Hydrogen-Based DRI EAF Steelmaking — Fact or Fiction?

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This paper will present a provocative rumination of the challenges to be considered and overcome before hydrogen-based direct reduced iron (DRI) steelmaking becomes a reality, or not. Considerations such as technology needs (H_2 generation, DRI carbon content, electric arc furnace needs and overall carbon balance) and economic viability (as understood currently) will be posed and discussed, along with the impact of carbon taxes.

It should be stated at the outset that, as far as the technology for hydrogen (H_2)-based direct reduced iron (DRI) electric arc furnace (EAF) steelmaking, there appear to be no significant issues with operating DRI shaft furnaces at 100% H_2. Operating an EAF with zero-carbon DRI (0%C_{DRI}) will be a major challenge at any charge rate (15% use by 2050), never mind the envisaged, long-term, 95% charge rate.[1] However, as an "outsider looking in" from a country already operating with 69.7% EAF steel production (2019 figures per AISI), therefore technically one of the "cleanest" steelmaking nations, the authors wonders how the undeniable push to convert future steelmaking (in the EU especially) to the H_2 DRI/EAF route will impact product cost and market share.

The extreme capital cost for this conversion, never mind development and sustainability of green hydrogen and green power, without which carbon dioxide (CO_2) mitigation goals will not be achieved, will challenge the worldwide competitiveness of compliant steelmakers/countries.

Considering this, and the probable need to significantly modify EAF technology (or find a replacement thereof), begs the question why more consideration of CO_2 mitigation from the blast furnace/basic oxygen furnace (BF/BOF) route is not being addressed given this route constitutes 92% of CO_2 generation for 72% of steel production.

This paper will look at the status quo, the challenges to overcome and technology required to make this direction an economically viable (as understood currently) reality, or not.

The Issues

CO_2 Generation and Required Mitigation —

The global steel industry uses 8% of the overall energy demand and contributes 7% of the total CO_2 generated by humanity (2.6 gigatons [GT] CO_2 in 2020; 2.8 GT CO_2 in 2015)[1–3] (Fig. 1). Global CO_2 emissions by country (Fig. 2)[4] show China producing 28% whilst the EU, which is mandating more reduction, is only producing 10%. Coal accounts for 75% of the energy demand in the steel industry, contributing to most of the CO_2 generation as an iron oxide reductant in the BF process. Coke provides structure and mechanical support to the bed of materials in the reactor shaft.

Fig. 1 summarizes generation and CO_2 mitigation required and projected steel demand in 2050. The desire to decarburize and become a hydrogen economy (using H_2 as the fuel source) is fueled by the massive anticipated increase in CO_2 generation from industry and

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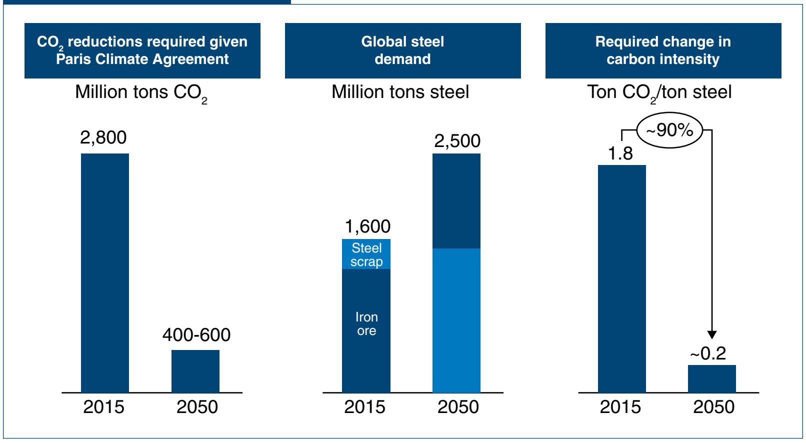
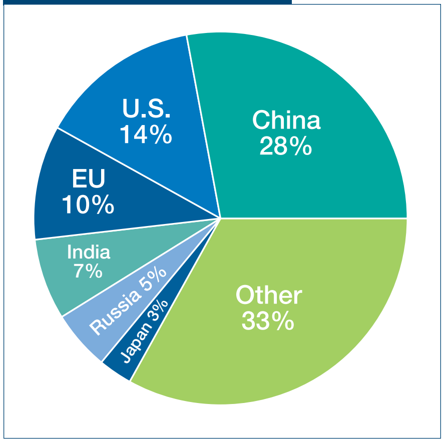
Figure 1



Required changes in carbon intensity 2015 to 2050.[1]

Figure 2



CO_2 generation by country.[4]

transportation. Success, of course, assumes cheaper and "greener" methods of H_2 production become reality, along with green power.

The primary decarburization process suggested for the steel industry is conversion to steelmaking in an EAF using ultimately a charge of 95% H_2-produced DRI. What will be the other 5%? Pig iron (PI) for C replacement?[1]

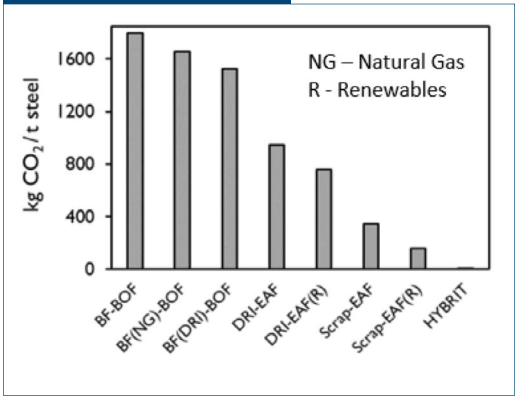
CO_2 Generation by Steel Mill Type — Table 1 shows the total CO_2 generated by worldwide steel mills with subclassification by integrated mills (IMs) and EAF minimills (MMs).[1,4] The IMs produce 72% of world steel and 92% of the CO_2 whilst the MMs produce 28% of world steel and only 8% of the CO_2 generated by the steel industry. With CO_2 generation in the MMs five and a half times less than the IMs, coupled with its lower dependence upon diminishing quality iron ore sources, its recycling rate of 80–90% globally, and the economic benefits (one-third of the energy of conventional IMs when using 100% scrap), the MM route is where CO_2 remediation has been focused.

Table 1

CO_2 Generation by Steel Mill Type[1,4]

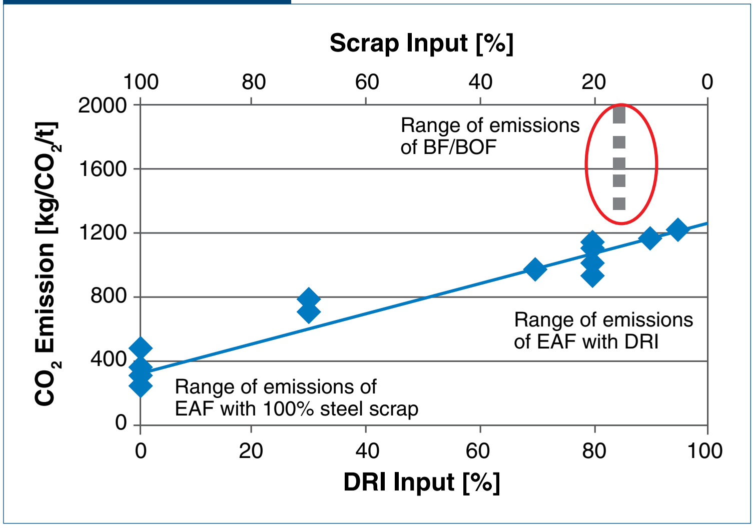
	MT_{steel}	%	MT CO_2	%	T CO_2/T_{steel}
Total	1,869.0	–	3,170.2	–	1.6962
BF/BOF	1,346.0	72	2,961.2	92	2.2000
EAF	523.0	28	209.0	8	0.3996

Figure 3



CO_2 generation by steel route.[5,6]

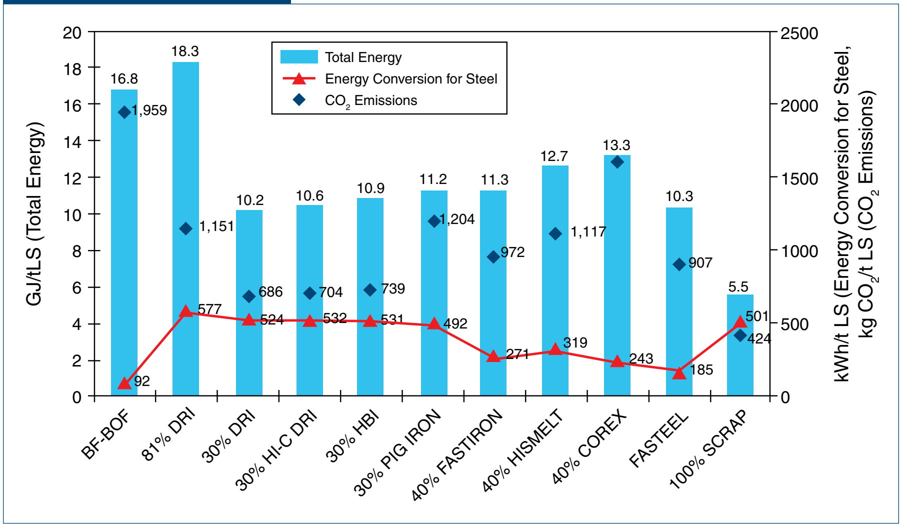
Figure 4



Impact of direct reduced iron (DRI) on steelmaking CO_2 emissions.[7]

CO_2 emissions from the BF/BOF route can be diminished significantly with the incorporation of H_2, renewables and a move to the scrap-based EAF route (Fig. 3).[5,6] Whilst EAF-scrap operations produce the lowest CO_2 emissions, increasing %DRI in the charge increases the CO_2 emissions but, according to Fig. 4,[7] the emissions remain below those of the BF/BOF process route. Fig. 5 shows an analysis, using specific data given in Table 2, whereby the total energy requirement for 80% DRI exceeds that of the BF at 18.3 $GJ/T_{\text{liquid steel}}$ (GJ/T_{ls}) versus 16.8 GJ/T_{ls}, though DRI CO_2 emissions are only 1,151 kg/T_{ls} compared to 1,959 kg/T_{ls} in the BF (100% scrap is 5.5 GJ/T_{ls} and 424 kg/T_{ls} by comparison).[8]

Figure 5



Total and EAF energy and carbon emissions.[8]

Table 2

Some EAF Melt Program Specifics[6,8]

Process	% Met	Total iron (%)	Blended %C in AIU charge	Carbon (kg/t)		Thermal melting efficiency	Lime (kg/t)	O_2 (Nm^3/t)	kWh/t
				Charged	Injected				
90% Cold DRI	94	91.5	2.5	0	1	82.0	15.0	22.7	561.0
30% DRI	94	91.5	2.5	5.5	3	83.6	26.8	20.1	482.4
30% High-C DRI	94	90.1	4.0	1.0	3	85.2	26.9	20.2	506.0
30% HBI	93	92.5	1.5	9.0	3	81.6	30.3	20.3	476.1
30% pig iron	100	95.4	4.0	0	3	84.8	28.9	20.4	468.5
40% FASTIRON	100	94.4	4.5	0	4	87.7	29.8	30.0	237.2
40% HIsmelt	100	95.7	4.0	0	8	87.1	23.1	30.0	271.2
40% COREX	100	94.0	4.5	0	2	88.0	35.5	30.0	217.1
40% FASTEEL	100	94.4	4.5	0	4	88.4	29.8	30.0	151.4
100% scrap	93	92.1	0.4	10.5	3	82.3	32.6	20.3	440.8

Table 3 highlights areas of CO_2 generation in the EAF steelmaking process.[9] The production of raw materials for the EAF process generates the major volume of CO_2 emissions. This far outweighs the CO_2 generated during transportation and melting.

The generation rate quoted in Table 1 is based on current alternative iron source (AIS) — DRI, hot briquetted iron (HBI), pig iron (PI), hot metal (HM) — use in the EAF, not the projected future use rate of 95% DRI charge (Table 4).[1] As previously mentioned, an exhaustive assessment of various steelmaking routes using 30%, 50% and 80% AIS and their effect on total energy (ore to liquid steel), EAF energy and CO_2 emissions/T_{ls}, without CCS or green energy, was reported at the Electric Furnace Conference in 2002.[6] Selective data are presented in Fig. 5.[8] The %C contained in the AIS ranged from 1.5% in HBI, to 2.5% in DRI, 4.5% in HM and 4% in high-C DRI and PI. The 100% scrap charge contained 0.4%C.

As it can be seen from Table 4 pricing calculations, H_2-based DRI/EAF operations in the future will be the most expensive solution, even 23–33 years after the International Energy Agency (IEA) documents were written and green power and H_2 are supposed to be economically available. Crude steel by the H_2 DRI/EAF route will be US\$1,327.23/$T_{\text{crude steel}}$ (/T_{CS}) or US\$572.10/T_{CS} more than the anticipated cost of an O_2-rich smelt reduction process and US$457.77/$T_{CS}$ more than a NG DRI/EAF system with carbon capture units and storage (CCUS). [Note: these pricings do not include water costs.] With U.S. ex-works Midwest hot-rolled coil (HRC) pricing at US$1,190 in January 2021 and that of the EU US$785 and China US$601,[12] how will comparative prices look in the future with crude steel price so high?

The IEA envisages changes in steel and iron production routes (1990–2070) will see EAF steelmaking rise to more than 70% total production whilst iron production decreases from about 1.4 MT/year to 1.15 MT/year incorporating BF, DRI and smelt reduction (SR) plants with CCUs (Fig. 6[10]). Less than 200 MT/year will continue to be made via the BF route.

Table 3

CO_2 Sources in EAF Steelmaking[9]

	Summary of kg CO_2 per area			
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/T_{ls})	777	16	98	890

Table 4

Capex, Opex and Consumptions for Steelmaking Routes[1]

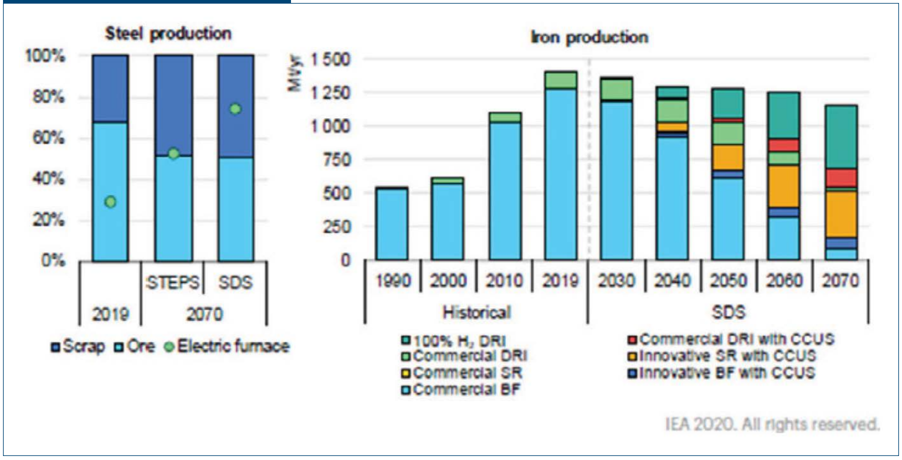
Route	Parameter	Units	Today	2030	Long term	Unit	Total cost
BF-BOF	Capex	US$/$\text{ton}_{\text{crude steel}}$	600	600	600	600	$807.31
	Annual opex	% of capex	23	23	23	138	
	Electricity consumption	GJ/$\text{ton}_{\text{crude steel}}$	0.70	0.70	0.70	21.00	
	Coal consumption	GJ/$\text{ton}_{\text{crude steel}}$	18.00	18.00	18.00	44.82	
	Natural gas consumption	GJ/$\text{ton}_{\text{crude steel}}$	1.00	1.00	1.00	3.49	
Natural gas-based DRI-EAF	Capex	US$/$\text{ton}_{\text{crude steel}}$	590	590	590	590	$852.61
	Annual opex	% of capex	25.00	25.00	25.00	147.50	
	Electricity consumption	GJ/$\text{ton}_{\text{crude steel}}$	2.50	2.50	2.50	5.00	
	Coal consumption	GJ/$\text{ton}_{\text{crude steel}}$	0.50	0.50	0.50	1.25	
	Natural gas consumption	GJ/$\text{ton}_{\text{crude steel}}$	10.10	10.10	10.10	36.26	
Natural gas-based DRI-EAF w/CCUS	Capex	US$/$\text{ton}_{\text{crude steel}}$	640	640	640	640	$869.46
	Annual opex	% of capex	23.00	23.00	23.00	147.20	
	Electricity consumption	GJ/$\text{ton}_{\text{crude steel}}$	2.70	2.70	2.70	81.00	
	Coal consumption	GJ/$\text{ton}_{\text{crude steel}}$	0.50	0.50	0.50	1.25	
	Natural gas consumption	GJ/$\text{ton}_{\text{crude steel}}$	10.10	10.10	10.10	36.26	
Hydrogen-based DRI-EAF	Capex	US$/$\text{ton}_{\text{crude steel}}$	945	855	755	755	$1,327.33
	Annual opex	% of capex	16	18	20	151	
	Electricity consumption	GJ/$\text{ton}_{\text{crude steel}}$	14.70	13.90	13.20	396.00	
	Biomass consumption	GJ/$\text{ton}_{\text{crude steel}}$	1.90	1.90	1.90	25.23	
Oxygen-rich smelt reduction w/CCUS	Capex	US$/$\text{ton}_{\text{crude steel}}$	530	530	530	530	$755.13
	Annual opex	% of capex	17.00	17.00	17.00	90.10	
	Electricity consumption	GJ/$\text{ton}_{\text{crude steel}}$	3.50	3.50	3.50	105.00	
	Coal consumption	GJ/$\text{ton}_{\text{crude steel}}$	12.10	12.10	12.10	30.13	

Qualifiers: Prices are the minimum quoted by IEA in 2017. IEA future (2040) biomass price is US$14/MMBTU (US$13.28/GJ); coal = US$10.40–20.3/T (US$2.49–4.85/GJ); electricity = US$0.108–0.203/kWh ($30/GJ); natural gas = US$3.40–10.30/MMBTU (US$3.59–10.87/GJ); CCUs = US$20/T CO_2; CO_2 tax = US$145 and US$160/T for emerging and advanced economies, respectively.

Notes: 25-year lifetime and 95% availability assumed for all equipment. Capture rate of 95% assumed for CCUS routes. Hydrogen-based DRI-EAF parameters include the electrolyzer costs. The hydrogen requirement for this route is estimated to lie in the range of 47 to 68 kg/t of DRI, with the midpoint of this range used for the cost calculations. For the DRI-EAF routes, a 95% charge of DRI to the EAF is considered. An iron ore (58% Fe content) cost of US$60/ton and a scrap cost of US$260/ton is assumed for all process routes, regions and time periods. Costs of electrodes, alloys and other wearing components are considered as a part of the fixed opex.

One hundred percent of the H_2 DRI and commercial DRI with CCUS will produce about 50% of the "iron." Innovative SRs with CCUS will make up the remainder.

Figure 6



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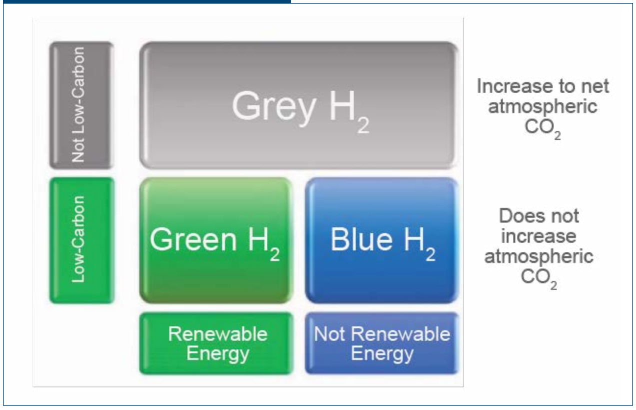
Global steel and iron production by technology in the Sustainable Development Scenario 1990–2070.[10]

The Hydrogen Economy — There are various hydrogen categories, with related CO_2 cleanliness factors, depending on their production energy source and whether CCUS is employed to remove, store and stabilize CO_2.[13] From highest to lowest CO_2 generation, these are:

1. Grey hydrogen — sourced from large-scale fossil fuel (hydrocarbon (HC – coal and natural gas (NG) decomposition) without CCS.
2. Blue hydrogen — either fossil fuel sourced with CCS or electrolysis using non-renewable electricity. CCUS and electrolysis involve great cost.
3. Green hydrogen — from water electrolysis using renewable electricity; challenged by the cost and scale of currently available commercial plants.[5,13]

Figure 7



Hydrogen types.

These definitions are graphically represented in Fig. 7, courtesy of Certify Canada: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.[10]

For the hydrogen economy to become a reality for steel and other industries, sufficient volumes of economical green hydrogen and electricity must be available. Obviously today, the biggest issue is the lack of commercial-sized H_2 plants with the required production volume, and handling systems (storage, distribution modes) are lacking. This makes H_2 extremely expensive, requiring lots of power for the multiple H_2 production units required to satisfy needs.

Air Liquide has begun operating a 20-MW (four electrolyzer units) proton exchange membrane (PEM) electrolysis plant in Becancour, Que., Canada. It's capable of producing 8.2 T H_2/day (98,703.7 Nm^3/day) — enough to produce 151.85 T DRI/day.[14] If one considers a 2 MT DRI/year plant, this would require 108,000 T H_2/year or 300 T H_2/day. That is 36.6 of these 20 MW PEM systems assuming a 360-day operating cycle for the DRI plant (36 PEMs if the DRI plant operates 365 days/year). When one considers the IEA anticipates 411 MT DRI/year will be produced by 2050 (162 MT commercial DRI, 37 MT Commercial DRI with CCUs and 213 MT at 100% H_2),[15] 11.502 MT of H_2/year will be required for the steel industry alone! Is this achievable or will there be a big shortfall? [Note: 2019 DRI production was 108.10 MT/year and by 2070 this is expected to be 638 MT/year (almost sixfold, requiring a 10.39 MT DRI/year increase).]

In other H_2 plant news, H2V announced a large-scale electrolyzer complex of 200 MW to be built in France; a 400-MW unit to be built for SSAB in Europe; HyBalance is operating a 1.2 MW production unit making 500 kg H_2/day without any CO_2 emissions; and a 30 T/day renewable liquid H_2 plant using renewable NG will be operational in Nevada by 2022.

Table 5 summarizes estimated capital and production costs, process efficiency and environmental impact for different H_2 generation technologies per IEA[1] whilst industrial power costs from 2017 and postulated out to 2030 and "long term" for various countries are given in their Iron and Steel Technology Road Map.[2]

Table 5

Capex, Opex, Life and Emissions Data for H_2 Technologies[1]

Technology	Parameter	Units	Today	2030	Long term
Water electrolysis	Capex	US/kW_e$	900	700	450
	Efficiency (LHV)	%	64	69	74
	Annual opex	% of capex	1.5	1.5	1.5
	Stack lifetime	hours	95,000	95,000	100,000
Natural gas reforming	Capex	US$/kW$_{H_2}$	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	US$/kW$_{H_2}$	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	US$/kW$_{H_2}$	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	US$/kW$_{H_2}$	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	US$/kW$_{H_2}$	2.1	2.1	2.1

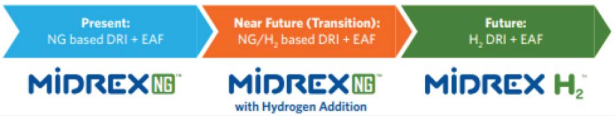
Notes: 25-year lifetime and 95% availability factor assumed for hydrogen production from natural gas and coal. Availability factors for electrolysis are based on the full load hours of electricity shown in the following table. For water electrolysis, possible revenues from oxygen sales have not been 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 Stand-Alone (Merchant) Hydrogen Plant With CCS."

H_2 DRI Production — The direct reduction shaft furnace processes use a reducing gas mixture of carbon monoxide (CO) and H_2. Technologically, there is substantial evidence "carbon" can be removed from the process and replaced by H_2.[5,13] However, increasing the H_2-to-CO ratio has a significant effect on the heat balance in the process since the absence of CO will result in an endothermic reaction (requiring heat balance adjustment). Also, there will be no DRI carburization, hence the resulting 0% C_{DRI} (Table 6) unless some NG is added to the system.[16] The 0%C_{DRI} will create most of the challenges for EAF melting as we know it. Perhaps carbon neutrality is what is needed?

Tenova, on the other hand, is advocating the need to continue producing DRI-containing C, the amount (1.5–5%) depending upon the DRI use (<2% special applications, 2–3% EAF fed by DRI only, 3–4.5% for EAF fed by DRI + scrap and 4.5% if DRI is replacing PI).[17] Fig. 8 shows some of the uses, predominantly in the food and beverage industry, for the selectively removed CO_2.

Table 6

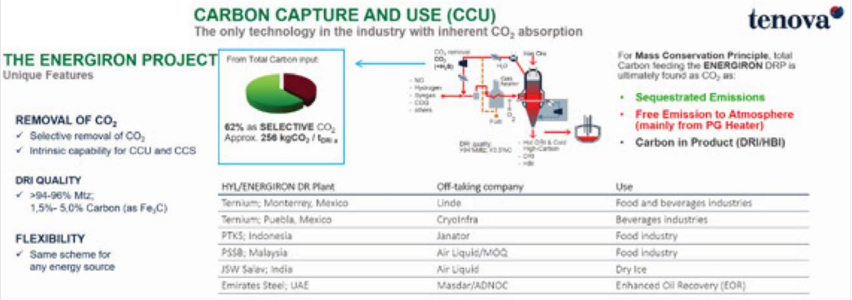
Midrex Process Using Hydrogen[16]



Feed gas		100% natural gas	Natural gas replacement by hydrogen			100% hydrogen
			20%	50%	70%	
Reducing gas	H_2	55%	62%	72%	77%	100%
	CO	35%	28%	18%	13%	0%
	Others	10% (mostly CO_2, H_2O, CH_4, N_2)				
	H_2/CO	1.6	2.2%	4.0%	5.9%	N/A
Carbon in DRI		2.5% (4% w/ACT)	~1.5%	~1.0%	~0.5%	0%
CO_2 emissions ($kgCO_2/t_{DRI}$)*		500 (<250 w/CCUS**)	400	250	150	From heater (if fueled by hydrocarbons)

*only includes CO_2 emissions from flue gas (largest source). **CCUS = carbon capture utilization and storage

Figure 8



CARBON CAPTURE AND USE (CCU)

The only technology in the industry with inherent CO_2 absorption

tenova

THE ENERGIRON PROJECT

Unique Features

REMOVAL OF CO_2
- ✓ Selective removal of CO_2
- ✓ Intrinsic capability for CCU and CCS

DRI QUALITY
- ✓ >94-96% Mtz;
  1,5%- 5,0% Carbon (as Fe_3C)

FLEXIBILITY
- ✓ Same scheme for any energy source

From Total Carbon input:

62% as SELECTIVE CO_2
Approx. 256 $kgCO_2 / t_{DRI}$

For **Mass Conservation Principle**, total Carbon feeding the **ENERGIRON** DRP is ultimately found as CO_2 as:

- Sequestrated Emissions
- Free Emission to Atmosphere (mainly from PG Heater)
- Carbon in Product (DRI/HBI)

HYL/ENERGIRON DR Plant	Off-taking company	Use
Ternium; Monterrey, Mexico	Linde	Food and beverages industries
Ternium; Puebla, Mexico	CryoInfra	Beverages industries
PTKS; Indonesia	Janator	Food industry
PSSB; Malaysia	Air Liquid/MOQ	Food industry
JSW Salav; India	Air Liquid	Dry Ice
Emirates Steel; UAE	Masdar/ADNOC	Enhanced Oil Recovery (EOR)

Tenova CCUs, CO2 Use and DRI Quality.[17]

Tenova DRI plants run normally with 70% H_2 and they have run at 90% for quite some time. Midrex plants nominally operate at 55% H_2 when fed by 100%NG (Table 6). The %H_2 in the reducing gas increases with increasing NG replacement whilst %C_{DRI} decreases. At the VAI Midrex plant, 20,000 Nm^3 NG/hour has been successfully replaced by 60,000 Nm^3 H_2/hour (three times the NG volume).

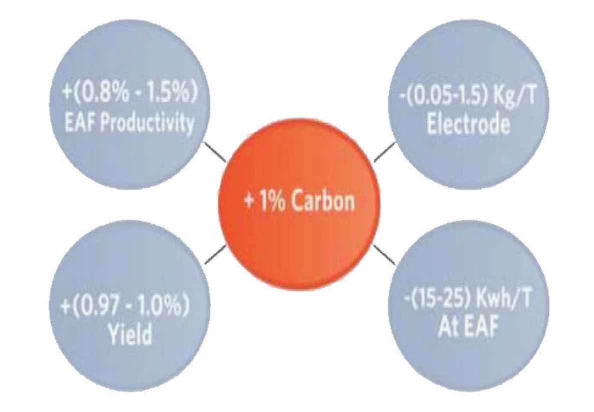
H_2 DRI EAF Challenges — The biggest challenge melting H_2 DRI in the EAF will be the 0% C_{DRI}.

Current EAF melting operations require C to supply chemical energy, reduce FeO (in the DRI and the slag) and create foamy slag (FS) by virtue of CO formed. In-situ C (contained in DRI (C_{DRI}), HBI (C_{HBI}), PI (C_{PI}) or HM (C_{HM})) is more efficient (>95%) than charging or injecting C (24% to 76%)[18,19] though the efficiency and value-in-use (VIU) of the in-situ C will be plant-specific.[19] ArcelorMittal, for example, runs 2.0–2.2%C at East Montreal but other ArcelorMittal plants run 2.2–2.7% (and have tested to 3.5%).[4,20] ArcelorMittal defined the benefit of 1% C_{DRI} on EAF operations (Fig. 9).

With chemical energy now 30–50% of the total energy input to the EAF (Table 7), in-situ C is a valuable benefit and has led to C between 1.5% (HBI) and 5% (high-C DRI or PI).[21] After the C_{DRI} reduces the FeO inherent in the DRI (completing the metallization thereof), the C will combust with "O_2" (from O_2 injection or [O] in the bath from FeO in the slag, volatiles in the scrap or other metal oxides (Table 7)). At 100% combustion efficiency, this will produce 9.09 kWh/kg C, so with >95% efficiency from in-situ C, >8.64 kWh/kg C will be donated to the system.[4,22,23]

C therefore contributes to reducing consumables (power, electrodes, refractories, etc.) and power-on time (POT)/tap-to-tap (TTT), so increasing productivity and yield.[20,24] Increased C_{DRI} compensates somewhat for increased kWh/ton required to melt DRI (presence of gangue) versus scrap and, because $(FeO)_{slag}$ is decreased, refractory life increases.[24,25] Additionally, unlike charge C, C_{DRI} contains no ash,

Figure 9



Effect of 1%C on EAF operations.[20]

Table 7

Example of an EAF Energy Balance[9]

Heat input	kWh/T	%	Heat output	kWh/T	%
kWh/T	430	55	Offgas sensible and calorific energy	279.4	36
C oxidation steel	175	23	Roof and sidewalls	49.5	6
Burner NG	38.5	5	Slag	56.1	7
Metal oxidation	64.9	8	Steel	385	54
Scrap volatiles	51.7	7	Miscellaneous	4.4	1
Electrode consumption	14.3	2	–	–	–
Total	774.4	–	Total	774.4	–

Table 8

Nucor Steel–Arkansas Results Using DRI[24]

	% DRI						
	100% scrap	25%	30%	35%	40%	45%	50%
kWh/ton	421	375	377	380	393	399	108
TTT (mins)	61	52	53	54	55	57	59

sulfur or volatiles, which are detrimental to the melt process and/or steel quality.

The FS generated by the CO increases the slag's surface area, improving removal of undesirable elements from the steel (including N, H, S, and P) and "refining" it. As the FS buries the electrodes, arc noise is significantly reduced and heat transfer/thermal efficiency is improved (>93%), further shortening the POT/TTT.

With high chemical energy input to the EAF, offgas system (OGS) losses (as high as 36% (Table 8[9])) must be minimized. Energy optimization, using offgas analysis (OGA), 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 (OFBs), volumes and injection angles.[23] Process optimization and OGA has highlighted and confirmed the need for efficient C sourcing, optimal O_2 solutions, FS practice, as well as optimum raw material mixes to ensure all the benefits listed above are garnered when producing the lowest cost quality steel.

In an integrated DR/EAF plant, the value of increasing $\%C_{DRI}$ (and costs whilst reducing DRI plant productivity) must be assessed site-specific versus the EAF benefits. Such analysis should include optimization of charges including availability, quality, VIU, and environmental impact of DRI and other iron units.[22]

Use of DRI in the EAF

One of the main reasons for DRI use in the EAF 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. If scrap supply is poor or non-existent, captive DRI plants can alleviate metallics sourcing issues.

If the EAF standard operating procedure (SOP) is optimized to take advantage of the unique chemical properties of DRI, major benefits are available. With educated use of DRI,[24,25] perceived disadvantages (primarily attributed to gangue content) can be negated whilst operations and costs can be improved (Table 8[26]). In-situ C_{DRI} (or C_{PI}) with >95% efficiency (assuming alignment with the available O_2 tools and OGS size can reduce the kWh/T, despite the gangue content (Fig. 7[4,20,22,25]). Nucor Steel–Arkansas found melting 50% DRI could lower kWh/ton and TTT below that of 100% scrap heats (Table 9[24]). Optimization is a must to avoid greater OG volume and energy loss with high % C and H_{DRI}.[22]

Table 9

Impact of Gangue in Asian Mills[26]

Gangue	Cost in US%/metric ton HBI added to the EAF				
	+ 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

Some of the cost benefits have been quantified:

- Continuous feeding DRI can save US\$29.50/T (no roof swings):[19]
  - Exceeding the optimal feed rate can cause "icebergs" (more so with HBI than DRI).
- Hot DRI (H_{DRI}) charging saves 20–30 kWh/100°C or US\$5–10/T_{ls}:[19,25]
  - Slower initial feeding without O_2 to a colder bath is required to prevent excessive C boils.

Other unquantified cost benefits have been reported, all related to C content (CO generation):

- Cleaner steel:
  - CO flushing reduced N, H and inclusions.
  - BHP 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.[26]
- Foamy slag:
  - Faster, earlier, formation improves arc stability, energy transfer and arc noise.

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

As previously mentioned, H_2 DRI production will result in $0\%C_{DRI}$ unless "C neutrality" prevails allowing in-situ C_{DRI} rather than injected, charged or PI equivalent C sourcing. As Table 4 showed, NG produced DRI with CCUS will cost US$869.46/$T_{CS}$ CRU[30] has looked at production costs for H_2 steelmaking and the C tax for EU steelmakers. Their figures show PEM steelmaking is US$3,700/T more expensive than the BF/BOF route. A US$200/T CO_2 tax would incentivize 60% of EU steelmakers whilst US$300/T CO_2 would incentivize 90%. Their model says 100% conversion is unlikely because C is needed to make steel!

So, what is the experience with 0% C_{DRI} and what challenges will it present?

Circored Trinidad 0%C HBI — The Trinidad Circored plant produced more than 300,000 T of 0% carbon H_2 DRI on an industrial scale using a two-stage fluidized bed process.[27] Some of the 95% met, 0% C Circal HBI was melted at North Star Steel Texas and results published.[28]

The initial melting trial determined:

- Meltshop 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.
- The best results were gained when feeding high % DRI with scrap continuously into large heels. Iceberg formation was avoided 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 T of HBI were charged as a single bucket layer.
- HBI densification of the charge resulted in a reduction in power-on time.
- 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 meltshop 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.
- Low residual levels were met using a large amount of pig iron.
- HBI could only ever partially replace PI (22 T HBI charged).

This plant experience suggests more energy, C, O_2 and PI will be required to melt 0% C DRI as we appreciate the options today. All of this will generate more CO_2 emissions from C reactions and power generation, unless green energy is available (0.295–1.005 kg CO_2/kWh – World Steel Association states 9.8 GJ fuel/MWh electricity) as well as an alternative C source(s) or new steelmaking method.

The IEA anticipates a future charge rate of 95% H_2 DRI. Today a lot of low-quality scrap can be accommodated with DRI use to produce low-residual, low-cost, quality steel because high-grade DR pellets (67%Fe iron or greater) are being used for DRI production. However, the projected future dearth of DR-grade iron ore[7,15] will compound the increased EAF energy requirement from 0%C DRI to melt the higher gangue content DRI inherent with low quality ore use (similar to those currently processed in BFs). There would be no C_{DRI} to reduce the higher FeO_{DRI} and complete the metallization. Incomplete metallization and missing C_{DRI} will increase the amount of gangue in the system, FeO_{slag}, yield loss and EAF power needed, unless substantial C is added to the EAF (per current operating guidelines). Therefore, 0%C_{DRI}, coupled with poor ores, would negate the benefit of using H_2 DRI. How will this enable the overall carbon footprint to be lowered?

Discussion

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 without the immense additional challenge of finding affordable green H_2 production routes. All opportunities depend upon green power and green H_2 supply volumes reaching required levels at acceptable prices — both extremely challenging.[4,5] H_2 is currently cost-prohibitive (requiring 720–800 MW

Table 10

ArcelorMittal Europe's Cost to Reach Carbon Neutrality

	AM Europe investment	Clean energy infrastructure	Production cost increase
Smart carbon	€ 15-25 billion	€ 15-30* billion	+30%
Innovative DRI route	€ 30-40 billion	€ 40-200** billion	+50-80%

* Leveraging mainly bioenergy and CCS. Could go much higher if green hydrogen fully leveraged

** Lower end of range based on blue H_2 CCS energy infrastructure; high end of range based on a green H_2 infrastructure

H_2 plant), especially when compared to the much cheaper current C tax for steelmaking (€25/T CO_2 and CA$25/T CO_2 versus the cost of mitigation (US$350–450/T CO_2,[5] US$457–572/T_{CS} (Table 4)). ArcelorMittal Europe's anticipated C neutrality costs puts the proposed CO_2 mitigation into perspective on a company basis (Table 10).

Important effects to consider when assessing the value versus environmental impact of replacing NG with H_2 in the DRI process include:

- Higher melt temperatures: melt temperature increases with decreasing %C in steel —more energy will be needed.
- Lower yield: likely as thermodynamically, low-C steels are associated with high %FeO_{slag} unless the FeO_{slag} is reduced after the initial melting stage.
- Less chemical energy: in-situ C_{DRI} will need to be replaced by other "C sources" 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.
- Carbon efficiency: twice as much carbon is likely to be required if not in-situ, adding more CO_2.
- Bath stirring: a replacement mechanism for CO stirring could be:
  - Injection.
  - Bottom porous plug or tuyeres using nitrogen, argon or CO_2[29] (or even O_2 with NG).
    - Industrial gas production requires more power.
    - Capture and use of CO_2 has associated costs and challenges (cooling, cleaning, pressurizing). [Note: use of CO_2 to replace argon in various areas of a 364 kT/year steel mill had a potential saving of US$1.15M/year.]
- Refractory systems: wear is likely to increase without C in the EAF through C dissolution and FeO_{slag} erosion unless refractory systems are re-thought. This will be compounded by lengthier heat times.
- Potential for icebergs: slower feeding rates, lengthier POT, reduced productivity and increased power use.
- Reduced productivity: slower bath reactions will lengthen POT and increase power use.
- Deeper EAF bath: lack of FS means a larger slag volume will be needed to bury the electrodes, maintain thermal efficiency (>93%), reduce noise and refine the steel. The additional slag formers and slag disposal required will increase costs.
- Low-quality ore use: increased gangue in the DRI will increase power, FeO_{slag} and require more C to reduce the FeO_{DRI} and FeO_{slag}.
- Scrap: even with 95% DRI charge, scrap will be needed. A global scrap industry SOP agreement (for identification, segregation and nomenclature along compositional lines) would equilibrate cost and quality of steelmaking. Guaranteed scrap quality, size and shape should elicit fees.

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 disposal (slag, in-house scrap and dust) and potential value.

Adoption of green steelmaking needs to be global to ensure equitable sharing of costs and technology development and steel pricing, not to mention significant inroads in addressing the global warming issue (U.S. and EU together produce less CO_2 than China alone (Fig. 2).

Conclusions

Use of H_2 DRI is dependent upon the economical availability of green H_2 and green power. Without them the environmental advantage will be lost.

There is evidence economical CO_2 emission-free production of DRI is feasible. Motivation to adopt the proposed H_2 DRI EAF steelmaking route may require significant hikes in CO_2 taxes.

Aging EU BFs and replacement thereof are part of the driving force to convert to H_2 DRI/EAF steelmaking, but how will countries with newer BF/BOF steel mills be made to embrace the cost to comply with CO_2 mitigation?

Long-term steel cost using the H_2 DRI/EAF route is US$1,327.23/$T_{cs}$ versus O_2-rich smelting process at US$755.13/$T_{cs}$ or the BF/BOF route at US$807.31/$T_{cs}$ (PEM steelmaking is US$3,700 more costly than BF/BOF steelmaking). The costs will not make compliant mills/countries cost competitive globally.

If H_2 DRI production develops as a major technology, with its resultant 0%C DRI, EAF steelmakers will be challenged to find an alternative C or new environmentally friendly energy source to:

- Compensate for the lack of C as a chemical energy source.
- Provide sufficient stirring in the bath for refining without C-generated CO.

- Provide sufficient slag foaming without C 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.
- Change EAF design.
- Create a new, single unit, combination melt and refining furnace.

VIU models used to optimize melting and minimize steelmaking cost will need to include an environmental algorithm.

We all want a greener earth to preserve life and the future, but as businessmen how are we looking at such a costly option? CO_2 abatement will be uneconomical unless governments subsidize the effort or there is world unity.

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, there will be a need for SOP changes, green power sources, alternative C and chemical energy sources, and possibly a new EAF design — shape, size, stirring capability, etc. — 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 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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