Forging the Future of Iron: Energy, Economics, and Emissions

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Agenda

Industry Background

Where today's iron comes from and what that means for emissions.

Reduction Basics

How reducing gases convert iron ore into direct reduced iron.

Energy Sourcing

Decarbonization is an energy problem, not an ironmaking problem.

Bioenergy Utilization

Charm Industrial's approach to novel bioenergy sourcing to secure new biogenic reducing gas.

Novel Paths for Production

Other approaches to ironmaking that need to be considered.

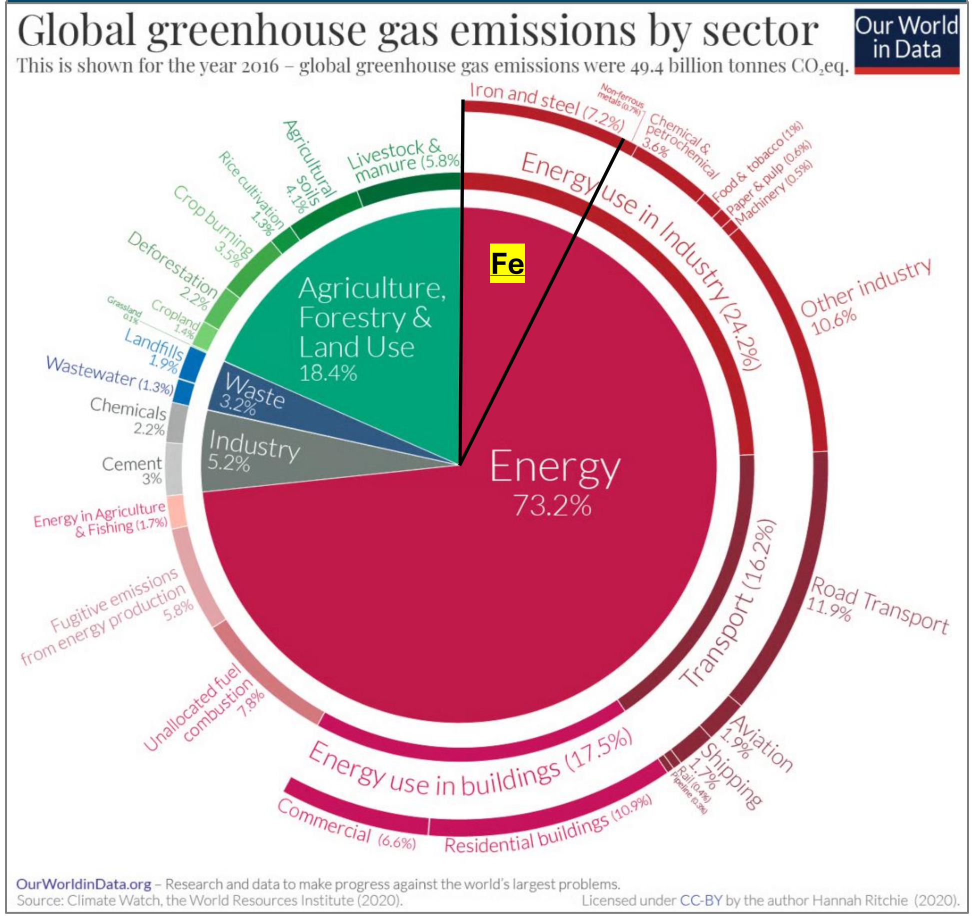
Route Comparison

Where do we go from here?

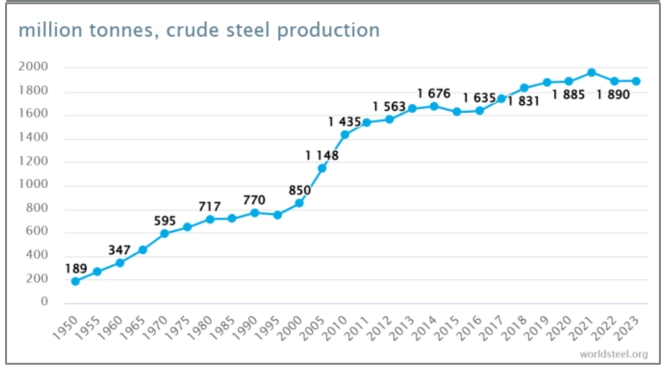
AI Disclosure: This presentation was developed with the assistance of generative AI. All factual data and citations have been independently verified against primary sources to ensure accuracy.

We’re Good at Making Iron Today – Why Discuss Alternatives?

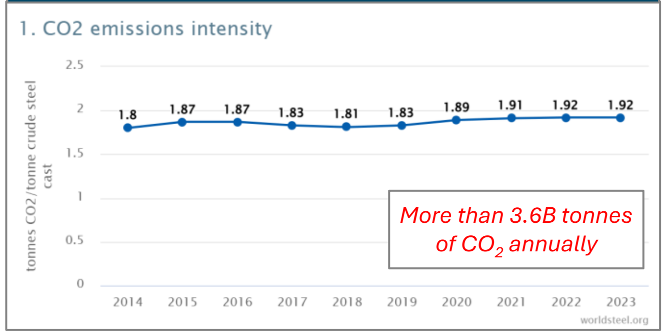
The global iron and steel industry is one of the world’s largest producers of greenhouse gases including CO_2[1]



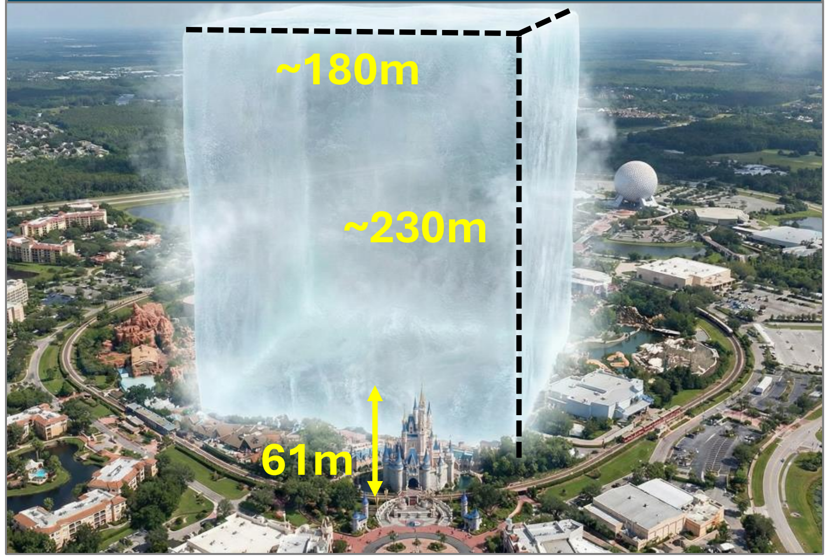
WorldSteel data[2] shows global crude steel production approaching 1.9 billion tonnes (1.84B in 2024[3])



This is occurring at the same time the world average CO_2 intensity per tonne of steel shows marginal increase[4]

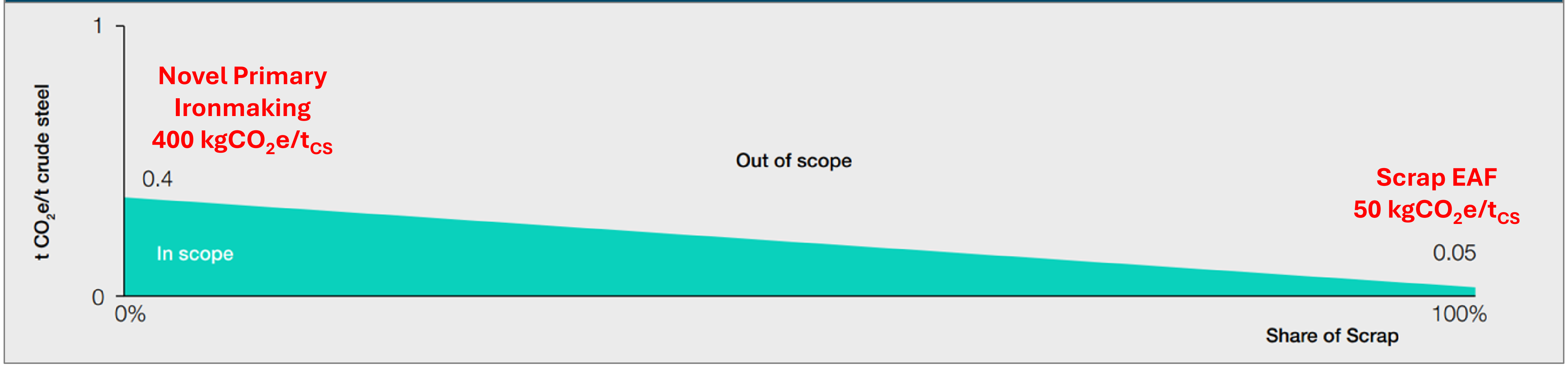


If annual iron and steel emissions were a block of dry ice - we’d make ~300 of these.



Market Demand & Desire for Near Zero Steel

"Near zero" crude steels are defined on a sliding scale:
less than 50 $kgCO_2e/t$ for 100% scrap based steel, and 400 $kgCO_2e/t$ for primary material (no scrap)[1].



First Movers Coalition

- 10% of annual steel procurement as NZS by 2030[1]
- Announced 2.3M in annual demand for NZS to date[2]

Stegra

Formerly H_2 Green Steel

- Pre-sold 1.5 Mtpy[3] of near zero steel
- Plans for 5 Mtpy of steel production by 2030

CBAM

- EU CBAM suggests 8-12 Mtpy of reduced imports to Europe from carbon border adjustments[4]

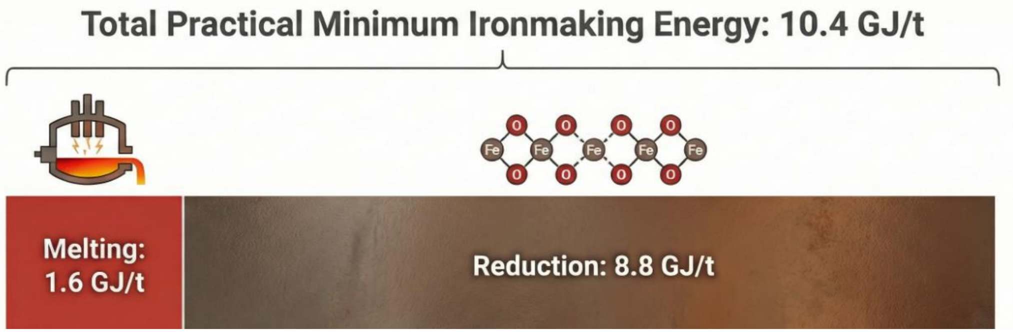
Where Does Today's Metallic Iron Originate?

Compiled global estimate of different process energy intensities & CO_2 intensities from various sources[1-5]

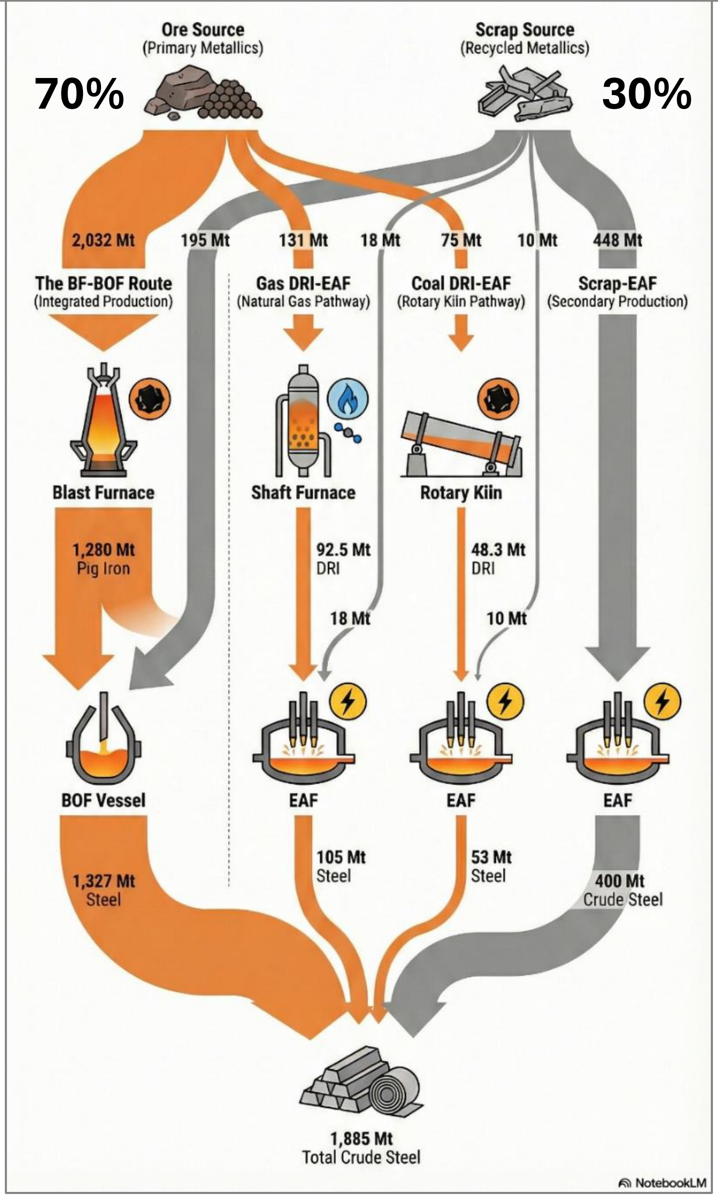
Production Route	Feedstock	Energy Intensity (GJ/tcs)	Total GHG Intensity (CO_2e Scope 1, 2, 3)
BF-BOF	Iron Ore + Coal	21.4 - 22.7	2.66
Gas-DRI-EAF	Iron Ore + Nat. Gas	17.1 - 21.8	1.66
Coal-DRI-EF	Iron Ore + Coal	20.4 - 21.6	2.70 - 3.00
Scrap-EAF	100% Steel Scrap	2.1* - 5.2**	0.71
Global Average	Mixed	21.0	2.18

Different data definitions provide the range. At the low end, *2.1 is an estimated site energy usage whereas **5.2 is an equivalent "Primary Energy" assuming generation plant power losses.

Practical Minimum considers unavoidable energy required for impurities in the ore, scrap contaminants, and gas heat losses[5]. It does not consider sintering, cokemaking, or energy losses at the point of production for electricity. This is why there is a gap between global data, true thermodynamic minimums, and practical minimums.

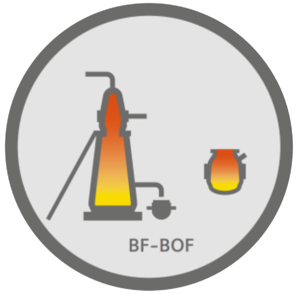


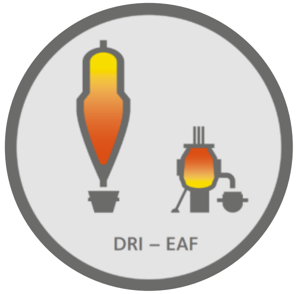
Illustrative **AI generated** global material flows pieced together from many sources[1-5 & 6-13]



Comparison of BAU Routes (North American Context)

- Shoutout to the **decarbSteel**[2] tool from CMU, funded in part by the AIST's **Sustainable Technologies for Steel Manufacturing Grant**[3]

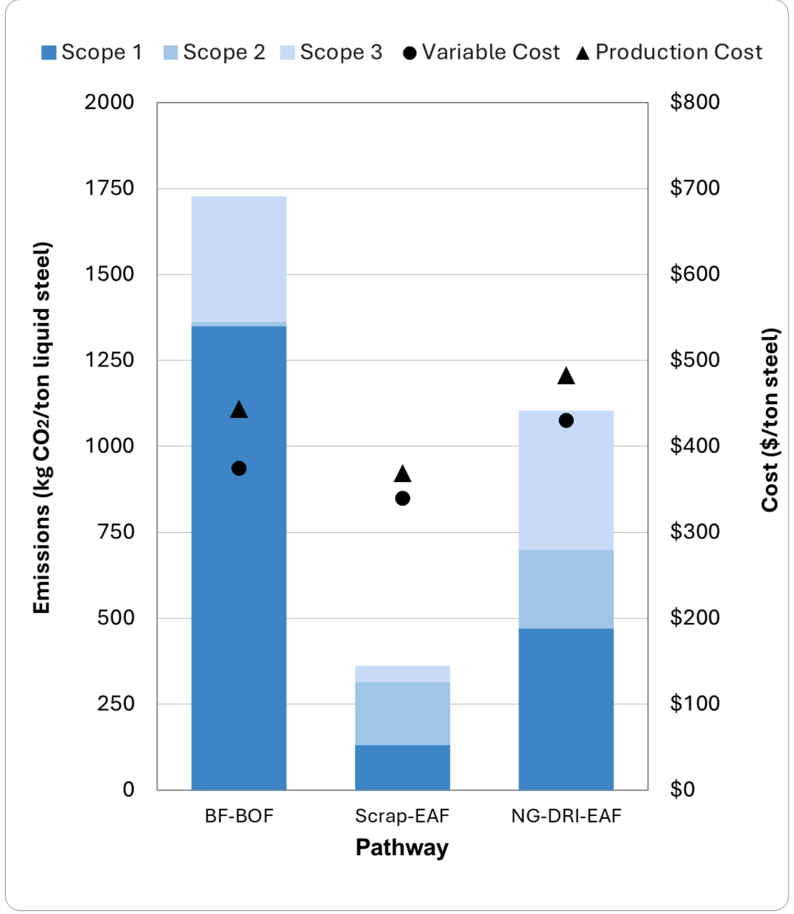




Process Route:	BF-BOF	EAF	DRI-EAF
Purpose & Upside	Counter-current reduction and smelting of high gangue ores	Efficient scrap melting & flexible operations	High grade ore reduction and melting for high quality steel
Downsides	Expensive integrated facility requiring high CAPEX and high CO_2	Limited grade quality without high scrap control and metallic use	Limited feedstock flexibility because of EAF, needs low-cost NG
Emissions Considerations	Scope 1: Coal/coke Scope 2: *Limited* Scope 3: Lime, pellets, O_2	Scope 1: Injection C Scope 2: Electricity Scope 3: Fluxes	Scope 1: NG Scope 2: Electricity Scope 3: Fluxes, pellets, NG

***Noted scope emissions are illustrative and not exhaustive, emphasizing the largest sources per category*

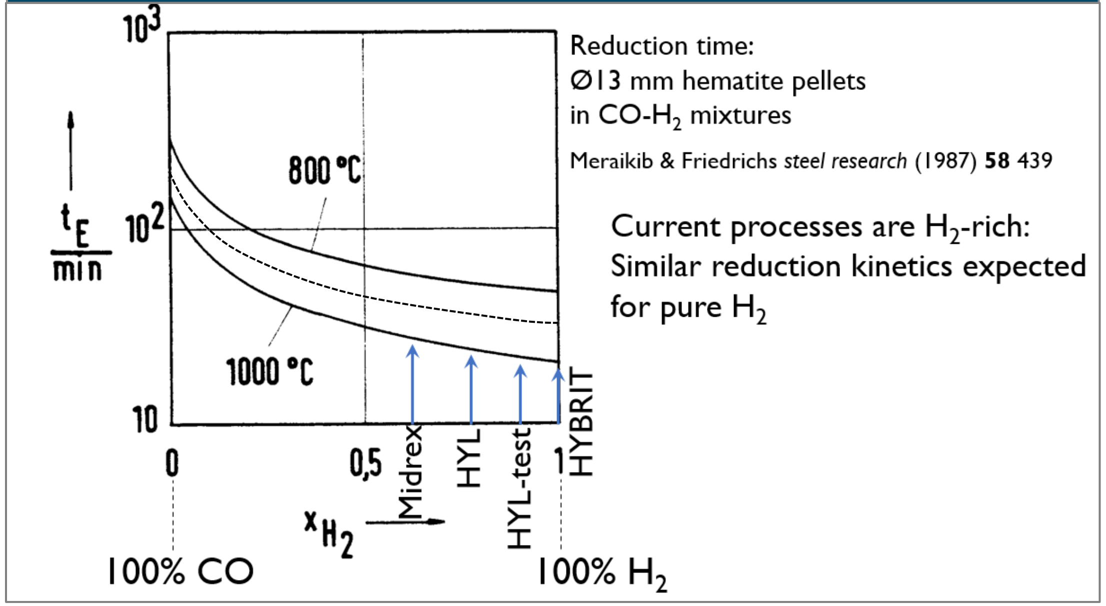
Modified decarbSTEEL v5 from CMU[1]: Comparing BF-BOF,



Shaft Furnace - Key Levers & Opportunities

Gas Composition Flexibility

Data from Meraikib & Friedrichs[1] shows the difference in reduction rate by temperature and gas composition.

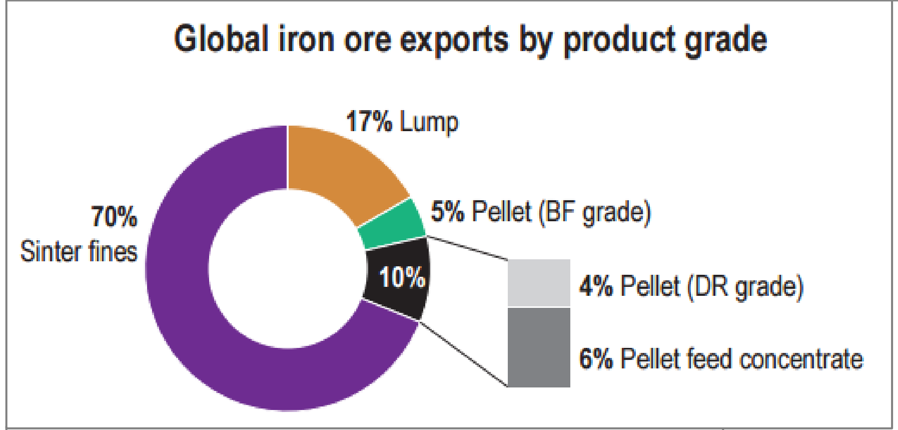


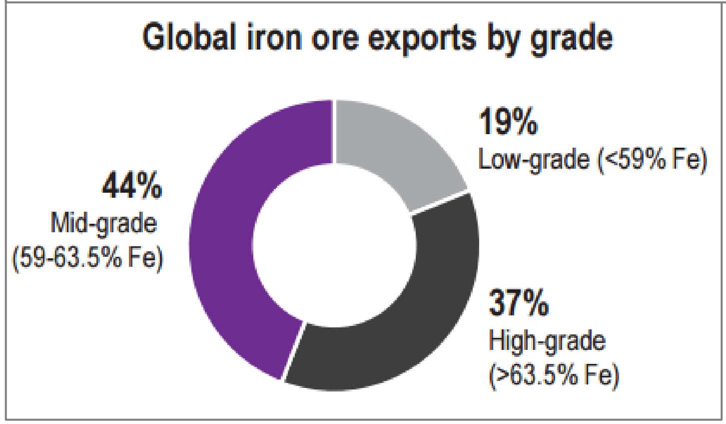
Current processes are H_2-rich: Similar reduction kinetics expected for pure H_2

H_2:CO Ratio	0	0.6	1	1.6	3	9
t_E (min)		55	45	40	38	32

Ore Grade Adaption (*Plant Dependent*)

Fast Markets Research from 2021[2] highlights seaborne iron ore travels around the world.





While pellets are the primary focus of today's discussion, fluidized bed reduction is proven and usable for sinter fines to apply gas-based reduction to more feedstocks.

Including captive pellet plants, pellets make up about 24% of annual iron consumption globally[2]. Estimated at 597 Mtpy[3].

Hydrogen DRI – The Most Marketed Alternative

- Benefits from decades of shaft furnace experience
- Option for partial adoption in pre-existing DRI systems
- Nearest technologically viable alternative to pre-existing fossil fuel-based processes, barring CCS integration

Why hydrogen?

- No direct site emissions except water
- Independence from fossil fuels
- Fast reaction kinetics offer higher throughput

From Stegra[1], installation of 200MW of electrolyzer capacity needed to supply H_2. Targeting 740MW of capacity[2].

90% of 3 Mile Island NPP[3]

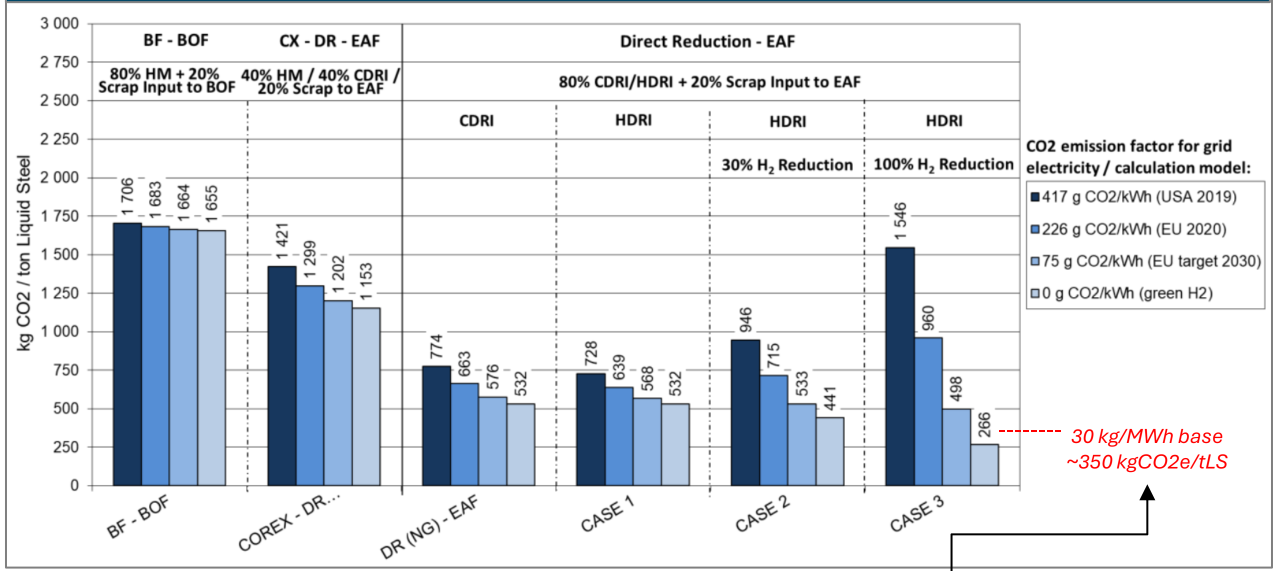
Roughly 8.5 EAFs producing 1.5 Mtpy steel

Hydrogen DRI – Energy Usage & Emissions Sensitivity

Must still supply energy to break Fe-O bonds, just a different sourcing mechanism

- From an emissions perspective, H2-DRI competes with NG-DRI, using about 10.5 GJ/t_{DRI}[1]
  - NG combustion emissions: 50.15 $kgCO_2e/GJ_{NG}$
  - NG upstream emissions: 12.04 $kgCO_2e/GJ_{NG}$ [**fugitive methane**]
  - Total emissions estimated per tDRI: 62.19 $kgCO_2e/GJ_{NG}$
  - Total DRI Emissions from NG: 653.00 $kgCO_2e/t_{DRI}$
- Reduction with H_2 requires about 58 kgH_2/t_{DRI}, implying 11.25 kg_{CO2e}/kg_{H2} as breakeven.
- What does this mean for grid-cleanliness to breakeven on electrolysis?
  - 55 kWh/kg_{H2} = 3.19 MWh/t_{DRI} PLUS ~1MWh gas heating
  - 653/4.19 = ~156 kg_{CO2e}/MWh (***ceiling***)

Milner et al.[1] provide a holistic comparison of different production routes and their estimated CO_2 emissions.



Reality:

- "It Depends" as individual situations are highly regional
- We ultimately care about $/tCO_2e abated; emissions abatement cost is key

NREL[2] estimates total **life cycle emissions** of wind around 10 kg/MWh, solar PV 40 kg/MWh. Batteries alone are around 33 kg/MWh; combined residential PV+LI systems can be 85 kg/MWh[3]. Quebec, the gold standard of low CO_2 hydroelectric power, has full life cycle emissions of 34.5 kg/MWh[4].

Hydrogen DRI – Key Cost Drivers

Factoring in other process and embodied emissions, CO2e breakeven occurs around 100 kg/MWh

Relative tCO2e per tSteel: H2-DRI-EAF minus NG-DRI-EAF											
		kgCO2e/kWh									
		0.00	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
kgH2/tDRI	46	-0.42	-0.34	-0.26	-0.18	-0.10	-0.02	0.18	0.38	0.59	0.79
	50	-0.42	-0.34	-0.25	-0.16	-0.08	0.01	0.23	0.45	0.66	0.88
	54	-0.42	-0.33	-0.24	-0.15	-0.05	0.04	0.27	0.51	0.74	0.97
	58	-0.42	-0.33	-0.23	-0.13	-0.03	0.07	0.32	0.57	0.82	1.07
	62	-0.42	-0.32	-0.21	-0.11	0.00	0.10	0.37	0.63	0.89	1.16

Strictly looking at economic performance, H2-DRI is only competitive at very low electricity costs

H2 Favored

Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF											
		$/kWhe									
		$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
kgH2/tDRI	46	-$29	-$6	$17	$40	$62	$85	$108	$131	$154	$176
	50	-$28	-$4	$21	$45	$69	$94	$118	$142	$167	$191
	54	-$27	-$1	$25	$50	$76	$102	$128	$154	$180	$206
	58	-$26	$1	$28	$56	$83	$111	$138	$165	$193	$220
	62	-$26	$3	$32	$61	$90	$119	$148	$177	$206	$235

NG Favored

At higher costs of natural gas, the opportunity for green H2 becomes larger.

Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF (46 kgH2/tDRI)											
		$/kWhe									
		$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
NG $/MMBtu	$4	-$14	$9	$31	$54	$77	$100	$123	$146	$169	$192
	$8	-$38	-$15	$8	$31	$54	$77	$100	$123	$145	$168
	$12	-$61	-$38	-$15	$8	$30	$53	$76	$99	$122	$145
	$16	-$85	-$62	-$39	-$16	$7	$30	$53	$76	$99	$121
	$20	-$108	-$85	-$62	-$39	-$16	$6	$29	$52	$75	$98

H2 Favored

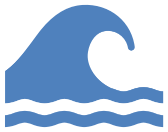
NG Favored

Considering change in steel emissions divided by change in steel cost estimates abatement cost.

Abatement Cost ($/tCO2e): H2-DRI vs. NG-DRI											
		kgCO2e/kWh									
		0.000	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
$/kWhe	$0.02	$40	$50	$65	$95	$172	$958				
	$0.04	$148	$183	$240	$348	$634					
	$0.06	$256	$316	$415	$602	$1,095					
	$0.08	$364	$450	$589	$855	$1,556					
	$0.10	$471	$583	$764	$1,108	$2,018					

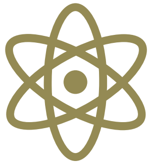
H2 Net Emitting

Nominal estimated cost of CO_2e abatement for a H2 DRI to EAF using low emissions and low-cost power in a region like Quebec.
NG-DRI-EAF offers \$62/t_{CO2e} abatement versus BF-BOF w/ \$6.45/MMBtu NG.

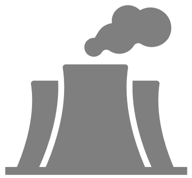


H_2 DRI can work where electricity is readily available, at low cost and low emissions.

These regions are extremely limited globally and will end up going to first movers.



While nuclear power can achieve low-emissions power, it is too expensive to be cost competitive with natural gas.



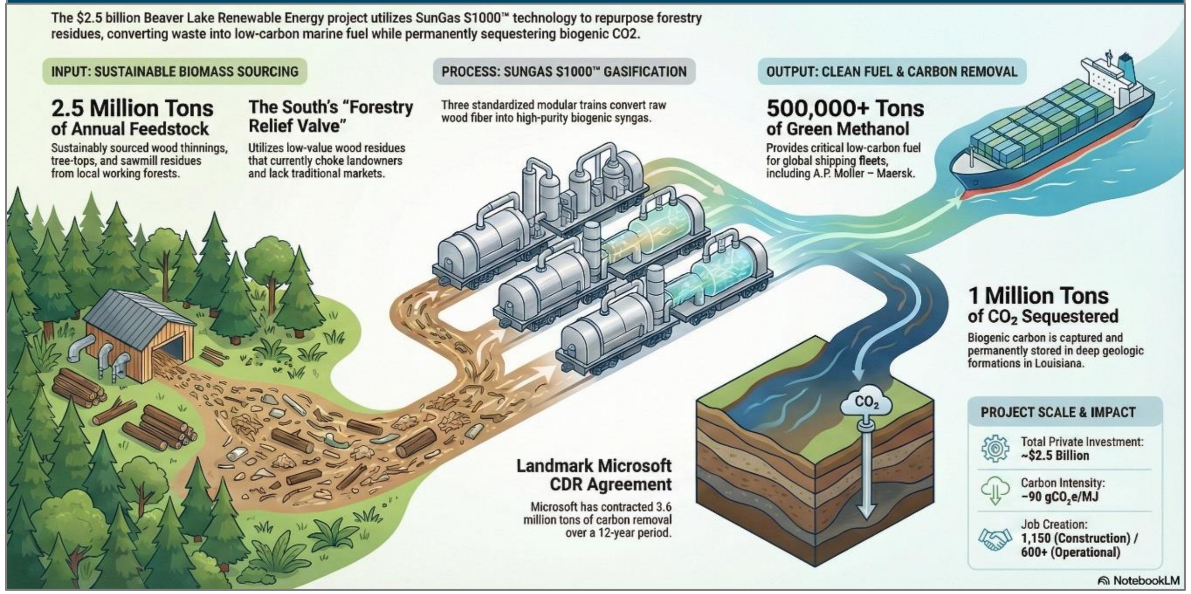
Calculations assume 30-year plant life. Changing this changes CAPEX sensitivity for FOAK equipment.

There was an implicit assumption 5 years ago that power prices would continue falling. The rise of AI data centers suggests this will not occur.

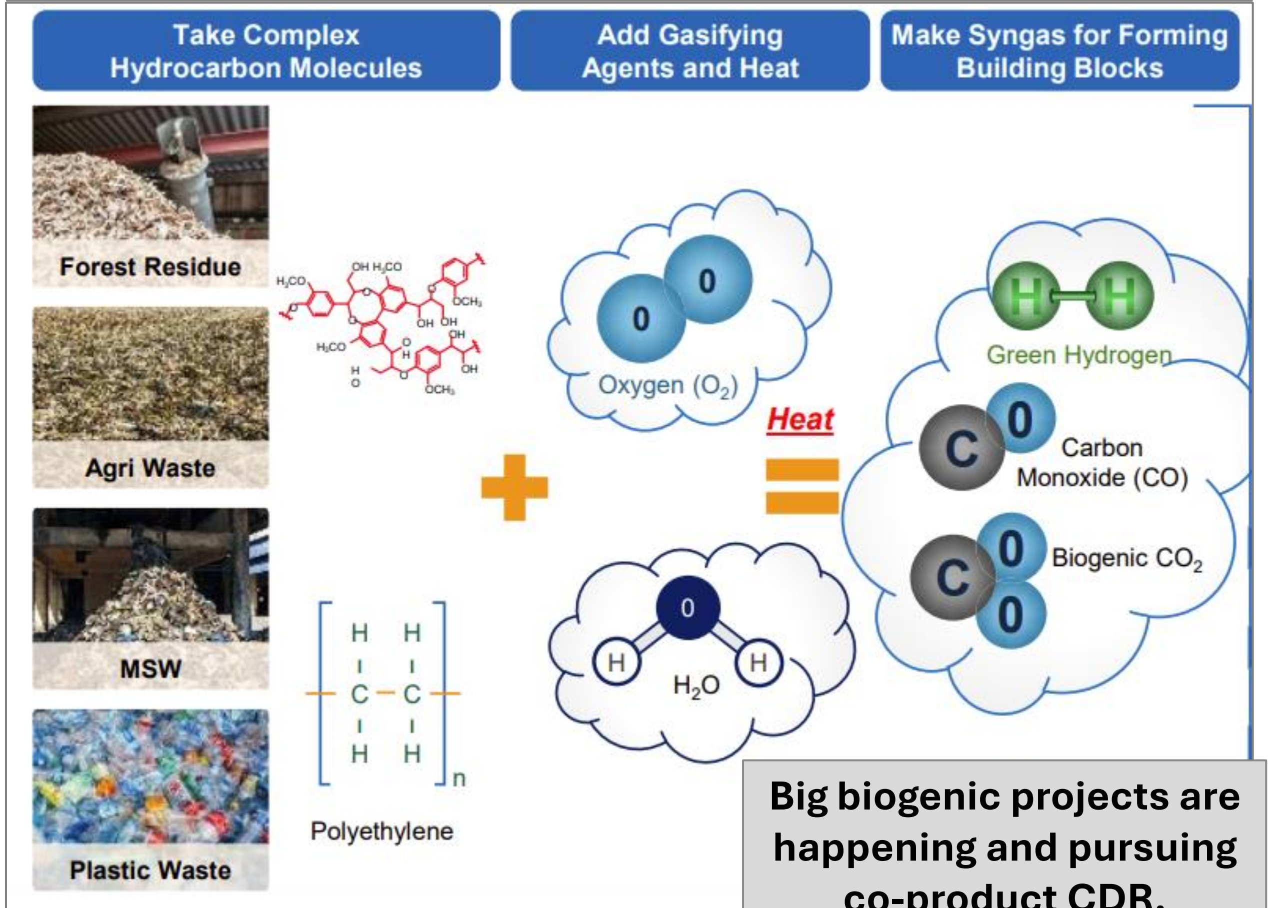
Biogenic Syngas DRI – Alternative Energy Sourcing

- The bioeconomy has seen it's share of stops and starts, and is undergoing another resurgence
- Ethanol has long been produced, and other forms of green chemicals are being developed like MeOH, backed by international companies like Maersk.

Beaver Lake Renewables[1] is building a >500,000 metric ton per year green methanol from gasified biomass in Louisiana



SunGas Renewables[2] is the technology provider for this gasification project. At 2.5M tpy of woody feedstock, you could run a 2Mtpy DRI facility.



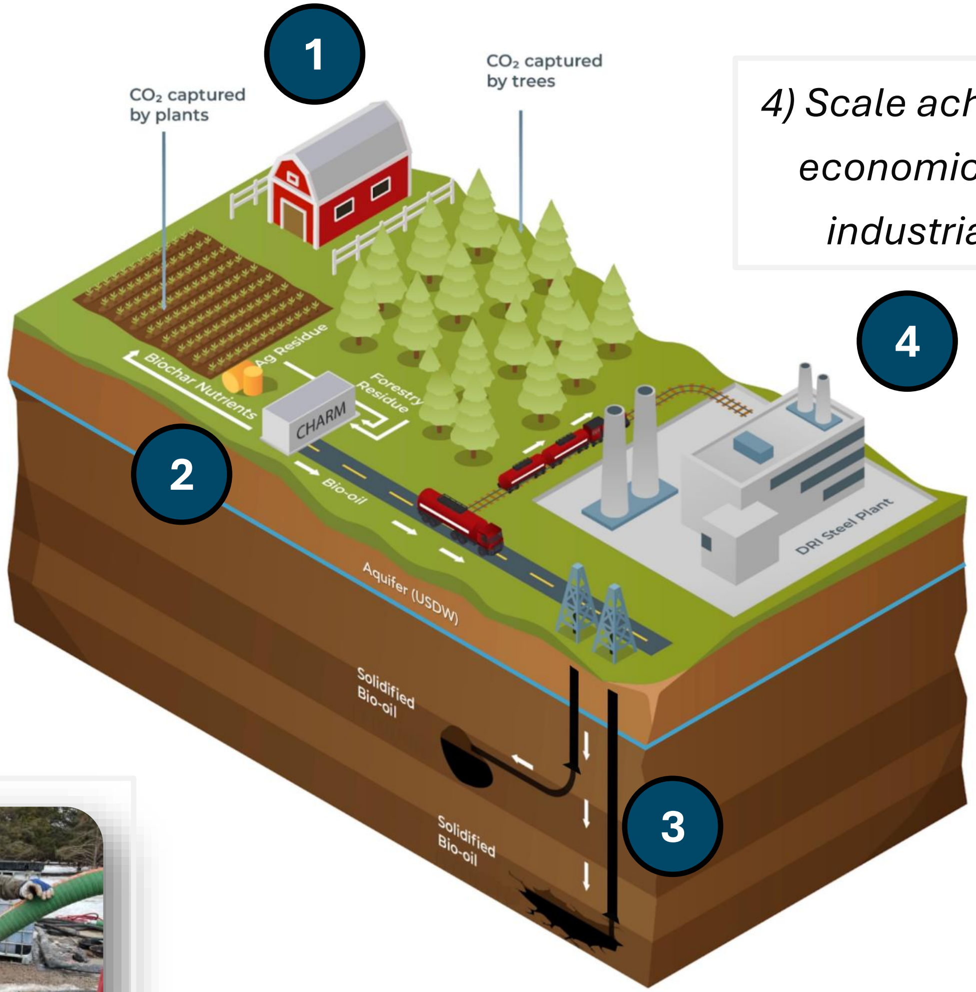
Big biogenic projects are happening and pursuing co-product CDR.

Charm Industrial: Bioenergy Industrialization & CO_2 Removal

1) Charm uses plant residues from farms and forests

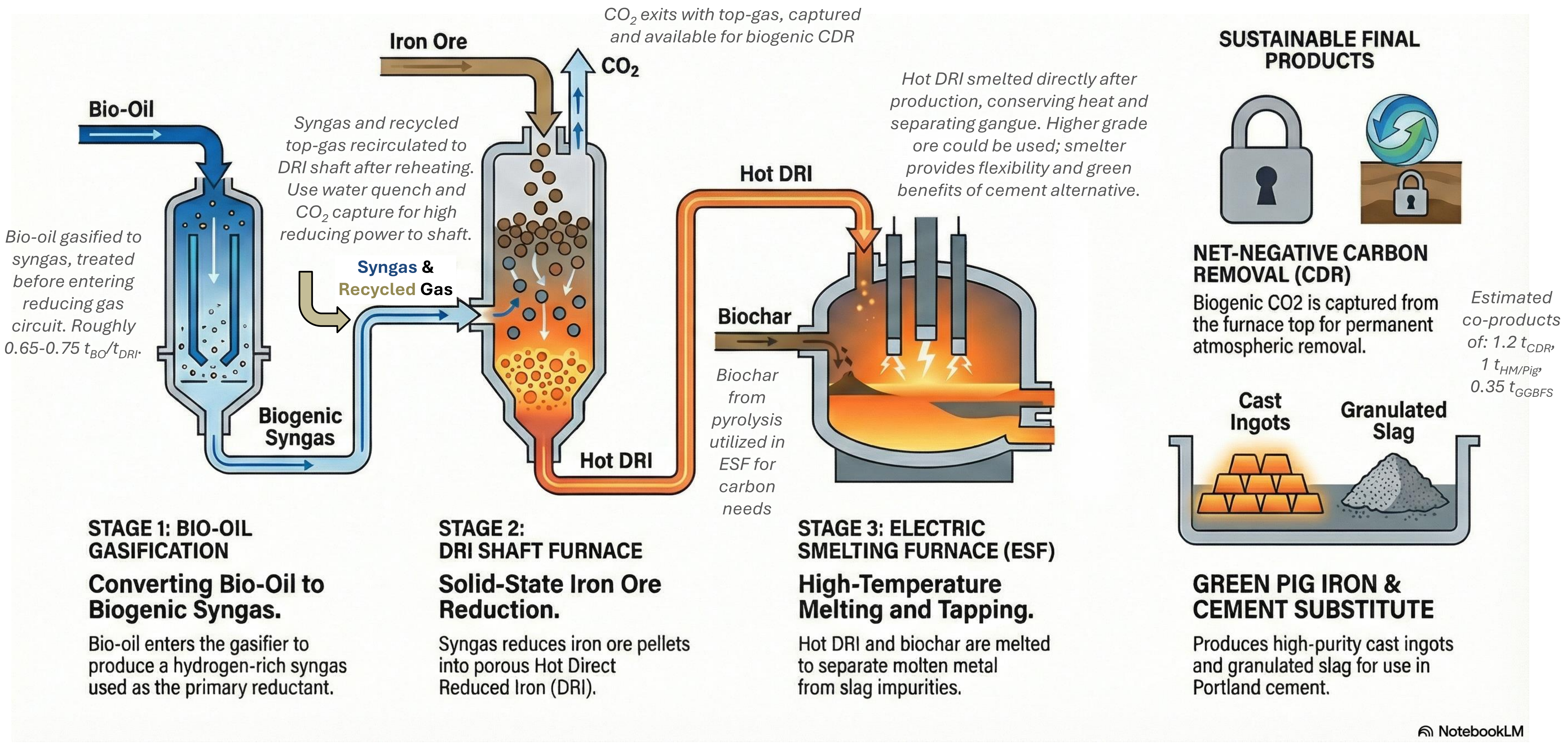
2) With heat and minimal oxygen, Charm converts biomass into biochar and bio-oil via pyrolysis

3) Charm injects the bio-oil deep underground for permanent carbon removal, and applies biochar on fields



4) Scale achieves suitable economics to support industrial activities

Biogenic Syngas DRI – Schematic & Energy Flow



Biogenic Syngas DRI – Cost Drivers

Biomass Sourcing

- Secure sufficient economical biomass to supply the gasification process.
- 1 Mtpy of DRI production requires[1]:
  - 1.1 Mtpy dry **wood**
  - 3.0 Mtpy dry **corn stover**

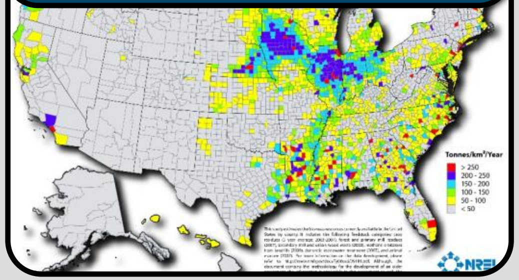
Transportation

- Aggregate bio-oil at scale for gasification and DRI plant
- Achieve suitably low-cost rail economics
  - Bulk crude shipping rates are around \$0.06/t-mi[2]
    - Ex. \$30/t for 500mi

Gasification TRL

- Replace reformer or electrolyzers with bio-oil gasifier. Instead of a NG-reformer the facility needs a gasifier and process gas heater, with CO_2 capture:
  - *MXCOL*
  - *Energiron w/ gasifier*
- Higher complexity means higher CAPEX (est. +50%) compared to Midrex base

Regional Relevance

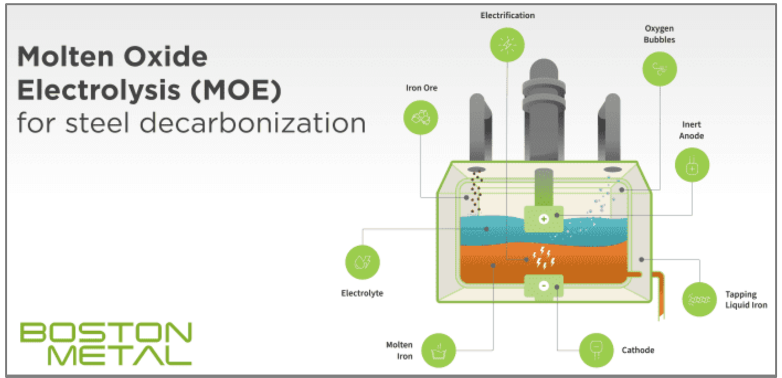


- Recognize that this approach is regionally limited to areas with biomass and CCS
- For CCS capabilities, require compression, transportation, and sequestration for supercritical CO_2
  - Expect <\$50/t_{CO2}[3]

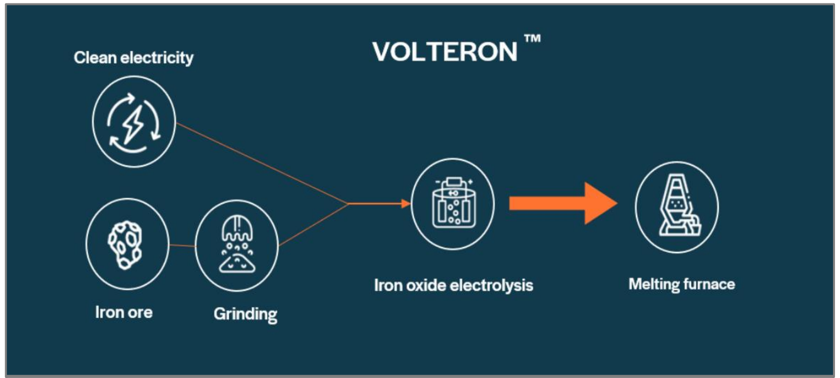
Novel Ironmaking & Direct Electrification

- Streamlined plant design and direct electrification may reduce total energy demands[1]
- Lower Technology Readiness Level (TRL) and under active development
  - **LT Electrowinning (Electra)**: 500 tpy demo by mid-2026, "commercial scale" by 2029[2]
  - **MOE (Boston Metal)**: Working on niobium first for higher value (2026), est. demo for steel by 2028[3]
  - **Volteron (ArcelorMittal & John Cockerill)**: 40-80ktpy by 2027[4]

Reduction: 9.4-10.8 GJ/t
Melting (EAF): 1.4 GJ/t
Total before losses: 10.8-12.2 GJ/t



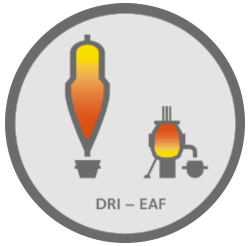
Reduction & Smelting: 10.8 GJ/t
Estimated Energy Losses: 20-30%
Estimated total w/ losses: 13.5-15.4 GJ/t

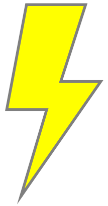
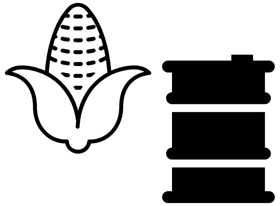


Reduction: 9.4 GJ/t (*demoed at pilot scale*)
Melting (EAF): 1.4 GJ/t
Total before losses: 10.8 GJ/t

Making a rough estimate, most of these processes likely end up near 15 GJ/t depending on final process design. This is an improvement over 15-20 GJ/t for H_2 DRI-EAF, but still a large energy load.

Comparing the Pathways Forward



Process:	NG DRI	H2 DRI	Electrolysis+	Biogenic DRI
Pros:	• Available today • Low-cost today • Many improvement pathways (H_2 blend, CCS, reduced fugitive methane emissions)	• Utilizes pre-existing DRI technology	• Expected lowest energy requirement of all ironmaking technologies	• Leverages pre-existing DRI facility concepts • Co-produces 3 “green” products for future markets
Cons:	• Emissions intensive compared with alternative low-CO_2 technologies	• Requires electricity at a massive scale • Requires electrolyzer mass deployment • Requires carburization still for EAF operations	• Requires electricity at a massive scale • Requires carburization if EAF used	• Requires sufficient low-cost biomass • Technology risk associated with gasification
Expected Cost:	**Low (2)** *Assuming BF-BOF is the “low” benchmark*	**High (4)**	**Medium (3)** *Lower energy requirement relative to H_2 DRI-EAF path*	**High (4)** *CDR revenues can shift this price point lower.*

Final Thoughts – No Shortage of Options & Choices

Energy Reality
Ironmaking takes much more energy than steelmaking alone. Technological advances won't solve a thermodynamic limit.

Transition Ready DRI
Adopting DRI-EAF today over BF-BOF can save ~400 kg_{CO2e}/t before factoring in future improvement. That's 24Mt in 20 years.

Raw Materials
EAF alone will not be a solution, because primary iron is needed and most ore exceeds gangue limits for traditional EAFs.

Regionality
Solutions are driven by regional energy pricing. Using natural gas today, and moving towards CCS, appears LCA favorable.

Alternative Abatement & Carbon Dioxide Removal
Within 5 years we will see proof for <\$200/tCO_2 carbon removals at scale.
However, it will not be able to satiate all of today's CO_2 emissions, so we need to balance the pathway between "good enough" economical decarbonization and CDR availability.

Questions?

Feel free to reach out!

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Bonus Slide: LNG Embodied Emissions (GWP100)

- The North American natural gas pricing situation is not globally common. Understanding the H2 DRI to NG DRI tradeoff in conditions where embodied emissions are higher and costs are higher is reviewed below.
  - Delivered LNG to NG costs are assumed to rise to ~$9/GJ
  - Combustion emissions remain fixed at 50.15 kgCO2e/GJ, but Scope 3 emissions from methane slip and natural gas combustion during transportation rise to ~31.2 kgCO2e/GJ

Larger operating window for H2 from grid when greater embodied emissions of NG are considered.

	Relative tCO2e per tSteel: H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
kgH2/tDRI	0.00	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
46	-0.56	-0.48	-0.40	-0.32	-0.24	-0.16	0.05	0.25	0.45	0.65
50	-0.56	-0.47	-0.39	-0.30	-0.21	-0.12	0.09	0.31	0.53	0.75
54	-0.56	-0.47	-0.37	-0.28	-0.19	-0.09	0.14	0.37	0.61	0.84
58	-0.56	-0.46	-0.36	-0.26	-0.16	-0.06	0.19	0.43	0.68	0.93
62	-0.56	-0.45	-0.35	-0.24	-0.14	-0.03	0.23	0.50	0.76	1.02

Purely an economic consideration, this figure does not change since NG is sensitized.

	Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF (46 kgH2/tDRI)									
	$/kWhe									
NG $/MMBtu	$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
$4	-$14	$9	$31	$54	$77	$100	$123	$146	$169	$192
$8	-$38	-$15	$8	$31	$54	$77	$100	$123	$145	$168
$12	-$61	-$38	-$15	$8	$30	$53	$76	$99	$122	$145
$16	-$85	-$62	-$39	-$16	$7	$30	$53	$76	$99	$121
$20	-$108	-$85	-$62	-$39	-$16	$6	$29	$52	$75	$98

H2 Favored

NG Favored

Green H2 becomes more favorable when NG price raised to $9/GJ

H2 Favored

	Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF									
	$/kWhe									
kgH2/tDRI	$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
46	-$47	-$24	-$1	$22	$45	$67	$90	$113	$136	$158
50	-$46	-$22	$3	$27	$51	$76	$100	$124	$149	$173
54	-$45	-$19	$7	$33	$58	$84	$110	$136	$162	$188
58	-$44	-$17	$11	$38	$65	$93	$120	$148	$175	$202
62	-$43	-$15	$14	$43	$72	$101	$130	$159	$188	$217

NG Favored

When LNG is considered, abatement costs are about 50% lower combining higher emissions and cost.

	Abatement Cost ($/tCO2e): H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
$/kWhe	0.000	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
$0.02	-$1	-$2	-$2	-$2	-$3	-$5				
$0.04	$80	$94	$113	$143	$192	$295				
$0.06	$162	$190	$229	$288	$388	$595				
$0.08	$244	$286	$344	$433	$584	$895				
$0.10	$326	$381	$460	$578	$779	$1,195				

H2 Net Emitting

Bonus Slide: NG Embodied Emissions (GWP20)

- The standard LCA practice is to use GWP100, however, GWP20 is another standard recognizing that warming potential of methane on a 20-year basis is about 3x more impactful.
  - NG costs are assumed at \$6.45/MMBtu baseline (\$6.11/GJ)
  - Combustion emissions remain fixed at 50.15 kgCO2e/GJ, but Scope 3 emissions from methane slip and natural gas combustion during transportation rise to ~35 kgCO2e/GJ

Larger operating window for H2 from grid when greater embodied emissions of NG are considered.

	Relative tCO2e per tSteel: H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
kgH2/tDRI	0.00	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
46	-0.59	-0.51	-0.43	-0.35	-0.26	-0.18	0.02	0.22	0.42	0.63
50	-0.59	-0.50	-0.41	-0.33	-0.24	-0.15	0.06	0.28	0.50	0.72
54	-0.59	-0.50	-0.40	-0.31	-0.22	-0.12	0.11	0.34	0.58	0.81
58	-0.59	-0.49	-0.39	-0.29	-0.19	-0.09	0.16	0.41	0.65	0.90
62	-0.59	-0.48	-0.38	-0.27	-0.17	-0.06	0.20	0.47	0.73	1.00

Direct economic comparison shows no change since the \$/GJ for NG has not changed.

H2 Favored

	Relative \$/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF									
	\$/kWhe									
kgH2/tDRI	\$0.00	\$0.01	\$0.02	\$0.03	\$0.04	\$0.05	\$0.06	\$0.07	\$0.08	\$0.09
46	-\$29	-\$6	\$17	\$40	\$62	\$85	\$108	\$131	\$154	\$176
50	-\$28	-\$4	\$21	\$45	\$69	\$94	\$118	\$142	\$167	\$191
54	-\$27	-\$1	\$25	\$50	\$76	\$102	\$128	\$154	\$180	\$206
58	-\$26	\$1	\$28	\$56	\$83	\$111	\$138	\$165	\$193	\$220
62	-\$26	\$3	\$32	\$61	\$90	\$119	\$148	\$177	\$206	\$235

NG Favored

Purely an economic consideration, this figure does not change since NG is sensitized.

	Relative \$/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF (46 kgH2/tDRI)									
	\$/kWhe									
NG \$/MMBtu	\$0.00	\$0.01	\$0.02	\$0.03	\$0.04	\$0.05	\$0.06	\$0.07	\$0.08	\$0.09
\$4	-\$14	\$9	\$31	\$54	\$77	\$100	\$123	\$146	\$169	\$192
\$8	-\$38	-\$15	\$8	\$31	\$54	\$77	\$100	\$123	\$145	\$168
\$12	-\$61	-\$38	-\$15	\$8	\$30	\$53	\$76	\$99	\$122	\$145
\$16	-\$85	-\$62	-\$39	-\$16	\$7	\$30	\$53	\$76	\$99	\$121
\$20	-\$108	-\$85	-\$62	-\$39	-\$16	\$6	\$29	\$52	\$75	\$98

H2 Favored

NG Favored

Higher embodied emissions for NG result in more favorable \$/tCO2e abated with H2.

	Abatement Cost (\$/tCO2e): H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
\$/kWhe	0.000	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
\$0.02	\$29	\$34	\$40	\$50	\$65	\$94				
\$0.04	\$107	\$124	\$148	\$183	\$239	\$347				
\$0.06	\$185	\$214	\$255	\$316	\$414	\$600				
\$0.08	\$263	\$305	\$363	\$449	\$588	\$852				
\$0.10	\$340	\$395	\$471	\$582	\$762	\$1,105				

H2 Net Emitting

Bonus Slide: LNG Embodied Emissions (GWP20)

- Combining both assumption sets, NG costs are directly more expensive, and the associated CO2 impact is higher under the GWP20 scenario.
  - Delivered LNG to NG costs are assumed to rise to ~$9/GJ
  - Combustion emissions remain fixed at 50.15 kgCO2e/GJ, but Scope 3 emissions from methane slip and natural gas combustion during transportation rise to ~75 kgCO2e/GJ

Large drift in grid emissions favorability considering high GWP20 from methane + LNG.

	Relative tCO2e per tSteel: H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
kgH2/tDRI	0.00	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
46	-0.87	-0.79	-0.71	-0.63	-0.55	-0.47	-0.27	-0.06	0.14	0.34
50	-0.87	-0.79	-0.70	-0.61	-0.52	-0.44	-0.22	0.00	0.22	0.43
54	-0.87	-0.78	-0.69	-0.59	-0.50	-0.41	-0.17	0.06	0.29	0.53
58	-0.87	-0.77	-0.67	-0.57	-0.47	-0.38	-0.13	0.12	0.37	0.62
62	-0.87	-0.77	-0.66	-0.56	-0.45	-0.34	-0.08	0.18	0.45	0.71

Purely an economic consideration, this figure does not change since NG is sensitized.

	Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF (46 kgH2/tDRI)									
	$/kWhe									
NG $/MMBtu	$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
$4	-$14	$9	$31	$54	$77	$100	$123	$146	$169	$192
$8	-$38	-$15	$8	$31	$54	$77	$100	$123	$145	$168
$12	-$61	-$38	-$15	$8	$30	$53	$76	$99	$122	$145
$16	-$85	-$62	-$39	-$16	$7	$30	$53	$76	$99	$121
$20	-$108	-$85	-$62	-$39	-$16	$6	$29	$52	$75	$98

H2 Favored

NG Favored

Green H2 becomes more favorable when NG price raised to $9/GJ; no change to base LNG.

H2 Favored

	Relative $/tSteel Difference: H2-DRI-EAF minus NG-DRI-EAF									
	$/kWhe									
kgH2/tDRI	$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09
46	-$47	-$24	-$1	$22	$45	$67	$90	$113	$136	$158
50	-$46	-$22	$3	$27	$51	$76	$100	$124	$149	$173
54	-$45	-$19	$7	$33	$58	$84	$110	$136	$162	$188
58	-$44	-$17	$11	$38	$65	$93	$120	$148	$175	$202
62	-$43	-$15	$14	$43	$72	$101	$130	$159	$188	$217

NG Favored

Considering LNG & GWP20 the relative abatement cost of CO2e drops significantly.

	Abatement Cost ($/tCO2e): H2-DRI-EAF minus NG-DRI-EAF									
	kgCO2e/kWh									
$/kWhe	0.000	0.020	0.040	0.060	0.080	0.100	0.150	0.200	0.250	0.300
$0.02	-$1	-$1	-$1	-$1	-$1	-$2	-$3	-$13		
$0.04	$52	$57	$64	$72	$82	$97	$172	$776		
$0.06	$104	$115	$128	$145	$166	$195	$347	$1,564		
$0.08	$157	$173	$193	$218	$250	$294	$522	$2,353		
$0.10	$209	$231	$257	$291	$334	$392	$697	$3,141		

H2 Net Emitting

You're beginning to see nuclear power economics here, which combined with reduced energy demand from electrolytic process are probably quite favorable $/t_{CO2e}$ basis.

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