costs and challenges associated with cooling and cleaning the CO_2.
- Refractory wear is likely to increase (C dissolution, longer melt times, and FeO erosion) unless refractory systems are re-thought.
- Potential for icebergs, which will slow feeding rates, lengthen POT, reduce productivity, and increase power use.
- Bath reactions will be slower, which will lengthen POT, reduce productivity, and increase power use.
- Lack of foamy slag means more slag volume will be needed to bury the electrodes, maintain thermal efficiency (> 93%), reduce noise, and refine the steel, all of which likely will require a deeper bath. Also, additional slag formers will be required and disposal requirements will increase, thereby increasing costs.

Assessing the cost implications of 0% C DRI in the EAF would be very broad and site specific depending upon the quality of the ore, metallics, and scrap; the specific local costs for the consumables; the value of potential lost productivity; availability and type of power and H_2; and effluent (slag, in-house scrap, and dust) disposal and potential value.

Any future scrap-based steelmaking will require that the global scrap industry agrees to identify and segregate scrap materials along compositional lines to ensure lowest cost steelmaking. Adoption of 'green' steelmaking needs to be global to ensure equitable sharing of costs and technology development and equitable global steel pricing, not to mention significant inroads in addressing the global warming issue (USA and EU together produce less CO_2 than China alone ***[see Figure 2b]***.

CONCLUSIONS

There is evidence that producing economical DRI without CO_2 emissions is feasible assuming 'green' H_2 is forthcoming or 'blue' H_2 is adopted as a compromise. If H_2 DRI production develops as a major technology, with its resultant zero carbon DRI, EAF steelmakers will be challenged to:

- Provide sufficient stirring in the bath for refining without carbon-generated CO
- Provide sufficient slag foaming without carbon as a foaming agent
- Ensure that there is not significant yield loss through high FeO formation
- Limit loss of productivity through long melt down times and formation of 'icebergs'
- Ensure the availability and use of renewable electricity to prevent nullification of the environmental advantage of using H_2 to make DRI

Hydrogen DRI production is an exciting development but there are significant technical and economic challenges around both the ironmaking and steelmaking steps that need to be addressed. To compensate for the issues, we will need SOP changes, 'green' power sources, alternative carbon and chemical energy sources, and possibly a new EAF design – shape and size, stirring capability – or, better still, a completely new steelmaking process. Certainly, with less carbon to remove, the steelmaking step will have more emphasis on gangue removal, control of phosphorus, residuals, and dissolved gases. In a re-configured EAF steelmaking process designed for a 95% charge[1] of 0%C DRI, semi-continuous feeding of DRI into a deep bath with inert gas stirring could help overcome concerns with icebergs and yield loss and, hopefully, address productivity.

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MIDREX® Direct Reduction Plants

2020 OPERATION SUMMARY

Pictured: Tosyali Algérie

Despite the COVID-19 pandemic that was declared towards the beginning of 2020, MIDREX® Plants produced 65.7 million tons in 2020, 3.0% less than the 67.7 million tons produced in 2019. The production for 2020 was calculated from the 35.5 million tons confirmed by MIDREX Plants located outside of Iran and the 30.2 million tons for Iran reported by the World Steel Association (WSA). Approximately 8.1 million tons of hot DRI (HDRI) were produced by MIDREX Plants, which were consumed in nearby steel shops and assisted them in reducing their energy consumption per ton of steel produced and increasing their productivity.

MIDREX Plants have produced a cumulative total of more than 1,178 million tons of all forms of DRI (CDRI, HDRI, and HBI) through the end of 2020.

MIDREX Technology continued to account for ~80% of worldwide production of DRI by shaft furnaces. At least three MIDREX Modules* established new annual production records and at least nine established new monthly production records (no detailed production information has been received from Iran). Ten additional modules came within 10% of their record annual production and eight operated in excess of 8,000 hours.

Two new modules completed construction in 2020 and were ready to start operations: a 2.5 million t/y module designed to produce CDRI and HDRI, owned by Algerian Qatari Steel (AQS) in Bellara, Algeria, and a 1.6 million t/y HBI module belonging to Cleveland-Cliffs in Toledo, Ohio, USA that started operations at the end of the 4Q of 2020.

** A MIDREX Plant can include one or more modules*

2020 PLANT HIGHLIGHTS

ACINDAR

In its 42nd year of operation, ACINDAR's module operated at reduced capacity due to challenging local market conditions and was shut down for almost four months at the beginning of the COVID-19 pandemic. With over 32 million tons produced, ACINDAR has achieved the most production from a 5.5-meter MIDREX Shaft Furnace to date.

ANTARA STEEL MILLS

The first MIDREX HBI Module operated over its annual rated capacity and within 6% of its record annual production. Total iron of its HBI product was the highest of all MIDREX Plants, averaging 93.04% for the year. All production was shipped by water to third parties.

ARCELORMITTAL CANADA

After a record production year in 2019, Module 1 operation was impacted by reduced market demand due to COVID, causing a 5-month shutdown of this production module. Module 2 operated above rated annual capacity, despite being down the whole month of May and restarting operations in mid-June.

ARCELORMITTAL HAMBURG

In its 49th full year of operation, the oldest MIDREX Module in operation handily exceeded its annual rated capacity. Even though the plant did not operate at full capacity, its average annual electric energy consumption was the lowest of all MIDREX Plants at 84 kWh per ton.

ARCELORMITTAL LÁZARO CARDENAS

AMLC produced 19% over its annual rated capacity of 1.2 million tons in its 23rd year of operation. Its 6.5-meter reduction furnace has produced a total of 34.6 million tons of DRI, the most by a single module to date.

ARCELORMITTAL POINT LISAS

Forty years after the start-up of Module 1, all three MIDREX Modules in Trinidad and Tobago remained shut down throughout the year.

ACINDAR

Antara Steel Mills

ArcelorMittal Canada

ArcelorMittal Hamburg

ArcelorMittal Lazaro Cardenas

ARCELORMITTAL SOUTH AFRICA (SALDANHA WORKS)

After approximately 20.5 years of operation and 10 million tons of DRI production, the COREX® export gas-based MxCol® Plant was idled in January 2020 and remained shut down the rest of the year.

ARCELORMITTAL / NIPPON STEEL INDIA

Early in its 10th anniversary year since its start-up, Module 6 exceeded the 10-million-ton mark producing CDRI. With exception of Module 1 (recently converted to produce CDRI only in its 30th anniversary year, together with Module 2), AM/NS's other five modules operated at less than maximum capacity. Despite a marked reduction in production during the months of April and May due to COVID, the total production of the six modules was 4.54 million tons, which is within 7% of their DRI production record of 4.86 million tons set in 2018. Modules 2, 3, 4, and 5 produced 2.48 million tons of HDRI (over 93% of their production, with the balance being HBI). This increase in HDRI production and decrease in HBI production reduced their electric energy consumption in the DR plants and increased the benefit of using HDRI in the steel shop. Modules 5 and 6 operated using off-gas from AM/NS India's COREX Plant for ~18% of their energy input.

COMSIGUA

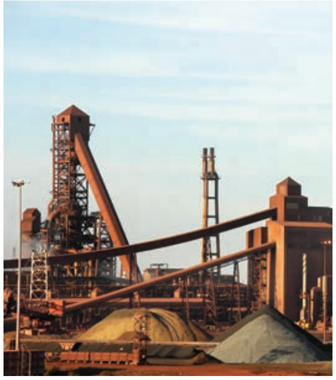
COMSIGUA's production of HBI decreased in 2020, restricted by the limited supply of locally produced pellets in Venezuela.

DELTA STEEL

The two modules in Nigeria did not operate in 2020.

DRIC

Both of DRIC's modules in Dammam, Saudi Arabia, operated above rated capacity and were within 5% of the annual production record of 1.09 million tons DRI set in 2019. Module 1 set a new monthly production record in October 2020. Both of these modules also broke annual average hourly productivity records, and between them exceeded the 10-million-ton mark since initial start-up in 2007.



ArcelorMittal South Africa

ArcelorMittal/Nippon Steel India (Formerly Essar Steel)

Comsigua

DRIC

ESISCO

After being shut down since January 2016 due to high natural gas prices in Egypt, as well as competition of foreign steel products, Beshay Steel restarted their MIDREX Plant in December 2019 and shut it down again in early March for the remainder of 2020.

EZDK

All three modules operated above rated capacity in 2020. In its 20th anniversary year of operation, EZDK's Module 3 operated within 10% of its production record with 8,169 hours of operation. Module 2 operated 8,350 hours and surpassed the 20-million-ton mark of DRI produced towards the end of 2020. EZDK continued to use lump ore in their oxide feed mix throughout the year.

FERROMINERA ORINOCO

Thirty years after its restart as a MIDREX Plant, Ferrominera Orinoco's HBI module in Puerto Ordaz, Venezuela, did not operate in 2020 due to limited availability of locally produced oxide pellets.

HADEED

Hadeed exceeded rated capacity for the 36th consecutive year in Modules A and B and for the 28th consecutive year in Module C. With over 22 million tons produced since start-up in July 2007, Module E has achieved the most production from a 7.0-meter MIDREX Shaft Furnace. Hadeed's four MIDREX Modules have produced over 96 million tons of DRI to date. Hadeed also owns an HYL module (Module D).

JINDAL SHADEED

In 2020, the HOTLINK® plant operated 15% above rated capacity and just 1% short of their 2019 record production. The plant operated 8,389 hours in 2020 and set a new monthly production record in March. The module is designed to produce mainly HDRI, with HBI as a secondary product stream. A major portion (~93 %) of its annual production of over 1.7 million tons was consumed as HDRI in Jindal Shadeed's adjacent steel shop. Jindal Shadeed has produced over 15 million tons since its start-up 10 years ago, despite natural gas availability limitations for most of the 10 years, while averaging 8,222 hours of operation.


ESISCO


EZDK


Hadeed Module E


Jindal Shadeed

JSPL (ANGUL)

In its 6th year of operation, Jindal Steel and Power Limited's (JSPL) MxCol Plant in Angul, Odisha State, India, restarted operations in January and remained in operation the rest of the year despite market conditions that were challenging at times. The plant broke their monthly production record twice in 2020, reaching 220 t/h average production rate in the month of December. This is the first MxCol Plant using synthesis gas from coal gasifiers to produce both HDRI and CDRI for the adjacent steel shop. HDRI production was 70% of total production, and coke oven gas (COG) use in the DR plant was ramped up in 2020.

JSW STEEL (DOLVI)

In its 26th year of operation, JSW Steel's module exceeded annual rated capacity. The system installed at the end of 2014 to reduce natural gas consumption by adding coke oven gas (COG) from JSW Steel's coke oven batteries to the reduction furnace operated throughout the year, providing 11% of the plant's energy requirement. The module surpassed the 30-million-ton milestone in 2020, and has averaged 8,025 hours of operation per year since its initial start-up in September 1994.

JSW STEEL (TORANAGALLU)

JSW Steel's HDRI/CDRI module in Toranagallu, Karnataka State, India, using COREX export gas as energy input, produced 75% of its annual production record set in 2018, and surpassed the 5-million-ton milestone in 2020. This is the second plant of its kind – the first one being ArcelorMittal's COREX/MIDREX Plant at Saldanha, South Africa.

LEBEDINSKY GOK

LGOK's MIDREX HBI Modules 2 and 3, located in Gubkin, Russia, and belonging to the Metalloinvest Group, set new annual and monthly production records in 2020, with both modules operating around 8,100 hours, and with HBI-3 exceeding the 2 million ton per year mark, the highest annual production from an HBI module and from a 7.0-meter MIDREX Shaft Furnace to date. HBI-3 broke its annual production record for the fourth consecutive year. With close to 27 million tons of combined production to date, the two modules surpassed the 25-million-ton milestone in 2020. LGOK HBI-1 is an HYL plant.

JSPL (Angul)

JSW Steel (Dolvi)

JSW Steel (Toranagallu)

LGOK HBI-2 and HBI-3

LION DRI

The Lion DRI module, located near Kuala Lumpur, Malaysia, remained shut down throughout 2020 due to insufficient market demand for locally produced steel products.

LISCO

Thirty years after the start-up of module 2, production by LISCO's two DRI modules and one HBI module in Misurata, Libya, continued restricted to less than 50% of rated capacity by factors outside the company's control.

NU-IRON

After breaking annual and monthly production records in 2019, Nucor's module in Trinidad and Tobago in 2020 set a new monthly production record during the month of October, reaching an average production rate of 225 t/h. Average DRI metallization for the year was the highest of all MIDREX Plants at over 96.2%, with 2.75% carbon in the DRI.

OEMK

OEMK's four modules had a combined annual production that was only 2.5% short of their record production of over 3.2 million tons in 2019. The production of all four modules was within 1-8% of their individual record annual production levels. Whereas module 1 underwent major repair work during its annual shutdown in August and went on to set a new monthly production record in October, modules 2, 3 and 4 had shorter shutdowns with modules 3 and 4 operating ~8,450 hours in the year. The total combined DRI output of OEMK surpassed the 75 million-ton milestone in 2020, and module 2, which started up in December 1985, reached its 35-year anniversary.

QATAR STEEL

Both modules started the year at full capacity, but in March Qatar Steel's dual product (CDRI/HBI) Module 2 was shut down for the remainder of the year and Module 1 began operating at reduced capacity due to poor market demand. Qatar Steel's Module 1 has produced over 27.5 million tons of DRI since its start-up in 1978, the most for a 5.0-meter shaft furnace.

SIDOR

All four of Sidor's MIDREX Modules were inactive due to the allocation of the limited supply of oxide pellets in Venezuela to the HBI plants, which produce HBI products for export.

LISCO

Nu-Iron Unlimited

OEMK

Qatar Steel Module 2

SULB

SULB's 1.5 million t/y combination module (simultaneous CDRI/HDRI production) in Bahrain operated below its annual rated capacity due to soft product demand. Approximately 1.0 million tons of HDRI were sent directly to the steel mill and 74% of the CDRI product was exported, mostly by sea. SULB has produced over 10 million tons since its start-up in 2013.

TENARISSIDERCA

TenarisSiderca operated for only a couple of months towards the beginning of the year and remained shut down for the rest of the year due to limited DRI demand by the steel shop. The module's DRI metallization percentage was second highest of all MIDREX Plants at 95.40%.

TOSYALI ALGÉRIE

Tosyali Holding's 2.5 million tons/year combination module, located in Bethioua, near Oran, Algeria, continued ramping up operations. In only its second full year of operation, they produced more than 2.23 million tons of direct reduced iron (DRI) in 2020, which is a world record for a single direct reduction module. They also set a plant monthly production record in March. Despite the market turmoil, the module operated essentially at rated capacity during the second half of the year. This is the largest capacity MIDREX Module built to date, with a 7.5 m diameter Shaft Furnace producing both HDRI and CDRI.

TUWAIRQI STEEL MILLS

The 1.28 million t/y combination module of Tuwairqi Steel Mills, located near Karachi, Pakistan, did not operate in 2020 due to market conditions.

VENPRECAR

VENPRECAR's HBI production was restricted by the limited availability of iron ore pellets in Venezuela.

voestalpine TEXAS

The voestalpine Texas 2.0 million t/y HBI module located near Corpus Christi, Texas, USA, set a new monthly production record in December 2020. voestalpine Texas is a 100% subsidiary of voestalpine AG in Austria.

EDITOR'S NOTE:
At the time of printing, no detailed information had been received from MIDREX Plants located in Iran.

SULB

TenarisSiderca

Tosyali Algérie

Venprecar

voestalpine Texas

Midrex News & Views

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

AQS Begins DRI Production in February

Algerian Qatari Steel (AQS) has announced the start-up of its 2.5 million tons per year (t/y) MIDREX® Direct Reduction Plant on February 13 and first production of on-grade Direct Reduced Iron (DRI) a few days after. The plant is capable of producing both hot DRI (HDRI) and cold DRI (CDRI) and is equipped to transfer and charge HDRI to the nearby AQS steel mill to take advantage of the retained heat. The first successful charge of HDRI to the AQS Electric Arc Furnace #1 (EAF #1) was on March 24.

The DRI plant was supplied by Midrex Technologies, Inc. and its consortium partner, Paul Wurth.

Midrex Certified for ISO 9001:2015

Midrex Global Offices, R&D Technology Center Included

Midrex Technologies, Inc's Quality Management System has been recommended for continued certification by DQS Inc. under ISO 9001:2015, following successful completion of the recertification audit of the headquarters in Charlotte. Midrex subsidiaries in Dubai, India, and the United Kingdom have achieved recommendation for their initial certification under the Standard this year as well.

"We are very proud of the efforts and achievements of Midrex teammates in the USA, UK, India, and Dubai that ISO 9001:2015 registration recognizes," Midrex Technologies, Inc. Vice President Operations, Chris Hayes, said. "Quality is one of our core values, and ISO certification recognizes that our policies and procedures are in keeping with the highest industry standards."

Midrex News & Views

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

John Linklater Named Midrex Gulf Services GM, Aashima Vadhera to Direct Finance for Asia & Middle East


John Linklater

John Linklater has been named to lead Midrex Gulf Services (MGS) in Dubai as General Manager. He will work to expand the scope of MGS - Dubai to include all plant optimization and support services provided by Midrex Global Solutions – digital optimization systems, remote data analysis and management, engineered solutions, technical field advisory assistance, equipment and materials supply, and integrated water services.


Aashima Vadhera

Aashina Vadhera, who manages the financial and administrative activities of Midrex offices in India and China and serves on the board of Midrex Gulf Services, will add similar duties for MGS in her new role as Director – Finance (Asia and Middle East).

Stephen Montague Featured In Industry Magazines

Interviews with Midrex President & CEO Stephen Montague were featured in recent issues of *Metal Market Magazine* and *Business Focus Magazine*. In the articles, Montague discussed the state of global iron and steelmaking, the role of direct reduction in lowering CO_2 emissions, and the unique culture of Midrex Technologies.

You can read the entire articles at: **www.businessfocusmagazine.com** and **www.fastmarkets.com**.

Lauren Lorraine: **Editor**

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