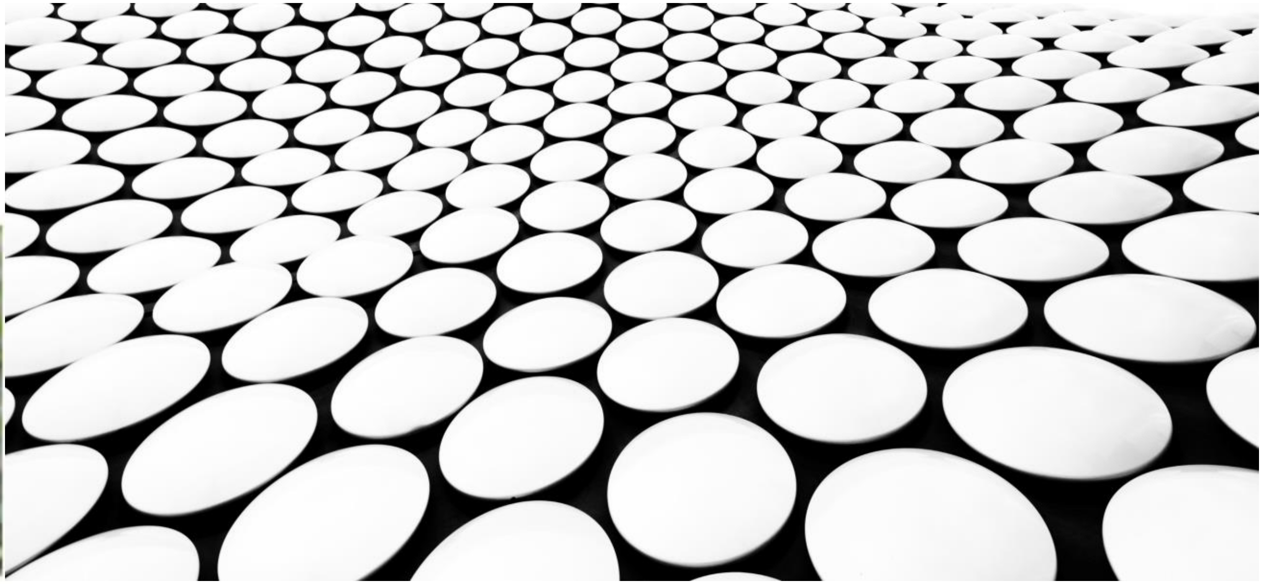
4th Australian & New Zealand Annual Steel Symposium

Handling the Future Dearth of H_2 and DRI Quality Iron Ore

AIST
ASSOCIATION FOR IRON & STEEL TECHNOLOGY

Australia and New Zealand Chapter



Introduction

- IEA steel decarburization solution – H_2 DRI EAF steelmaking BUT issues abound
  - Availability – green energy (GE) & H_2 (whatever color! <0.1% green 2021)
  - DRI quality iron ore – only 3% to 4%
  - Conversion is capital intensive & fraught with "build rate" impossibilities
  - Willingness to pay – clients for pricey clean steel; steel mills for GE & H_2
- Are there less capital-intensive alternatives with reduced techno-socio-economic impact than BF/BOF conversion &/or closure to consider?
  - BF Tuyere injection
  - HBI to the BF & BOF
  - CCUS
  - Coupling DRPs and low-grade ores to "melters" and BOFs
- How will non-compliance be handled? Heavy taxes on cheap, "black steel"?

IEA Solution – H_2 DRI EAF Steelmaking

➢ Globally, steel uses 8% energy, producing 7%-9% CO_2

❖ Coke (6%E in ‘15) needed to reduce Fe oxides & supply process energy

	MTe Steel	%	MTe CO_2	%	Te CO_2/ Te_{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

Plant Area	Direct CO_2 ($TeCO_2$/Te)	Order of Concern
Coke	0.794	2
Sinter	0.200	4
Pellet	0.057	10
BF	1.219	1
BOS	0.181	5
EAF	0.240	3

➢ Major steel emissions are from the primary end

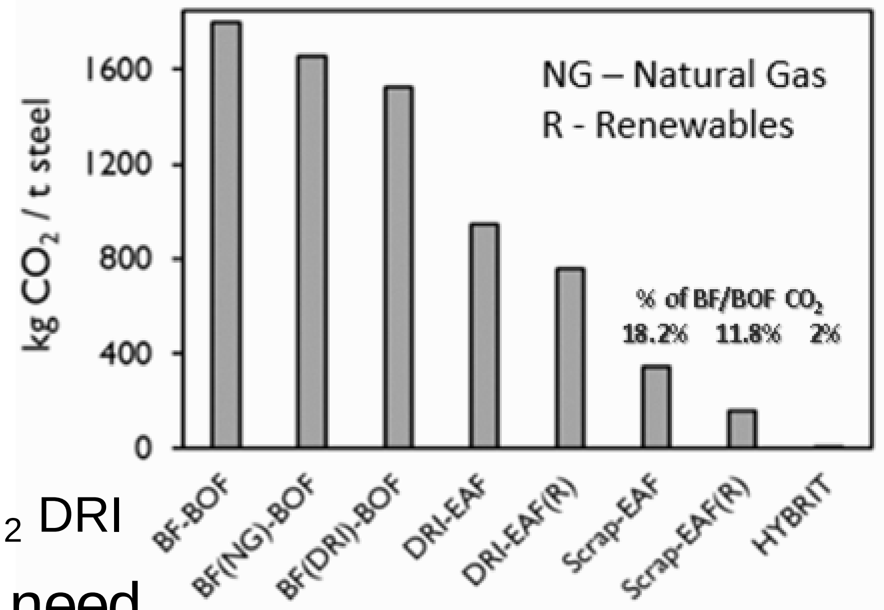
From the EU Commission – JRC Scientific & Policy Reports “Prospective Scenarios on Energy Efficiency & CO_2 Emissions in the EU I&S Industry”, 2012 publication

➢ BF with NG DTI or DRI decreases CO_2 by:

❖ ~9 to 16% (NG) & ~ 21% (DRI) - 2019

➢ 100% scrap EAF emissions:

❖ 18.2% BF/BOF; 11.8% with Renewable Energy (RE); 2% with H_2 DRI



❖ BUT 2050 H_2 availability is projected to be 4% - 11% of need

Challenges for EAF Green Steelmaking

- In 50y (to 2020) 104.4MTe$_{DRI}$/y produced; ~2.08MTe$_{DRI}$/y growth or **~2MTe plant/y**
- 120MTe H_2 2021 world production (<0.1% green). **DRPs alone need +9.6% & +21.3%**

Year		MTe/y DRI	# of 2MTe DRI / y plants	Years to grow	# DRI plants/ Year to 20XX	MTe H_2/ DRI plant	MTe H_2 /y (56.2kgH_2 /Te$_{DRI}$)	TW for Total H_2 (57.8MW /TeH_2)	# of 20MW PEMs	# of 400MW PEMs	# of EAFs for 2MTe/y
2050	Total DRI	411	205.5	28	7.34	0.113					15% DRI = 1.42BTe$_{Steel}$
	H_2 DRI	213	106.5		3.8		11.5	691.87	34.590 (1.24k/y)	1,730 (62/y)	710 total
2070	Total DRI	638	319	48	6.65						95% DRI = 2.74BTe$_{steel}$
	H_2 DRI	473	236.5		4.97		25.5	1,535.75	76,790 (1.6k/y)	3,840 (192/y)	1,370 total

2050 IEA	SDS	STEPS
ENERGY GJ/Te$_{steel}$	14.8	16.1
CO2 Te/Te$_{steel}$ (GTe/Y)	0.6 (1.2)	1.1 (2.7)
SCRAP EAF	38%	36%
100%H_2	8%	
DRI w CCUS	2%	
DRI	9%	11%
EAF STEELMAKING	57.5%	47.4%
SR-BOF w CCUS	10%	
BF/BOF w CCUS	3%	
BF/BOF	30%	52%
SCRAP	45.3%	44.7%
STEEL - BTe/y	2.0	2.2

- Green Energy for 52.45% EAF steelmaking (1.1BTe/y – Table ave.); More kWh for 0%C in-situ
  - **100% scrap:** 295 - 386kWh/Te (340.5kWh/Te$_{ls}$) = +375TW/y -
  - 80% 2.5%C DRI: 480 - 580kWh/Te (530.0kWh/Te$_{ls}$) = +583TW/y -
  - **80% 0%C DRI:** 650 - 704kWh/Te (677.0kWh/Te$_{ls}$) = +745TW/y

Delta 208TW/y

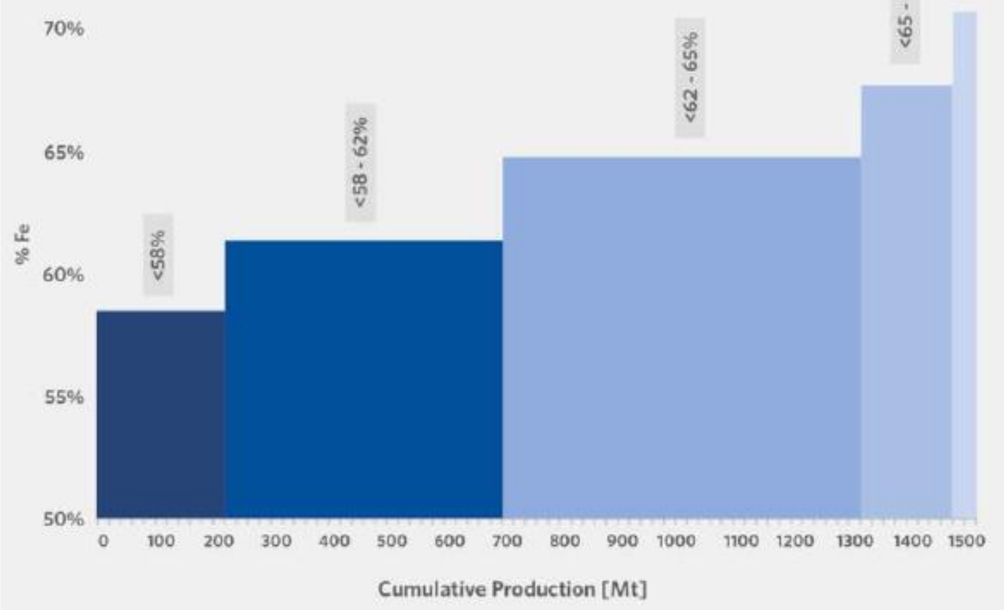
Delta 370TW/y

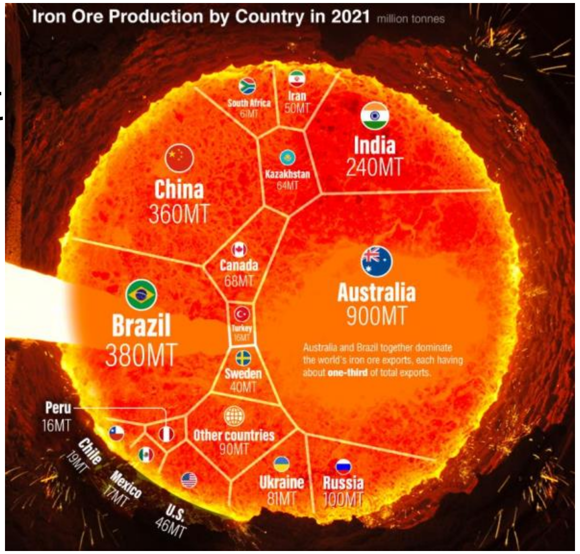
- RH IEA Table doesn't agree with others (11%-19% DRI? Only 8% H_2DRI; 30% to 52% BF/BOF

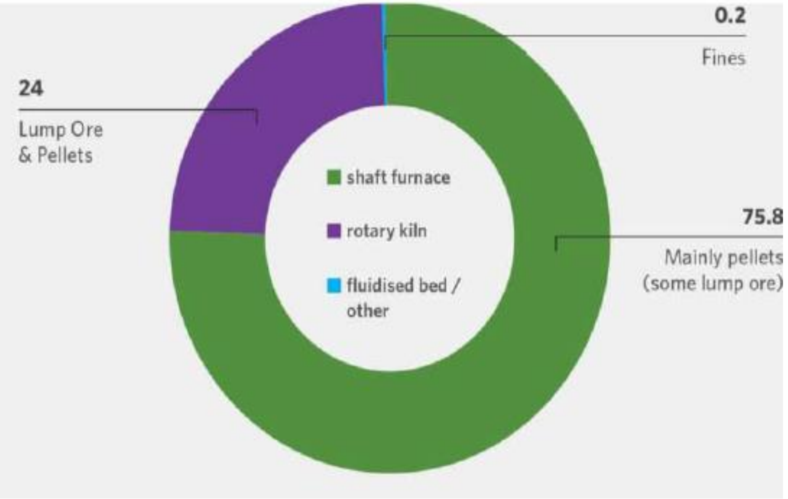
Traded Ore Type & Usage

- ➢ Producers: Australia, Brazil China
- ➢ 1.5BTe ore 2017, 168MTe DRI & deteriorating quality (Poveromo):
  - ❖ Sinter feed ores 63.9%Fe 1998 → 61.9%Fe 2019; increasing (SiO_2+Al_2O_3) 5.11% → 7.08% & P 0.048% → 0.067% respectively
  - ❖ Seaborne Fe pellet, concentrates & DRI quality pellet remained constant masking beneficiation need
- ❖ IIMA sees a significant DR shortfall
  - ❖ Announced DRI projects will use current available tonnage by 2030
    - ❖ Supply for own markets (Ukraine/Russia)
    - ❖ Low availability of suitable lump ore inc.
      - ❖ Baffinland Iron Mines (N Canada) IF expansion approved
      - ❖ Kumba's Sishin main trade
  - ❖ Some ores difficult & costly to upgrade Pilbara (W. Australia)

Source: CRU data 2017 – Seaborne Fe ore product by grade







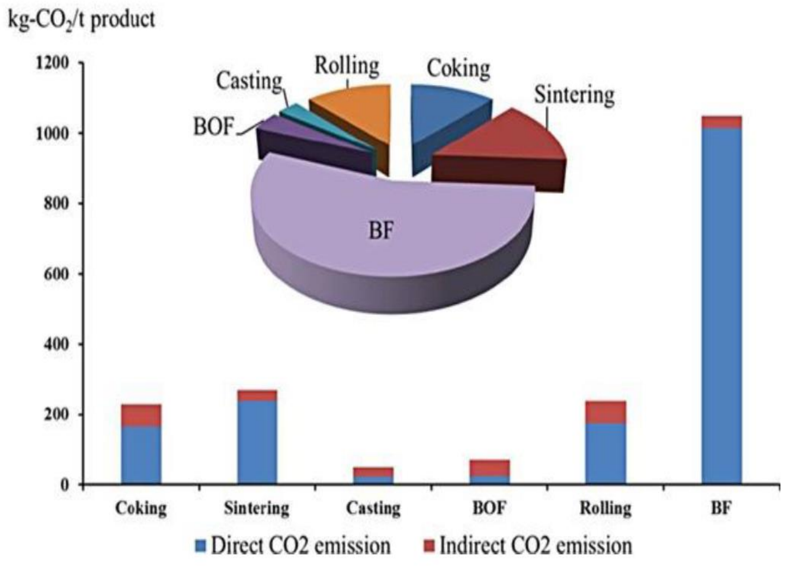
Source: DFM 6/22 Chris Barrington IIMA

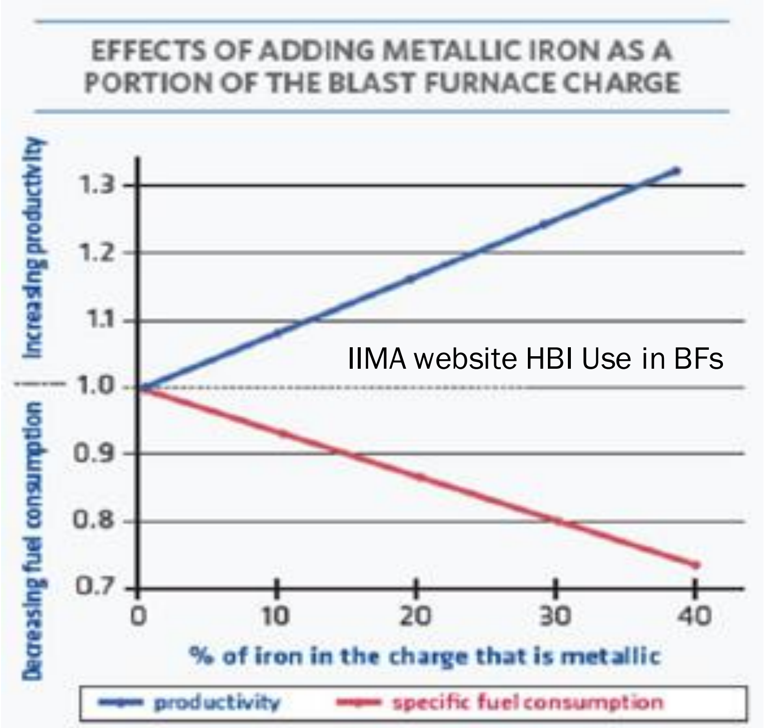
Ore Projects – Current, Failed & New Mines (IIMA & Direct From Midrex 6/22)

- South America:
  - Samarco increasing Te/y
  - Anglo American's Minas Rio (Br) – Bahrain Steel
  - CMP Chile high grade magnetite pellets
- Canada:
  - Champion Iron (PQ) expanding ore production & DR quality
  - IOC & AM Canada both increasing DRI pellets – AM 100% Port Cartier upgrade (10MTe)
  - New Millenium Iron's LabMag & KeMag (E Canada);
- USA - Mesabi Metallics (Nashwauk, MN)
- CIS countries have already upgraded beneficiation plants – only domestic consumption?
  - Ferrexpo likely to export to EU
  - Black Iron's Shymanivske (Ukraine) - 4MTe, increasing to 8MTe 68%Fe -
- Sweden & Norway:
  - LKAB converting from pellet producer to HBI supplier – 6 DRPs, 3 each at Malmberget & Kiruna for Lulea & Raahe (-7MTe progressively
  - Kaunis Iron (Sweden 2MTe) expanding concentrate
  - Tacora Resources (Norway)
  - Nordic Iron Ore, Beowulf Mining (Sweden)
- Mauritania - MOU for JV between Emirates Steel & SNIM Mauritania ore supplier
- Pellet plants next to DRP: Tosyali Algerie & SULB/Bahrain Steel & Tata (Ijmuiden - existing pellet plant)
- Australia's magnetite projects – Grange Resources' Southdown, Hawsons Iron, Magnetite Mines

BF Opportunities

- BF coke dependence → high direct CO_2 emissions
  - Minimum coke for structure & shaft permeability – replacement)
  - Chemistry dictates CO_2 evolution when converting FeO to Fe
- Kobe Steel - world's lowest coke rate (239kg/Te_{HM} 4/21)
  - Using 20% lump/80% self-fluxing dolomite pellets & increasing PCI to 220kg/Te; maintained slag rate 257kg/Te
  - Previous record held by Tata Steel Ijmuiden (261kg/Te_{HM})
- Charging metallics to BF - increase productivity, reduce fuels & C footprint (CO_2/Te_{HM})
  - Typically used scrap but challenged by:
    - Sizing needs (feed system) - sticking & hang-ups
    - Residuals' levels &
    - Oil/volatiles (waste recycling to the sinter plant!)
  - HBI avoids these

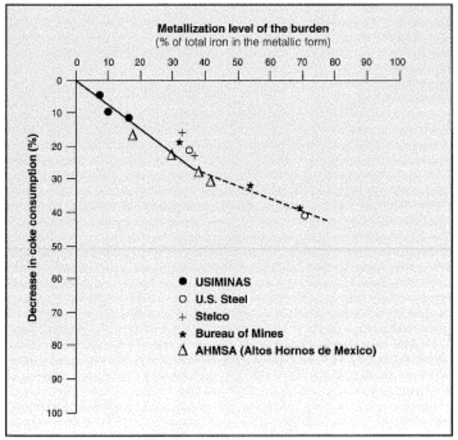


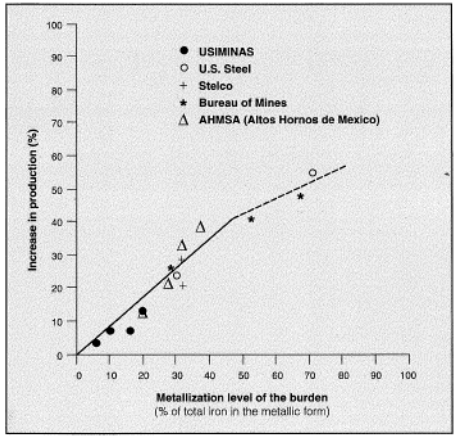


IIMA website HBI Use in BFs

HBI in BFs

- ➢ BF turn-down ration isn't good; Metallic charging is used as a "turn-up ratio" &
- ➢ HBI (pre-reduced Fe), requires melting (v. little reduction) & avoids scrap issues;
  - ❖ Reductants (energy needs) are greatly reduced
  - ❖ Tonnage increased – promoting flexibility for multi-BF shops (relines, shuts, market changes, low Opex)
    - ▪ Te_{HM}/h increase almost in proportion to metallic burden fraction
  - ❖ Cheaper option (usually) than buying external slabs/billets or losing market
- ➢ Early '60's, US Bureau of Mines (USBOM) successfully tested in Bruceton, PA BF
  - ❖ $\leq$70% HBI used in small and large diam. BFs!
  - ❖ USS successful tests led to HBI plant in Venezuela; other BF shops followed HBI use:
    - ▪ Stelco ONT; Yawata Steel & Kawasaki Steel; AHMSA MX; Burnpur, India; USSR; Romania; Czech.
    - ▪ Armco Middletown used 500net t/d (DFM 3Q '92)
- ➢ Early results from USBOM et al
  - ❖ Generally, per 10% metallization:
    - ▪ +7% to 8% productivity; -7% coke rate
    - ▪ 300kg HBI/Te_{HM} is maximum due to shifting of thermal equilibrium → low TG T°C



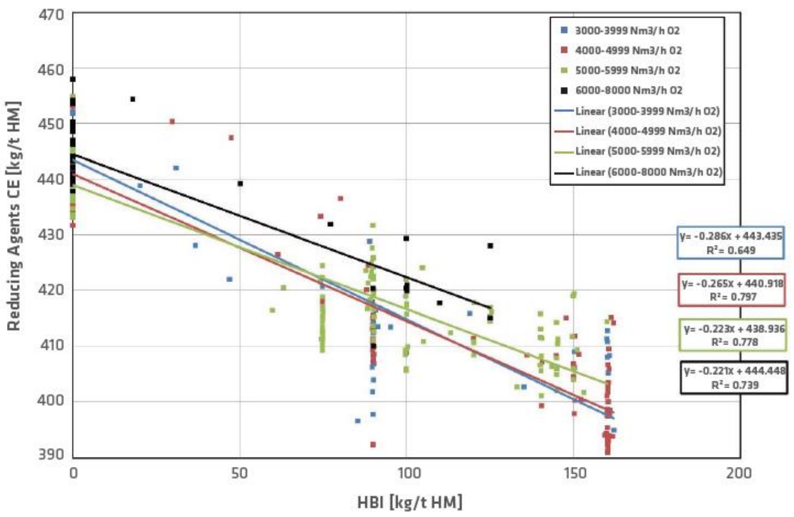


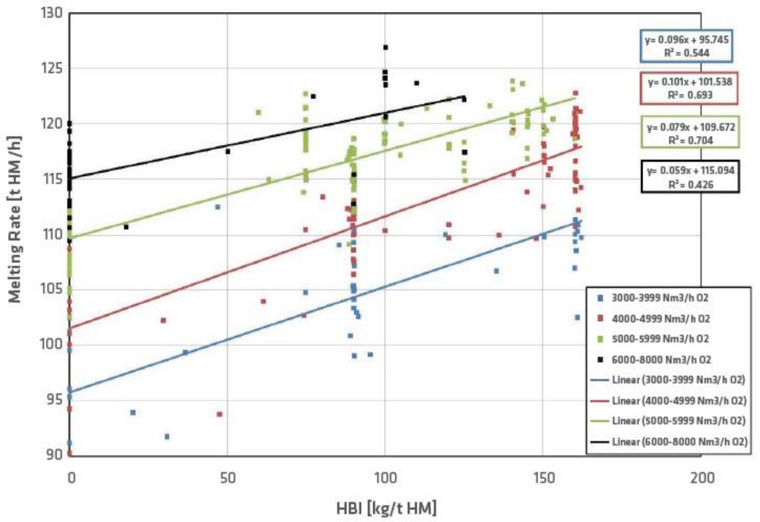
Results of BF HBI Use

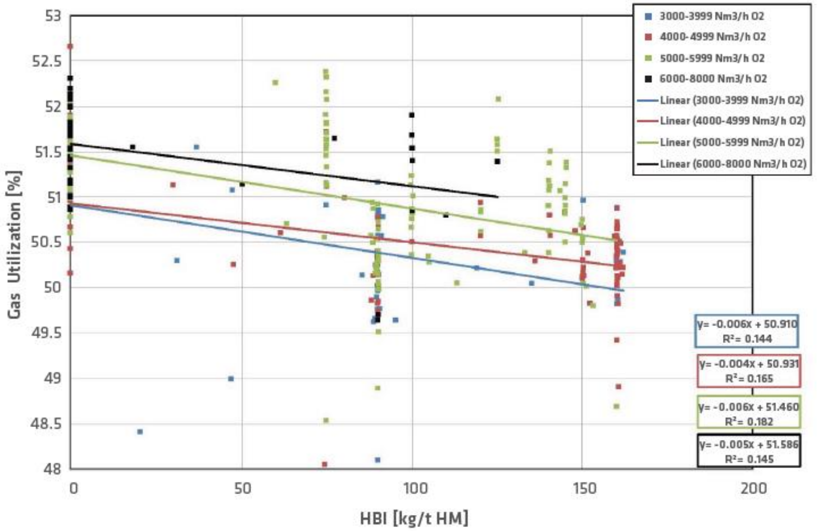
- 1993 AK Steel & Weirton Steel used 385kTe HBI (29% imports – 495kTe ‘94) in 3BFs
  - 150#/t_{HM} (75kg/Te)
- AK used continuously since 1980s (AK Steel, Iron & Steelmaker 7/94 & Impact of HBI Use in Integrated Steel Plants – DFM 17/09/2022
  - 30% HBI + scrap
  - Decreased fuel to 440kg/Te_{HM}
  - Productivity increased to 4Te/d/m3 working volume
- VAI Linz tested VAI TX HBI – 75 to 160kg HBI/$Te_{HM;}$ reported 100kg HBI/Te_{HM} (DFM 3Q 2020)
  - -25kg/Te_{HM} ECR/reducing agents (21.9 to 27.5kg & 40kg with 150kg/Te_{HM}) of that
    - (coke 10.9-18.1kg/Te_{HM} & PCI had to be adjusted for <coke)
  - <S with >C
    - 0.5% to 0.7%S coke so <coke (reductant), so <S in system & <S_{HM} (S α slag rate, recycled material, melt rate (faster rate, <time on coke, <S, $C_{\%S}$ (PCI)) & as S blocks HM carburization, <S_{HM} = >C_{HM}
  - +10% productivity (7.3-10.1%);
  - -0.75% less gas use (0.4% to 1.1%)
  - +1.5% TG calorific value (17.4kWh/Nm^3) & >CO/H_2 available as <reduction; higher CO
- No significant impact on TG T°C; negative influence on BF operation (permeability, cooling capacity, gas flow on walls)

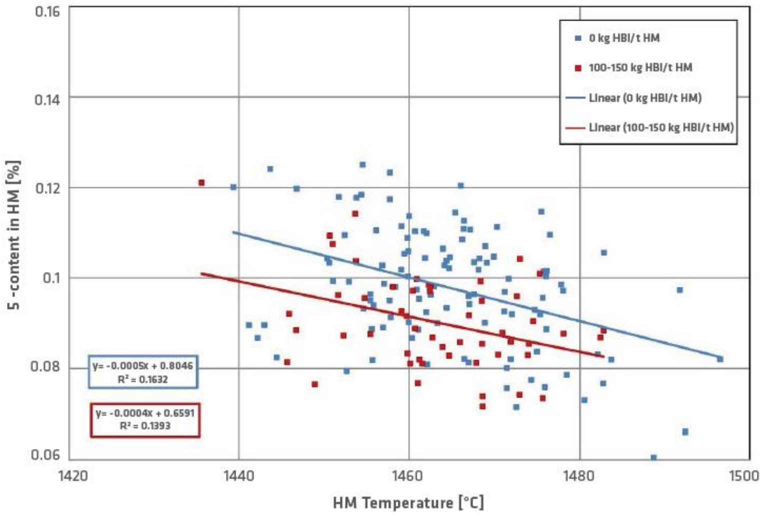
Results of BF HBI Use

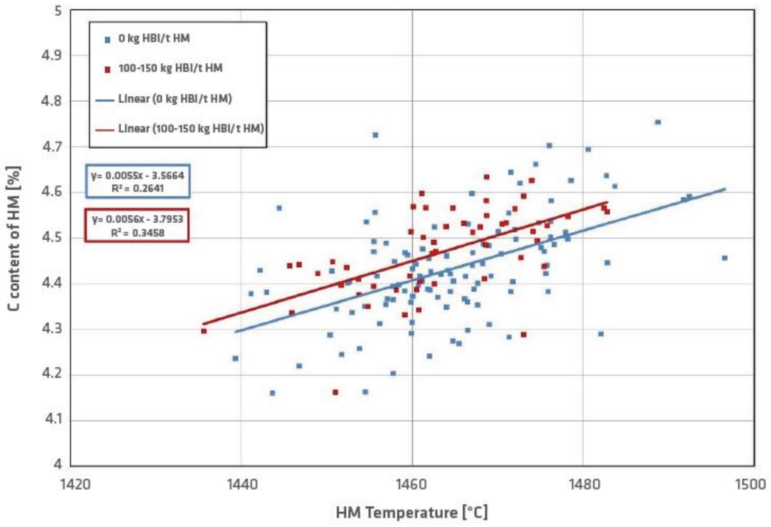
- VAI results for the extreme range of HBI volumes used
  - Reducing agents
  - O_2 flow rate(3k – 8kNm^3/h)
  - Melt rate
  - Gas use
  - $\%S_{HM}$ & $\%C_{HM}$





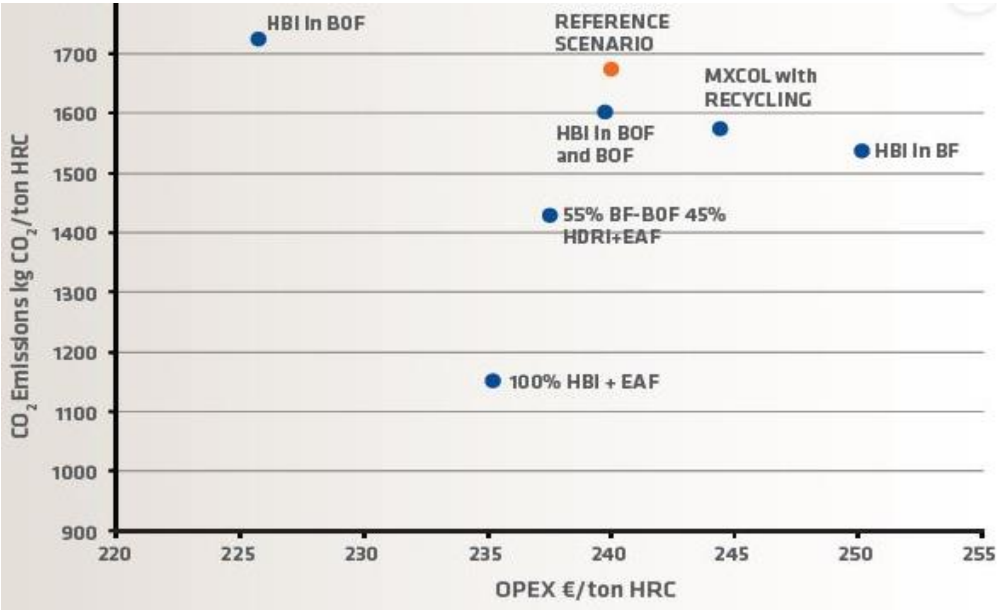






HBI in BF

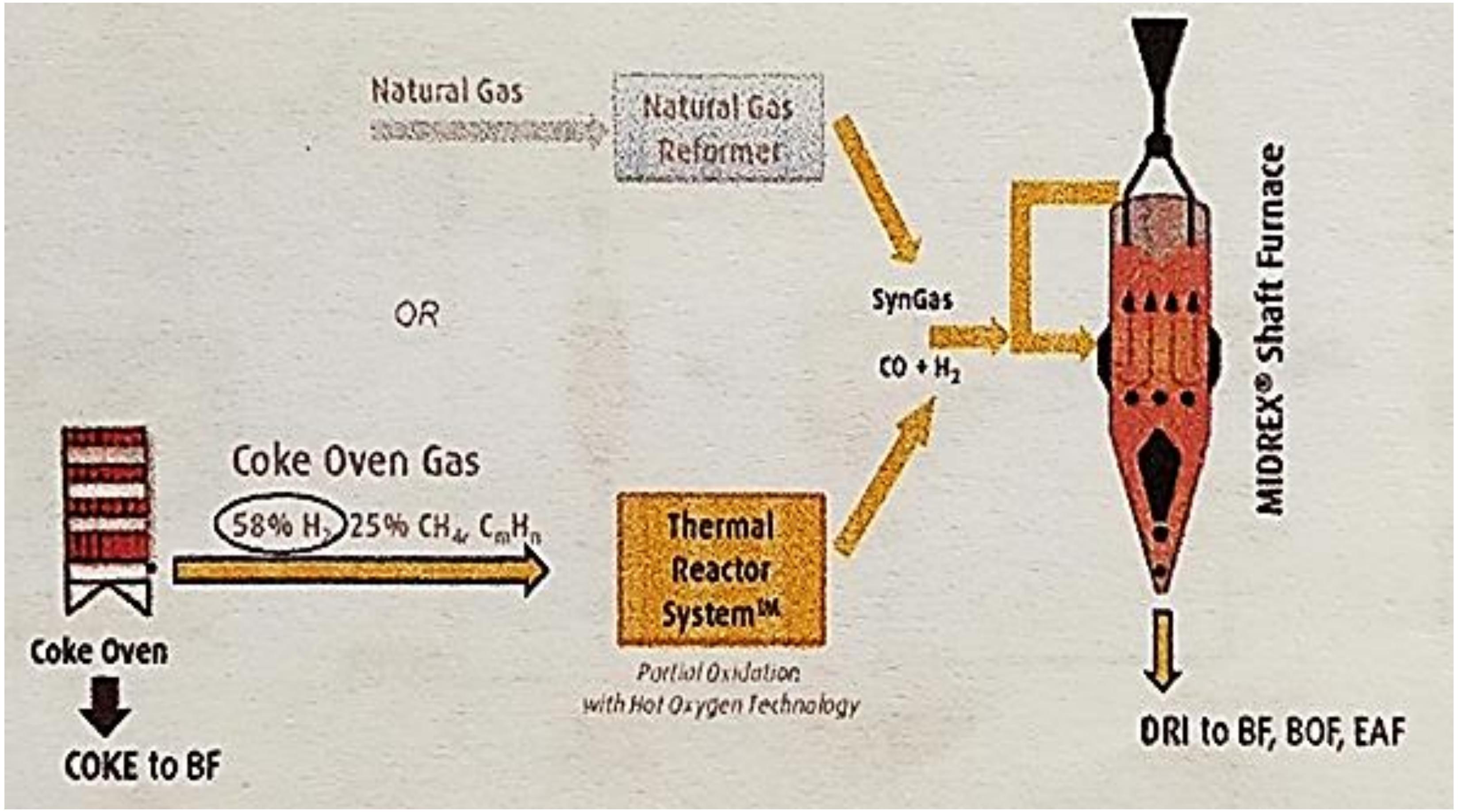
- DFM 2Q 1994 conversion costs
  - **Additional profit** = \$15,000/d; \$5.475M/y
    - \$34,050/d **or \$12.428M today**
  - 400#/t_{HM} (200kg/Te_{HM}) HBI used
  - Productivity +22.28% HM; +22.37% slab
  - Shipped +725t/d (659Te/d)
- Opex & CO_2 emissions/Te_{HRC}
  - +\$14, -12% (Impact of HBI Use in Integrated Steel Mills – MTI & Paul Wurth, Technical Article 6 2017



	Unit Cost \$/NT	Burden without Prereduced Metallics #/NTHM	Cost	Burden with Prereduced Metallics #/NTHM	Cost
Coke	100	960	\$48.00	830	\$41.50
Sinter	30	1100	16.50	1100	16.50
BOF Pit Scrap	50	50	1.25	50	1.25
HBI	120	0	0	400	24.00
Pellets	35	1980	34.65	1410	24.68
MATERIAL COST/NTHM			\$100.40		\$107.93
HM Production – NT/Day		3500		4280	
Slab Production – NT/Day (at 77% HM and 89% Slab Yield)		4045		4950	
Ship NT/Day (80% Yield)		3235		3960	
Added Tons Shipped/Day				725	
Added Daily Gross Sales at 350 \$/NT Selling Price				\$253,750	
Less Added Costs – HM 7.5 x 4280 ≈ 32,100 – Conversion Cost for 725 NT x 285 \$/NT ≈ 206,625				\$238,725	
ADDED DAILY PROFIT				\$≈15,000	

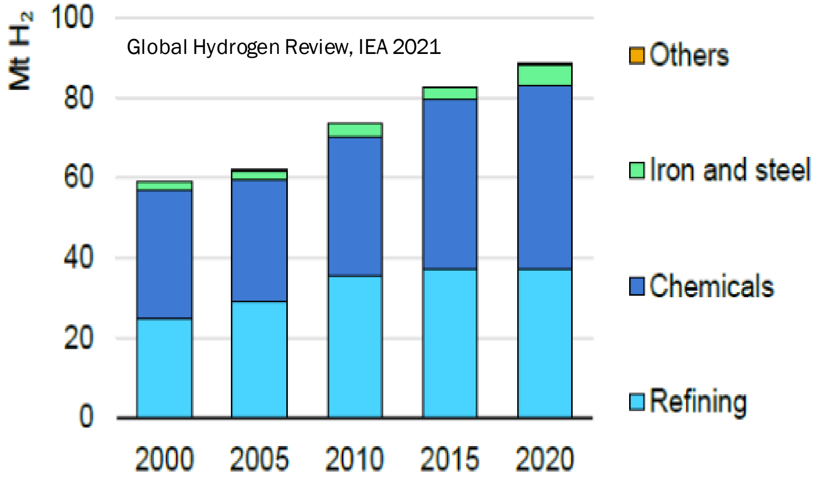
Coke Oven Gas (COG) for DRI Reduction

- Developed by Linde & Midrex
  - 1Te coke → 500Nm^3 COG → 1Te DRI;
  - ~30% more Fe units with same C footprint
  - ~0.3TeCO_2/Te steel reduction (-15%) for an IM
- NG & COG fueling of DRP optimizes & maximizes DRP/BF synergies
  - Using COG & other plant gases lowers Opex & CO_2
  - 20GJ COG/Te$_{DRI}$ – any more energy the system would be a Midrex MXCOL DRP



Other Brownfield BF Opportunities

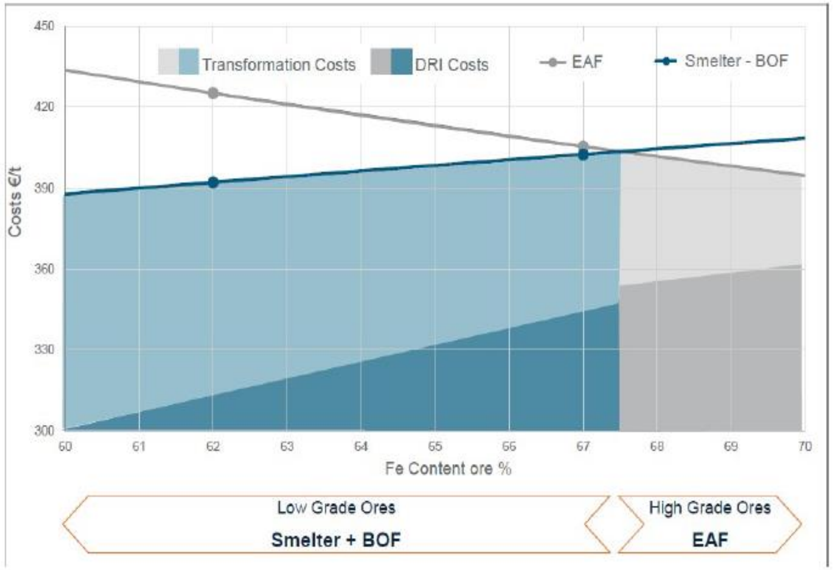
- Partial replacement of process gas & C with H_2 in BFs & DRPs (when available)
- Cleveland Cliffs using **NG (4"H"s!)** predicts 25%CO_2 reduction by 2030
  - **HBI use in BF; Pellets** (**-85% CO_2** vs sinter); 115kg/Te_{HM} **NG tuyere injection** (-9% CO_2 vs coke alone); 750kt coke battery closed
  - **Scope 1, 2, 3 = 1.63TeCO_2/Te_{steel}** (<FR 1.8TeCO_2/Te_{steel}, assuming 50% PI @1.1TeCO_2/Te_{steel}
    - FR only use 25% PI (50% prime, 25% obsolete) so about same Scopes
  - HBI in the BOF/EAF reduces CO_2 70% versus importing PI or DRI/HBI
- Hatch predicts PCI with 35kg of **900ºC H_2/T_{HM} tuyere injection** will produce
  - -20%CO_2, +1.8GJ (+35%) energy to steelworks; -100kg coke/T_{HM} for a **+\$45-\$110/T_{HM}**
  - Top gas recycle (TGR) & CCUS = 80% less CO_2 for ~0.4TeCO_2/T_{ls} (almost the same as expected from H_2 DRI EAF steelmaking!)
  - Blue or green H_2
- High H_2 injection compromises BF thermal characteristics
  - Can this be overcome? What is the sustainable maximum?
    - Credible sources quote 14 to 32kgH_2/Te_{HM} will reduce CO_2 by 8% to 30%
  - ULCOS top gas recycling trials in 2007 saw
    - 24% CO_2 reduction &
    - 120kg/Te_{HM} reduction in (PCI+Coke)



SAFs & OSBFs

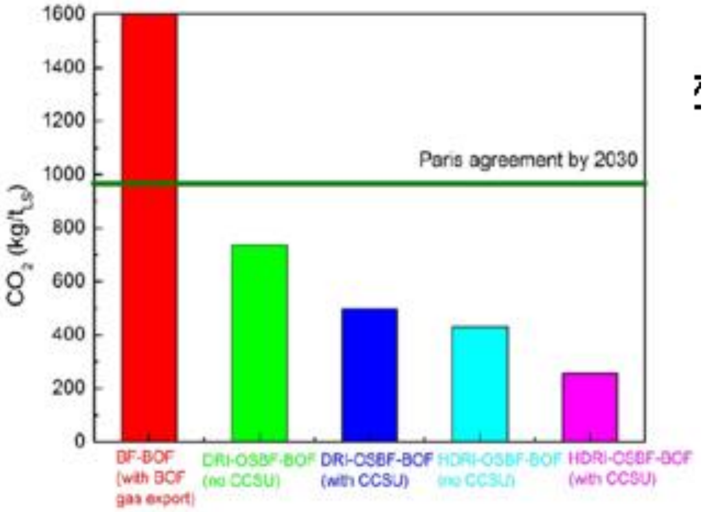
- Smelters can process a wide range of low-grade input materials including recycled materials but:
  - >67.5% Fe cheaper to process through DRI/EAF
- High power requirement for DRI:
  - 800 to 900 kWh/Te_{HM}, 400kg $slag/Te_{HM}$ SL/RN process 80% met.*
  - 780kWh & 190kg $slag/Te_{HM}$ projected for Pilbara ore 80% met.*

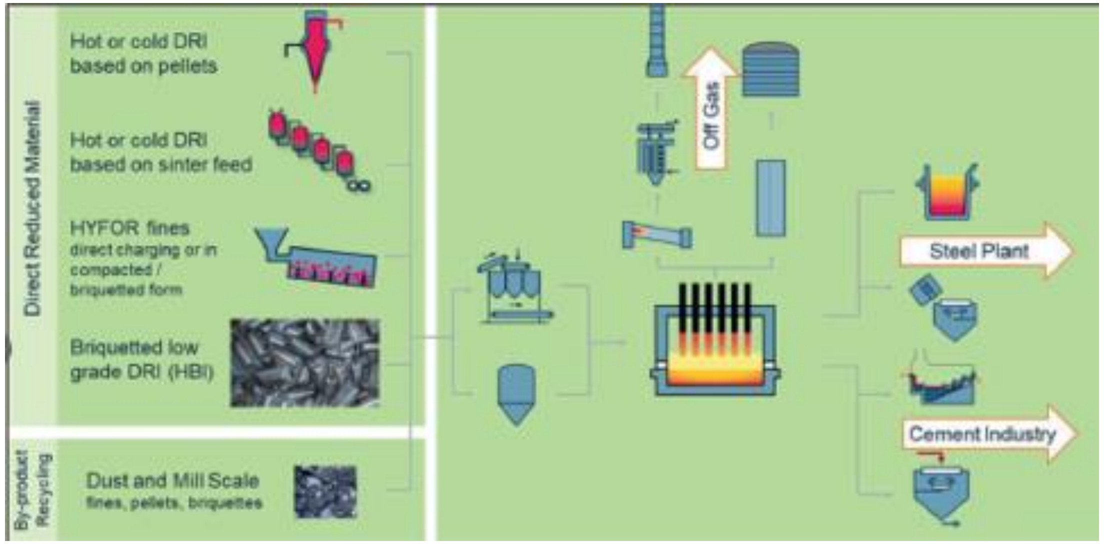
* Honeyhands – CIMR, Newcastle U



Wimmer – Two steps towards net zero carbon, STI 4/22 & AISTech 2022

- CO_2 emission significantly reduced:
  - DRI-OSBF-BOF
    - No CCSU–700 kg/tls
    - With CCSU – 500 kg/tls
  - HDRI- OSBF-BOF
    - No CCSU – 400 kg/tls
    - With CCSU – 250 kg/tls





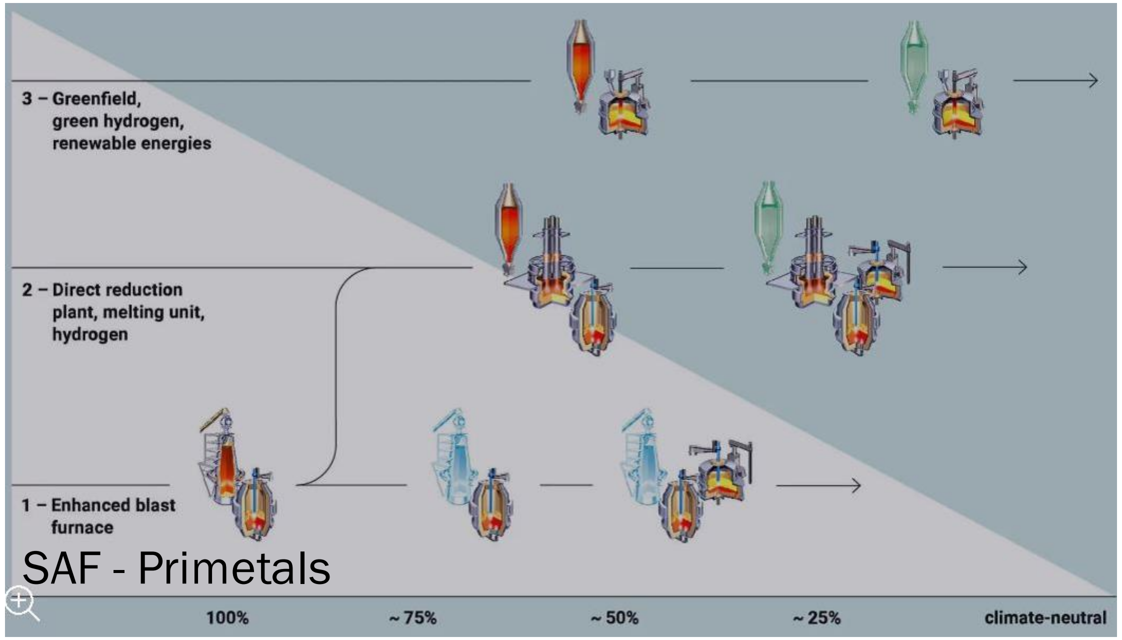
- NOTE: HDRI is H_2 DRI not Hot DRI

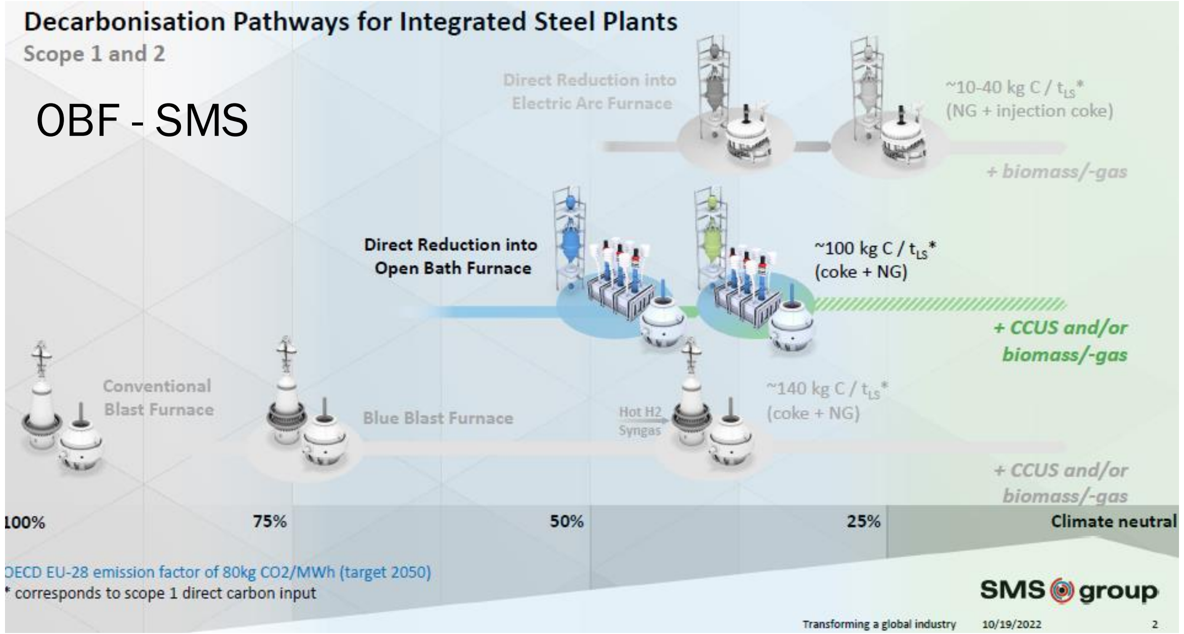
Cavaliere. P et al., JoM #2, P203 2022.

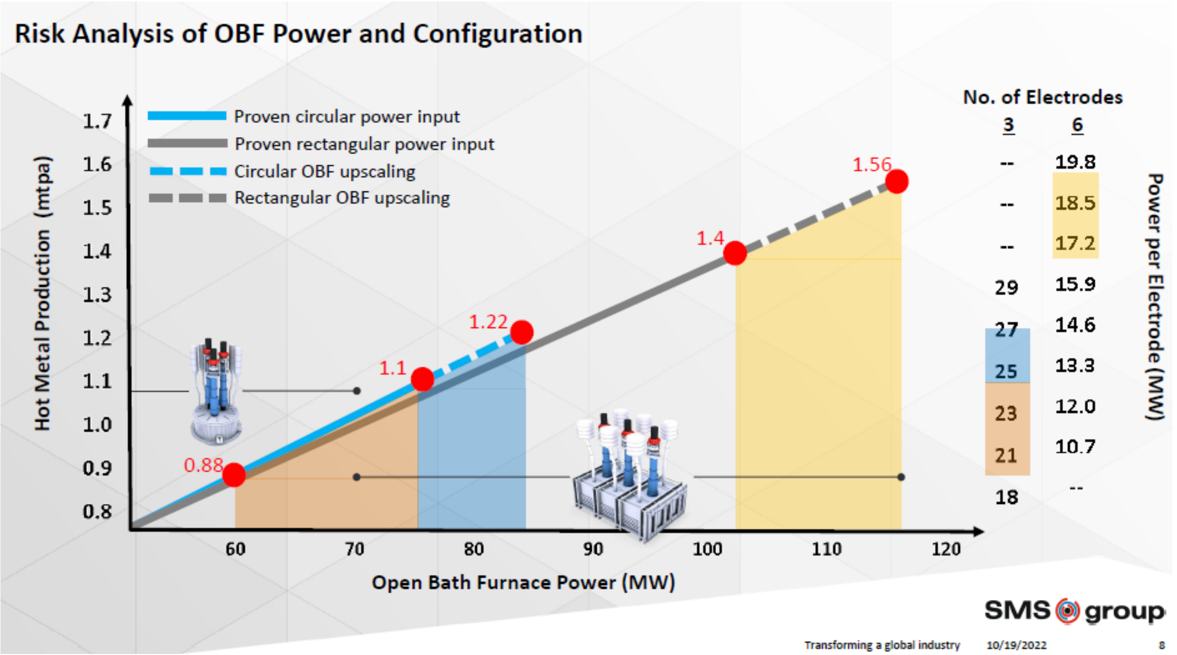
Intermediate "Melters" for Low-Grade Iron Ore or HBI

- Inmetco, RedSmelt, Iron Dynamics Fastmet, Sidcomer – to name a few
- USA's infamous steel SAF, SDI's IDI operation – modified from various industries
  - Allows SDI to circumvent scrap price volatility & prime availability - penetrate auto & OEM markets
  - **500kTe liquid iron/y** smelted in an SAF (using coal based DRI reduced in a NG fired RHF)
    - **Typical ore – 66%Fe**, 4.9%SiO_2, 0.33%Al_2O_3, 0.015%P, 3%H_2O; 85% sized 0.01.mm to 1.00mm
      - Magnetic beneficiation to reduce SiO_2
      - System off gases (OGs) preheat combustion air & heat ore, coal & pellets (charged to RHF at 150^oC)
    - **DRI chemistry – 15%FeO**, 70% metallic Fe, 1%Al_2O_3, 5%SiO_2, 5%C, 0.2%S, 85% metallization @ 1000^oC put in charge bottles with flux, coke, SiO_2 or other materials to charge to EAF
    - **HM chemistry – 95.8%Fe**, 3.2%C, 0.025%S, 0.5%Si @ 1500^oC
  - 400 to 500kWh/Te_{HM}
    - Refractory lined, non-tilting, vessel with 3 electrodes (1400mm, 16MVa each), 3 tap-holes - 2 iron & 1 slag.
    - Iron is desulfurized prior to EAFs
  - 1999 $100M Capex and full cost of $150/$Te_{(HM)}$ at capacity ($178M & $267/$Te_{HM}$ in 2022)
  - Achieved significant reduction in energy, POT, injected C & residuals
  - Issues: Refractory wear led to higher costs; infrequently operated

Impact on CO_2 & Scaling







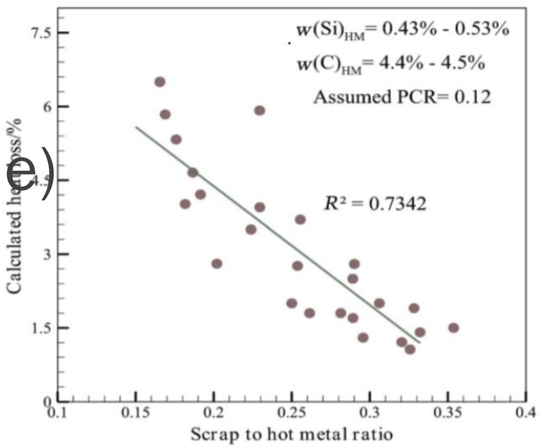
- ➢ Both positively impact C footprint
- ➢ Potential scaling issues
  - ➢ OSBF rectangular - higher productivity
    - ▪ 1.4MTe/y, 6 electrodes @ 17.2MW ea.
      - • Maybe 1.56MTe/y @ 117MW
    - ▪ Productivity & power affected by
      - • DRI/HBI temp; $\%C_{DRI\ \&\ HM}$; %revert added (mill scale, BOF sludge, $slags_{LF\ \&\ BOF}$; deS fines; dusts)

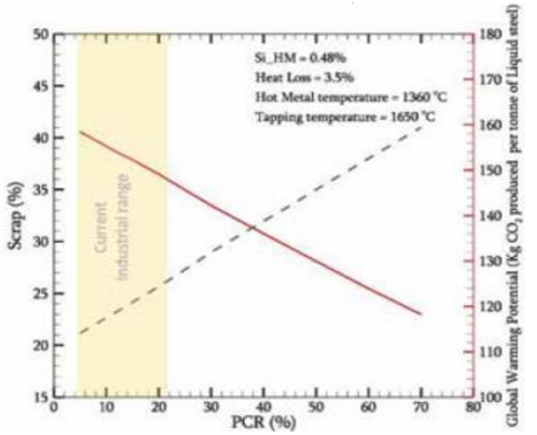
Brownfield BOF Opportunities

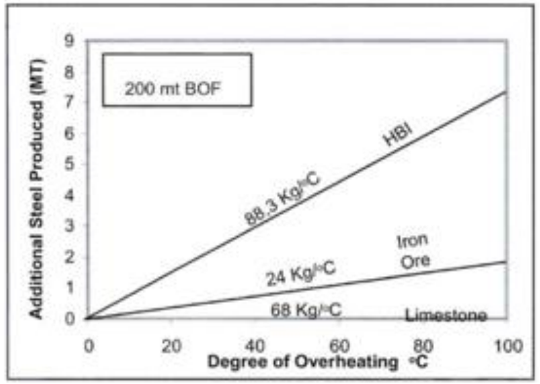
- BOF - high productivity, tolerates a wide range of inputs (EAF >versatile)
- Using **scrap as a coolant** – increases productivity, reduces CO_2
  - Current world ave. ~17%; USA 20% - 25%; 40%-45% tested in past
  - Cliffs & Brooks et al advocating higher use
    - Plant data derived program shows increasing scrap reduces heat loss
      - At a 35% scrap charge, heat loss is 0.9%; 10% scrap, heat loss is ~6.75%
    - Also showed increasing PCR from 10% to 30%
      - Increases scrap from 22% to 28% (dotted line, L axis)
      - Decreases GWP by 10% (red line, R axis)
      - Assumes PC heat can be transferred efficiently
- **HBI can replace scrap in BOF – 95kg/Te_{ls} (slopping)**
  - Higher cooling intensity & productivity vs scrap
  - Quality & density benefits
  - > predictable heat & mass balances

K. Pastucha et al, Steel quality improvement with HBI briquette use at new greenfield LD steelmaking plant Alchevsk Ukraine AIStech 09

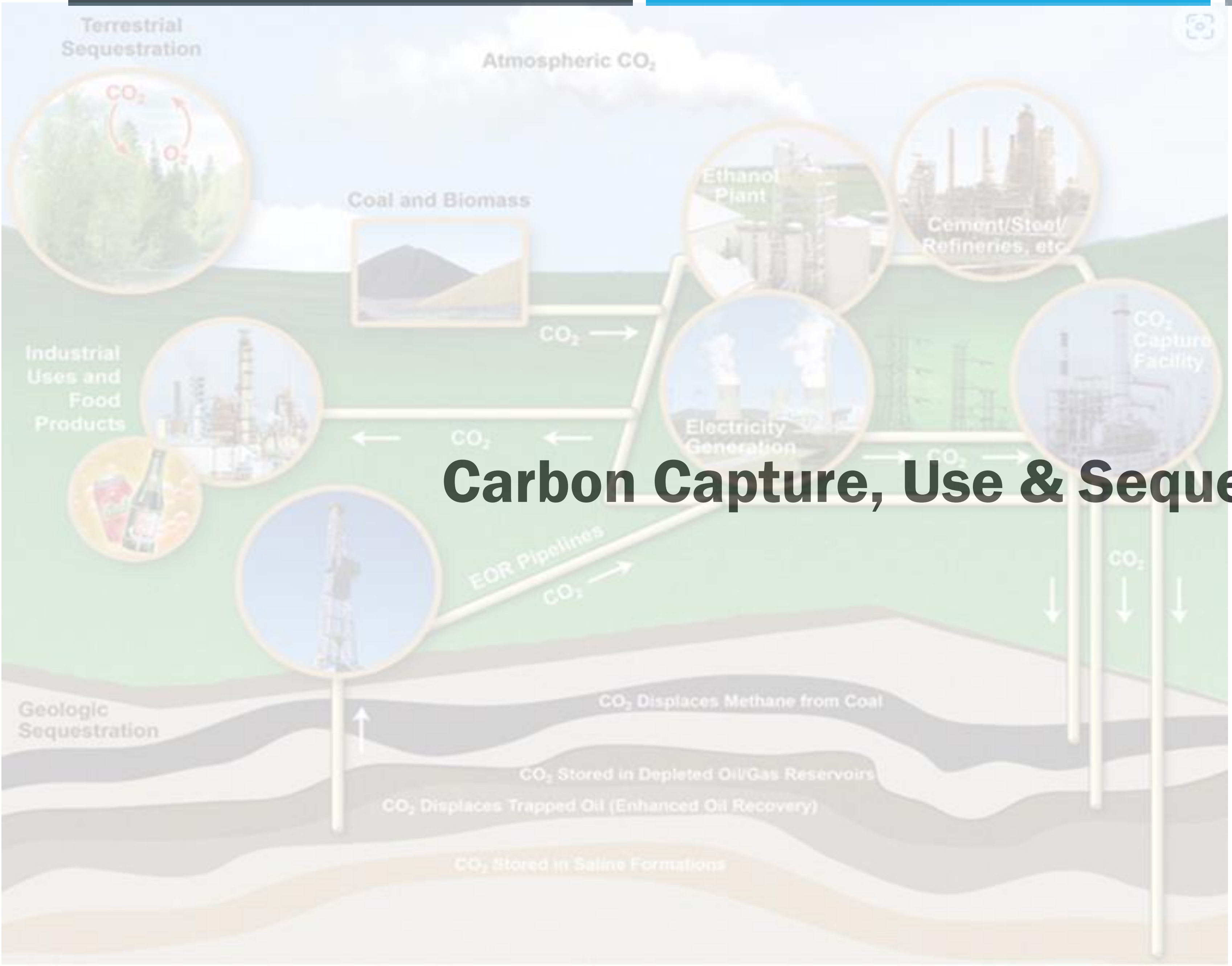
Material	Cooling Intensity versus scrap
Scrap	1.0
HBI	1.2
Iron ore	2.0 – 3.0
Limestone	3.0 - 4.0





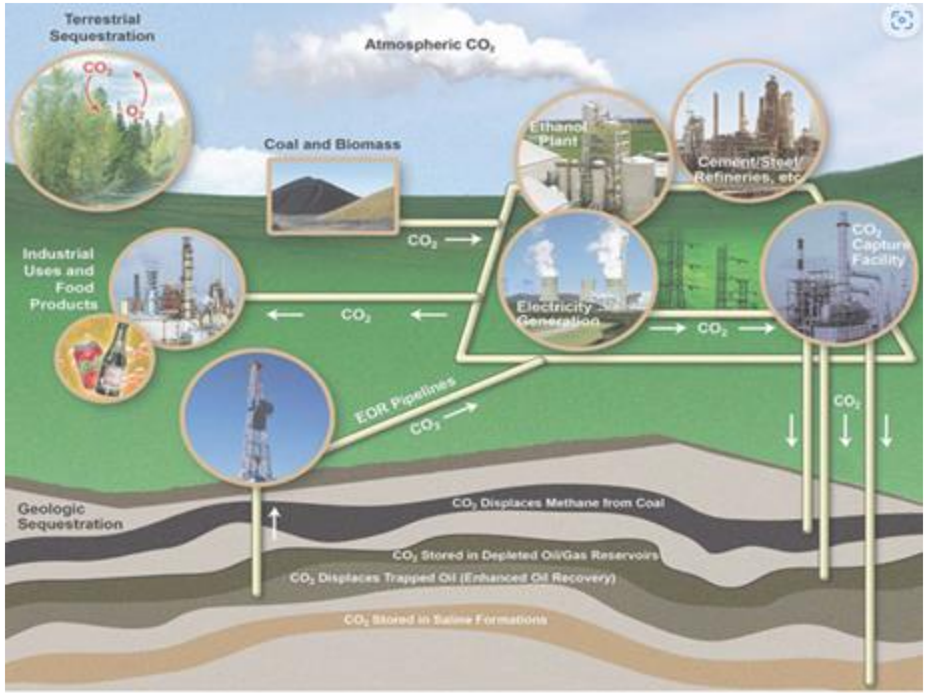


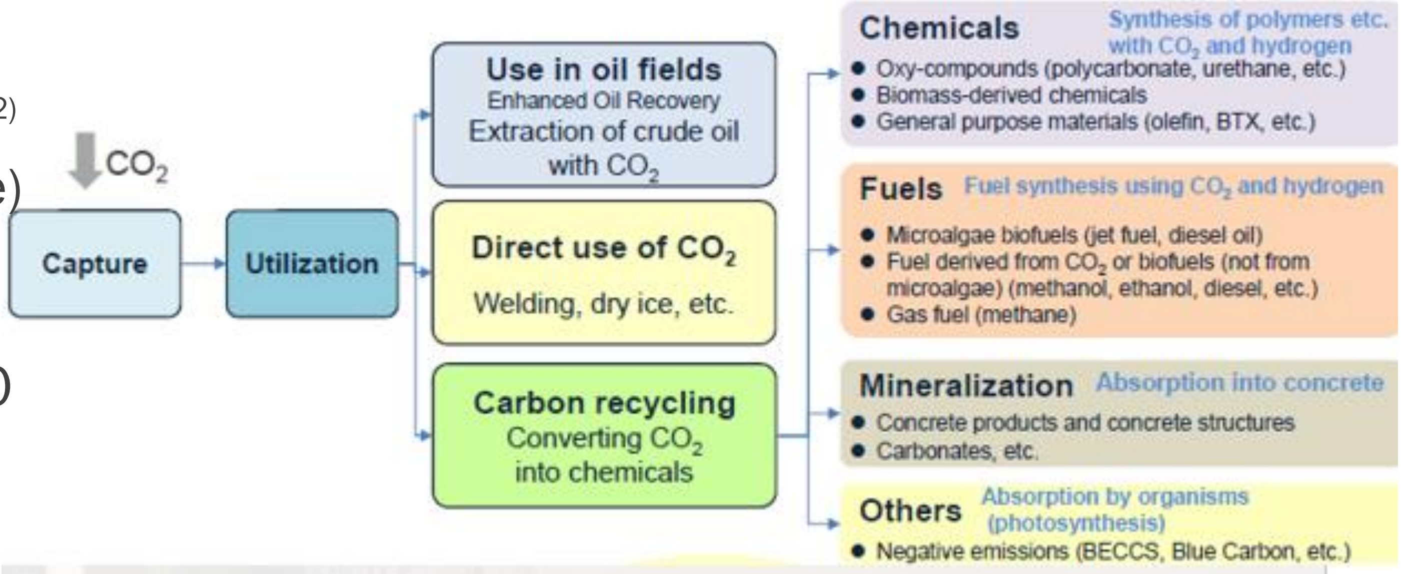
Carbon Capture, Use & Sequestration (CCUS)



CCUS Options

- Industry, transport, agriculture – hard to abate CO_2 (70%)
  - CCUS can address 54% of this; >economical than H_2 use
- Rejection of CCUS is some EU promoted CCUs
- Relatively high conversion cost for chemically stable CO_2 (Need volumes of C free H_2)
- Except for mineralization, storage is temporary
  - CO_2 released by combustion or decomposition
- Amount of chemicals & CO_2 fixation is limited
  - Capture and reuse in mills?
- Globally, 35 commercial facilities (IEA 2022)
  - 45MTeCO_2 capacity (0.12% global 36.3GTe)
    - Enhanced oil recovery CO_2 most profitable
    - CCU is cheaper for richer CO_2 sources
- >200 new CC facilities to operate by 2030 220MTeCO_2/y (0.6%)
  - Substantially under Net-Zero needs





Carbon Capture, Use & Sequestration (CCUS)

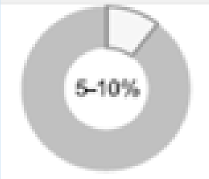
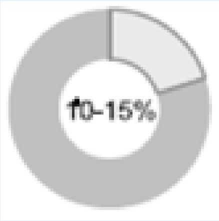
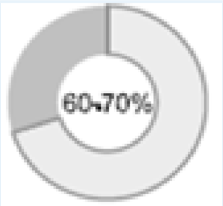
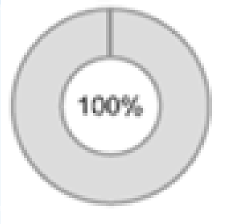
- Projects:
  - Lanzatech with AM Ghent will produce 65.4kTe Bio-Ethanol & remove 350kTe CO2/y
  - Carbon2Chem (TK) – NH_3 from steel mill gases
    - With RE will be C neutral (44%N_2, 23%CO, 21%CO_2, 10%H_2, 2%CH_4)
  - Carbon4Pr (AM + Dechema et al) – polyurethane foam & coatings
  - STEELANOL (AM Belgium + Lanzatech) – transforming BOF gas using bacterial fermentation
  - C^4U – EU project to use Ca as solid to separate CO_2 from BF, BOF, COG, elevate solid based capture technologies to TRL7 & design for optimal integration into IMs (https://c4u-project.eu/)
  - Columbus – CO_2 from innovative CaO kiln = green H_2 → synthetic fuels
    - CO_2 use technology also sourcing of CaO/dolo, H_2, O_2, e-CH_4. Energy integration/optimization

Summary

- No argument: RE & H_2 DRI EAF steelmaking should produce the greenest steel but
  - Unrealistic challenges & "build rates" (H_2, GE and DRPs) to meet climate goals
  - Exorbitant socio-economic conversion cost for 70.8% BF/BOF steel production
  - The steel industry challenged to garner H_2 supply vs richer industries
- Need more R&D activities to fully determine limits for green BF/BOF operations:
  - Lowest coke rate/replacement potentials?
  - Optimum NG & H_2 injection rates
  - HBI & scrap limits in BF & BOF
  - Maximizing PCR and heat transfer
  - Commercializing larger, cost efficient, productive
    - CCUS and
    - "Melters"

Potential Action to Reduce BF/BOF GHG Emissions (BF/BOF Roadmap)

ID Current GHG Emissions

Potential Decarbonization Pathways		Overall CO_2 Reduction Potential
1. Process Efficiency	Optimize BF input-pellets, scrap, HBI, PCI, H_2, NG, coke; stove O_2 enrichment	
	Top pressure recovery turbine for BF	
	Optimize the BOF charge mix	
2. Fuel Engineering	Replacement of in-plant fuels	
	COG/BFG/BOFG use	
	H_2 production from COG	
	Use of hot O_2 for blast	
	H_2 injection, PCI, NG injection	
3. Carbon Capture, Use & Storage	Capture top gases from BF, BOF, boilers, other sources	
	CO_2 to building materials, EOR, food, chemicals, greenhouses. H_2 back to the process	
	CO_2 to storage	
4. Green Steel	H_2 injection in the BF Hot O_2 injection	
	Fossil free steel, green H_2 based DRP + green kWh based EAF	

Renewable energy is imperative throughout

Implement Identified Projects & Renewable Energy for All Areas

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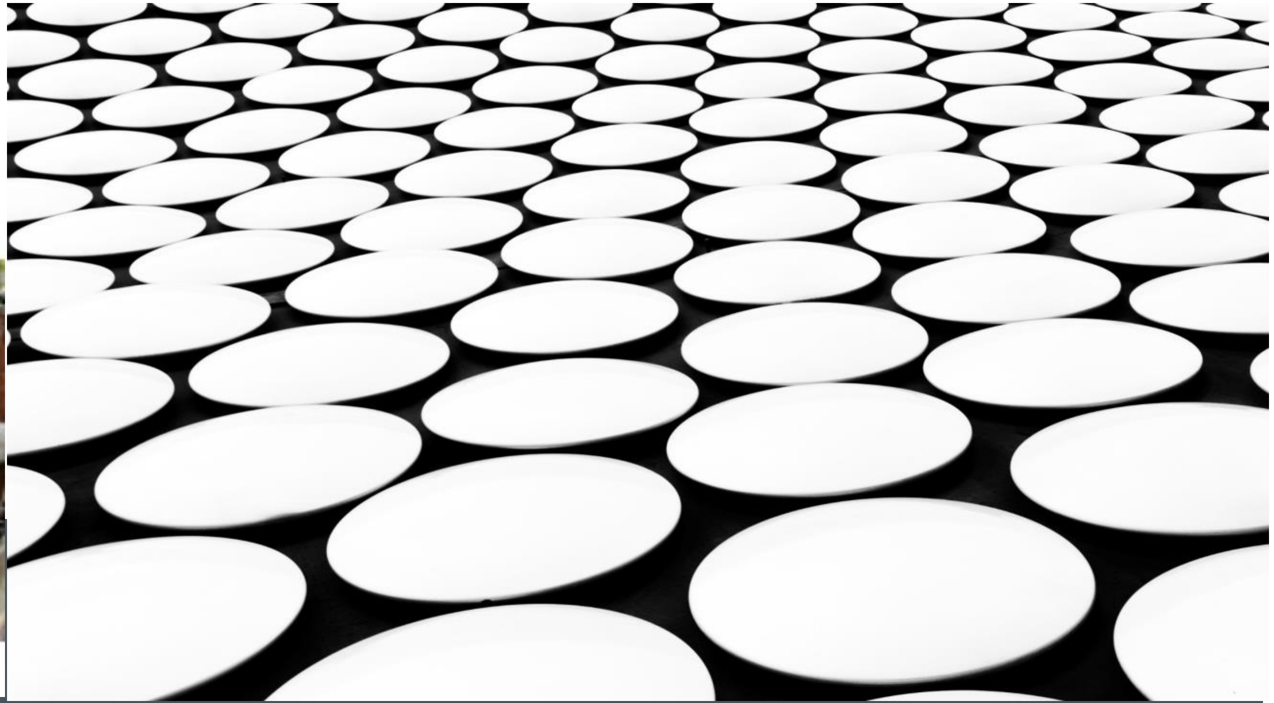
Australia and New Zealand Chapter



4th Australia & New Zealand Annual Steel Symposium

Thank you for your attention!

Questions?

Keynote for promised subject matter? drhornby62@gmail.com

Use of HBI in BFs

- *Additional References:*
  - *BF operations with pre-reduced burdens – J. of Metals 2/66*
  - *Recent developments in N. American Ironmaking – F. Rorick & J. Poveromo, 5th EU coke & ironmaking congress 2005*
  - *20papers at AIMEs1965 Ironmaking Conference, 7 dedicated to use of metallized burdens & metallized burden preparation with no commercial DRI available in USA!*
  - *Use of pre-reduced iron in the BF; Metallurgical, ecological & economical aspects, P. Schmöle, H. Lüngren, Stahl Und Eisen 2007, vol 4 P47-54*