Decarbonization of steel production: alternative Direct Reduced Iron and CCS

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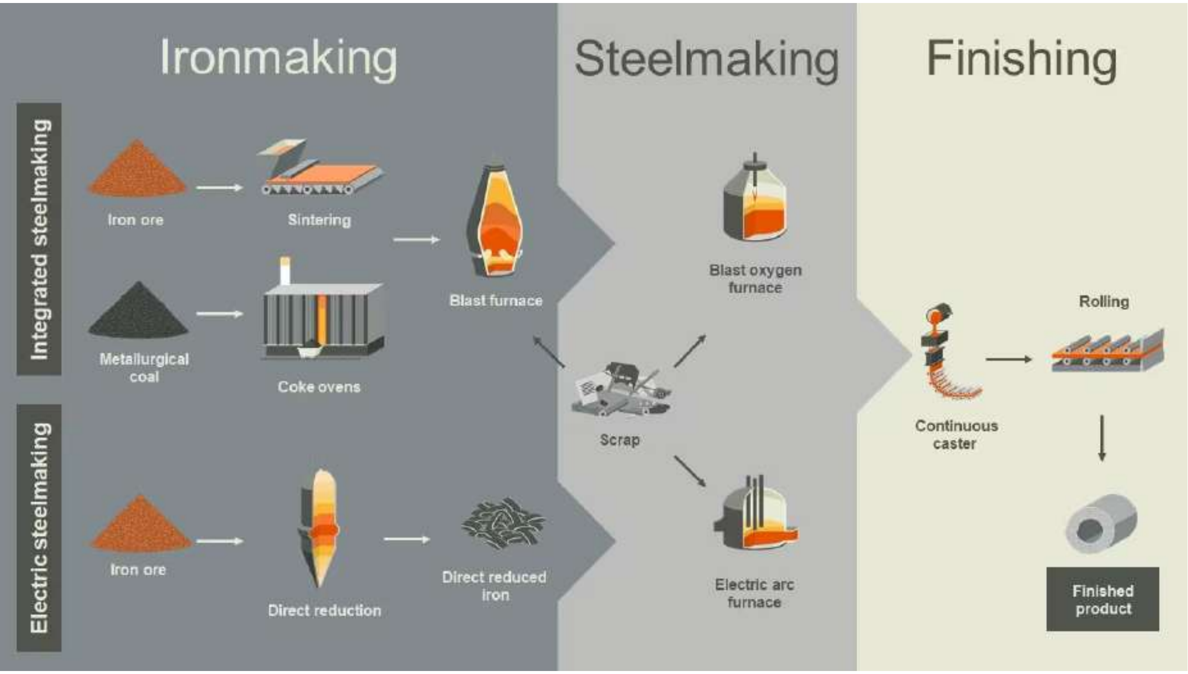
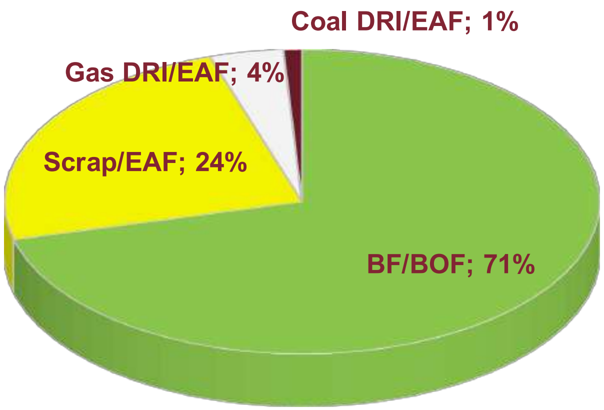
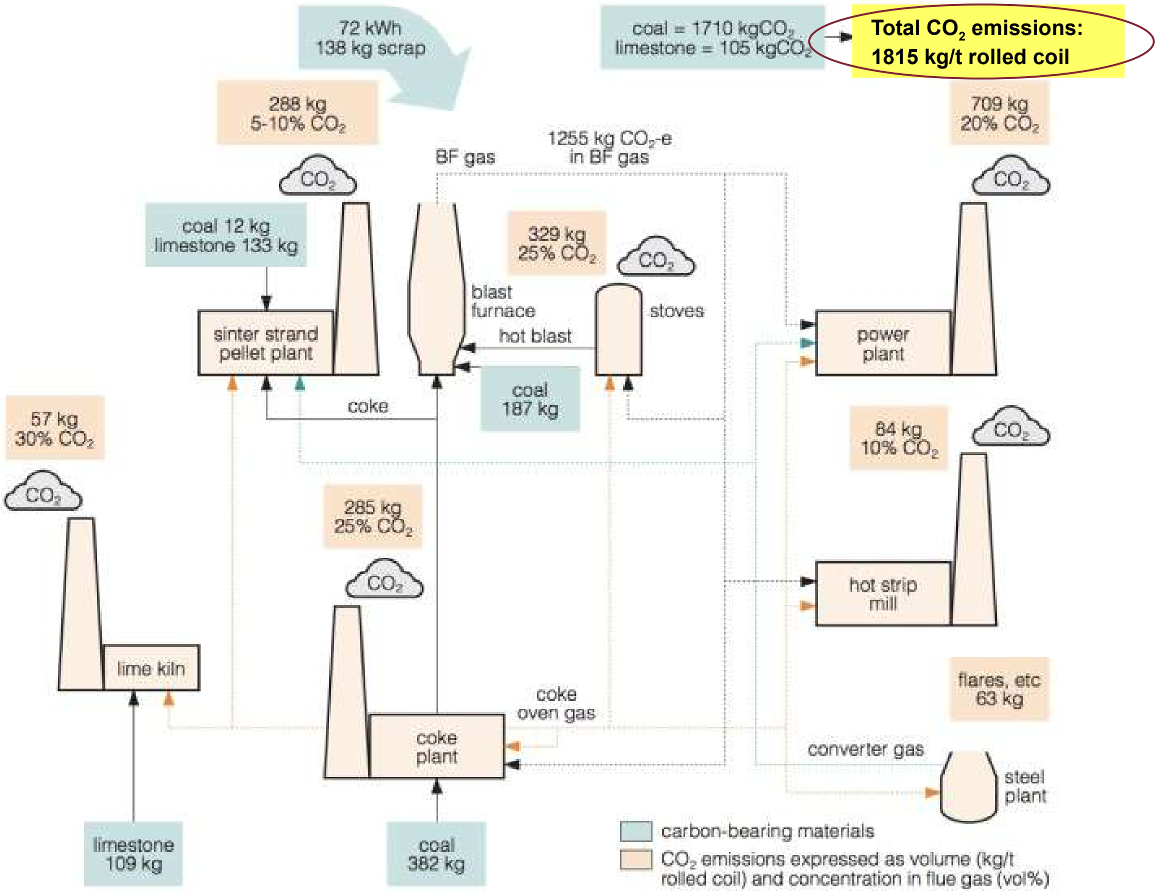
Steel production routes





- Laplace Conseil, "Impacts of energy market developments on the steel industry," 74th Sess. OECD Steel Comm., no. July, pp. 1–2, 2013

CO_2 emissions integral cycle BF/BOF



- Bui et al, ‘Carbon capture and storage (CCS): the way forward’, Energy Environ. Sci., 2018,11, 5, The Royal Society of Chemistry, 10.1039/C7EE02342A.

CO_2 emissions integral cycle BF/BOF

- Coking making:
  - Coke dry quenching: 27 $kgCO_2/t_{coke}$
  - COG Recovery: 6-9 GJ/t_{coke}
  - Biomass and waste materials: the amount of wood and waste plastics that can be added to the coking coal blend is currently limited to less than 2 wt.% due to detrimental effects on coke quality.

- Sintering:
  - Waste Heat recovery and Off-gas recirculation: 60 $kgCO_2/t_{sinter}$
  - Waste fuels: 19.5 $kgCO_2/t_{sinter}$
  - Biochar/Charcoal: Up to 20-30% can be used in the sintering bed.

- Cavaliere, P., & Cavaliere, P. (2019). *Clean ironmaking and steelmaking processes: Efficient technologies for greenhouse emissions abatement* (pp. 1-37). Springer International Publishing..

CO_2 emissions integral cycle BF/BOF

- Blast Furnace
  - Injection of:
    - COG: saving on coke
    - Oil: 50 $kgCO_2/t_{HM}$
    - Natural Gas: 55 $kgCO_2/t_{HM}$

    The furnace temperature limits the maximum injection rates. NG has a large effect on the flame temperature cooling with respect to other fuels, so, O_2 enrichment is required.
    - H_2: up to 40%
    - Plastic waste: The substitution of coke is limited to a maximum of around 40% since the injectants are unable to give the physical support for iron ore provided by coke.
    - Biomass

- Cavaliere, P., & Cavaliere, P. (2019). *Clean ironmaking and steelmaking processes: Efficient technologies for greenhouse emissions abatement* (pp. 1-37). Springer International Publishing..

CO_2 emissions integral cycle BF/BOF

- **Coke** cannot be completely eliminated in the BF operations; its minimum rate is in the order of <u>200 kg/t_{HM}</u>

- Cavaliere, P., & Cavaliere, P. (2019). *Clean ironmaking and steelmaking processes: Efficient technologies for greenhouse emissions abatement* (pp. 1-37). Springer International Publishing..

Alternative BF/BOF production

- HydroMetallurgy

- Smelting Reduction

- Direct Reduced Iron

- Hydrogen Smelting Reduction

Alternative BF/BOF production

- **HydroMetallurgy**
  Acid Leaching

iron dissolution:

$$Fe_2O_3(s) + 3H_2C_2O_4(aq) \rightarrow Fe_2(C_2O_4)_3(aq) + 3H_2O \quad (1)$$

photochemical reduction:

$$Fe_2(C_2O_4)_3(aq) + 4H_2O \rightarrow 2FeC_2O_4 \cdot 2H_2O(s) + 2CO_2(g) \quad (2)$$

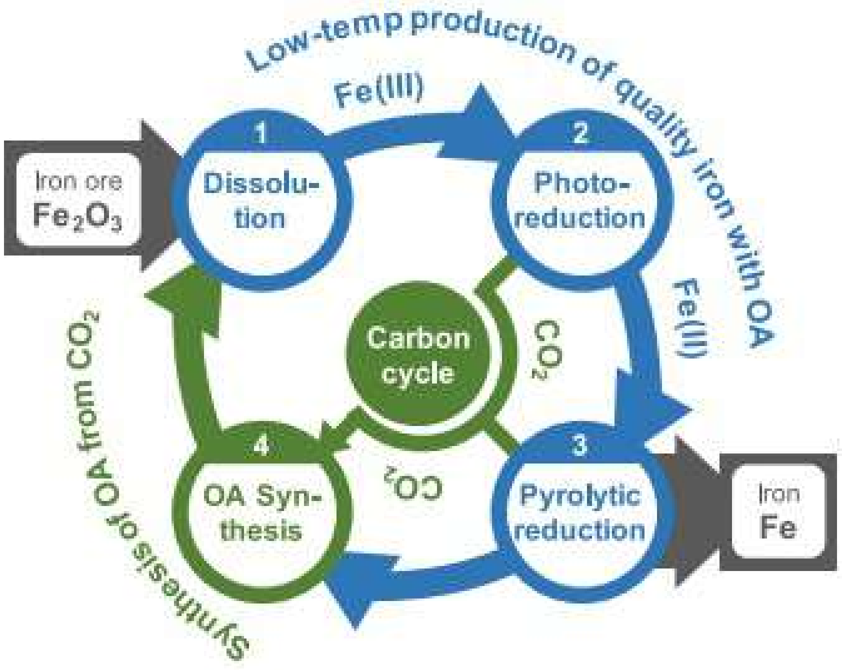
pyrolytic reduction:

$$FeC_2O_4 \cdot 2H_2O(s) + H_2 \rightarrow Fe(s) + CO(g) + CO_2(s) + 3H_2O \quad (3)$$

WGS: $$CO + H_2O \rightarrow CO_2 + H_2 \quad (4)$$

oxalic acid synthesis: $$2CO_2 + H_2 \rightarrow H_2C_2O_4 \quad (5)$$

net reaction: $$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (6)$$



- Santawaja, P., Kudo, S., Mori, A., Tahara, A., Asano, S., & Hayashi, J. I. (2020). Sustainable iron-making using oxalic acid: the concept, a brief review of key reactions, and an experimental demonstration of the iron-making process. ACS Sustainable Chemistry & Engineering, 8(35), 13292-13301.

Alternative BF/BOF production

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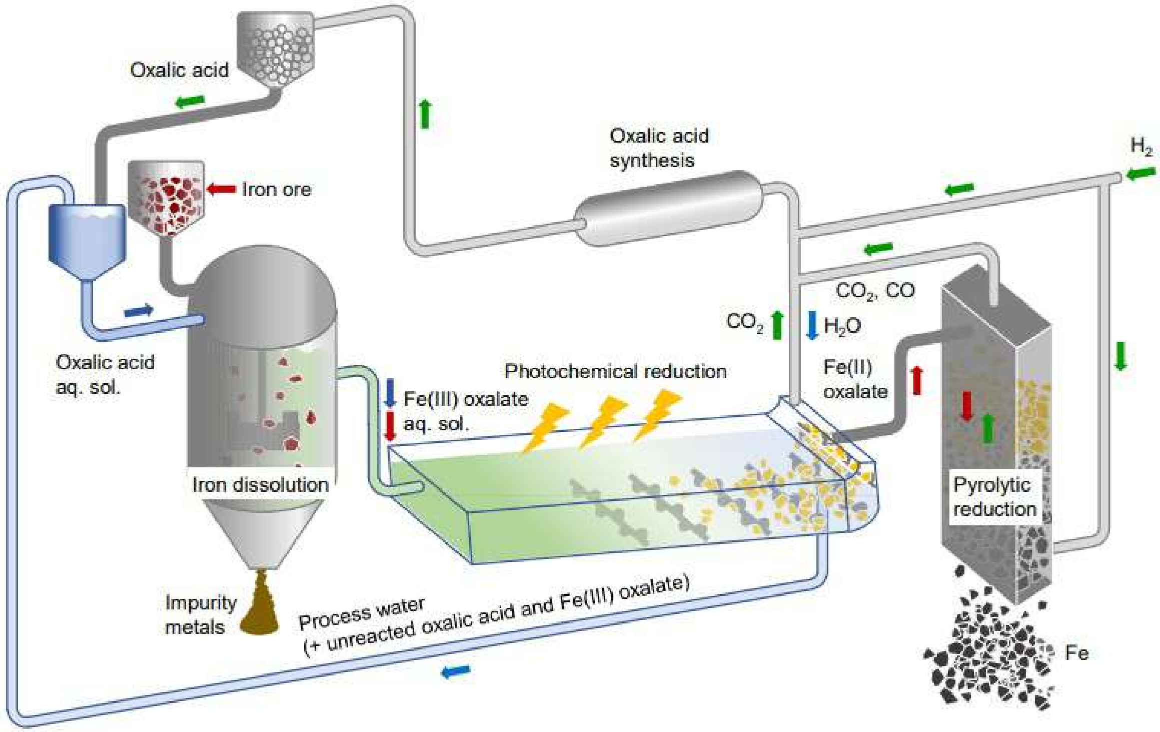
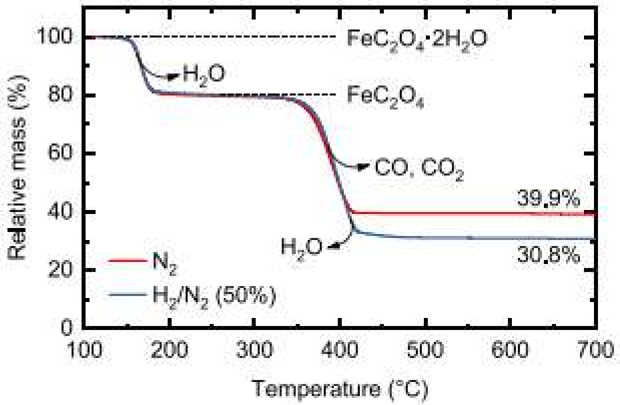
  Acid Leaching





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Alternative BF/BOF production

- **HydroMetallurgy**
  Acid Leaching

- Iron purity (on a metal basis): **80.5−99.7 wt %**
- Feedstocks consisting of **33.9−93.3 wt % iron**
- Highest temperature: **500 °C**
- Availability of diverse feedstocks
- The photochemical reduction needed **6 h** to reach full conversion, with the area fraction of solution surface exposed to light being **17%**
- Iron productivity **0.5 ton-Fe/day/m^3** (5−6 h and 0.4−0.5 mol-Fe/L)

- Santawaja, P., Kudo, S., Mori, A., Tahara, A., Asano, S., & Hayashi, J. I. (2020). Sustainable iron-making using oxalic acid: the concept, a brief review of key reactions, and an experimental demonstration of the iron-making process. ACS Sustainable Chemistry & Engineering, 8(35), 13292-13301.

Alternative BF/BOF production

- **HydroMetallurgy**
  Bio Leaching

- Geobacter metallireducens, Shewanella putrefaciens and L. ferriphilum reduce Fe^{+3} to Fe^{+2} under anaerobic conditions

- No need for coke

- Energy consumption reduction by 2,080 MJ/t of iron compared to the blast furnace

- The CO_2 directly emitted by the process entirely from biomass

- Efficiency of **93.85%** iron was achieved with L. ferriphilum, at 313 K at the end of **20 days**

- TC, E. (2005). Direct Biohydrometallurgical Extraction of Iron from Ore. Final Technical Report (No. INIS-US--0697). Michigan Technological University (United States). Funding organisation: US Department of Energy (United States)

Alternative BF/BOF production

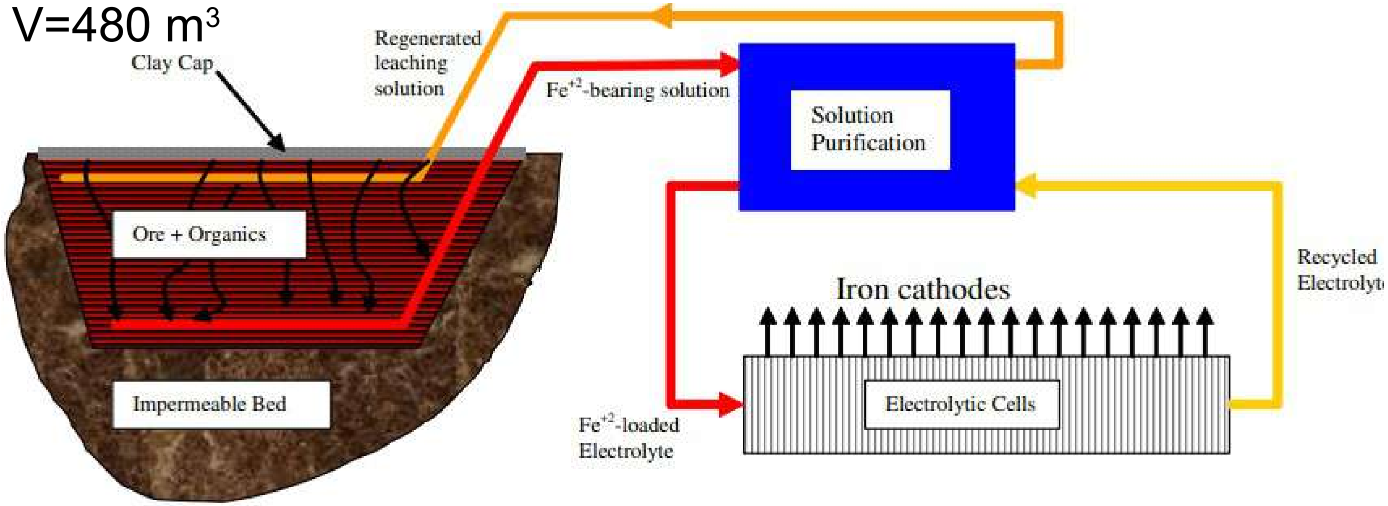
- **HydroMetallurgy**

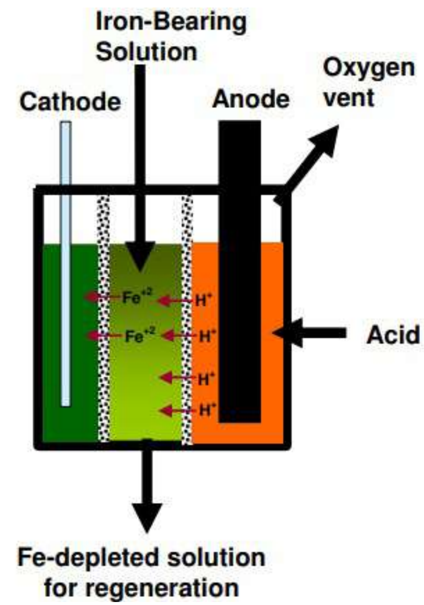
  Bio Leaching

t_{res}=20 d

Qv=1 m^3/h

V=480 m^3





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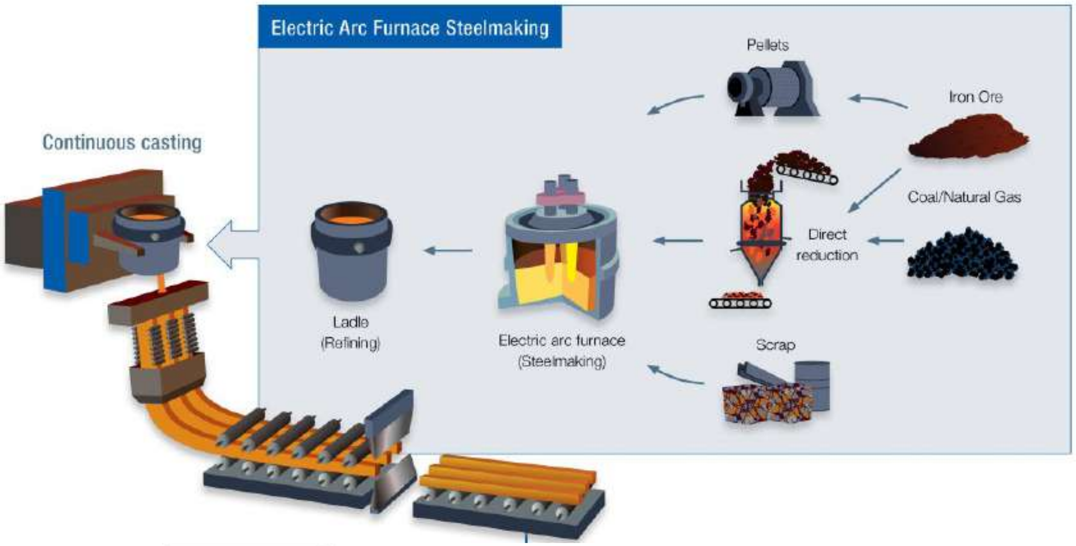
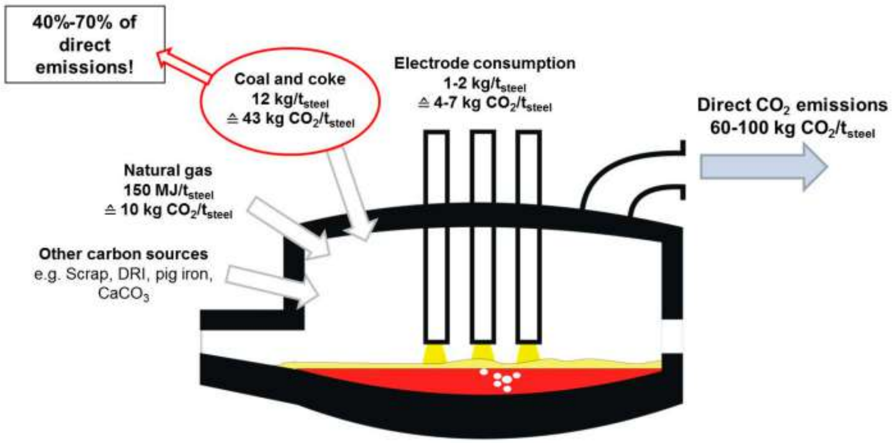
- Prabhu, S. V., Ramesh, G., Adugna, A. T., Beyan, S. M., & Assefa, K. G. (2019). Kinetics of iron bioleaching using isolated Leptospirillum ferriphilum: effect of temperature. International Journal of Innovative Technology and Exploring Engineering, 8, 76-81.

Alternative BF/BOF production

- Smelting Reduction

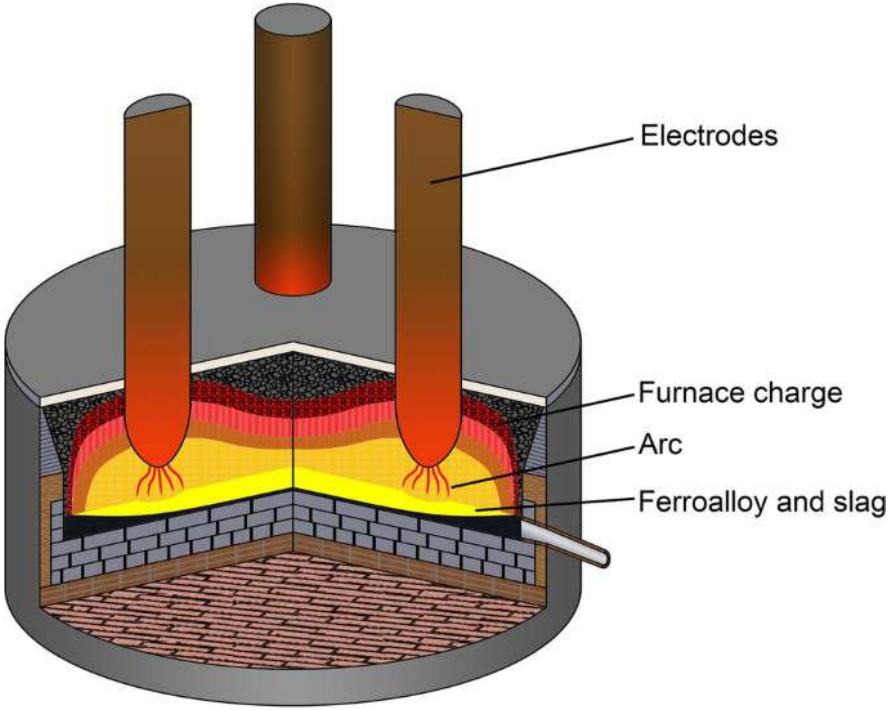
Electric Arc Furnace





Alternative BF/BOF production

- **Smelting Reduction**
  Submerged Arc Furnace



Alternative BF/BOF production

- **Direct Reduced Iron**

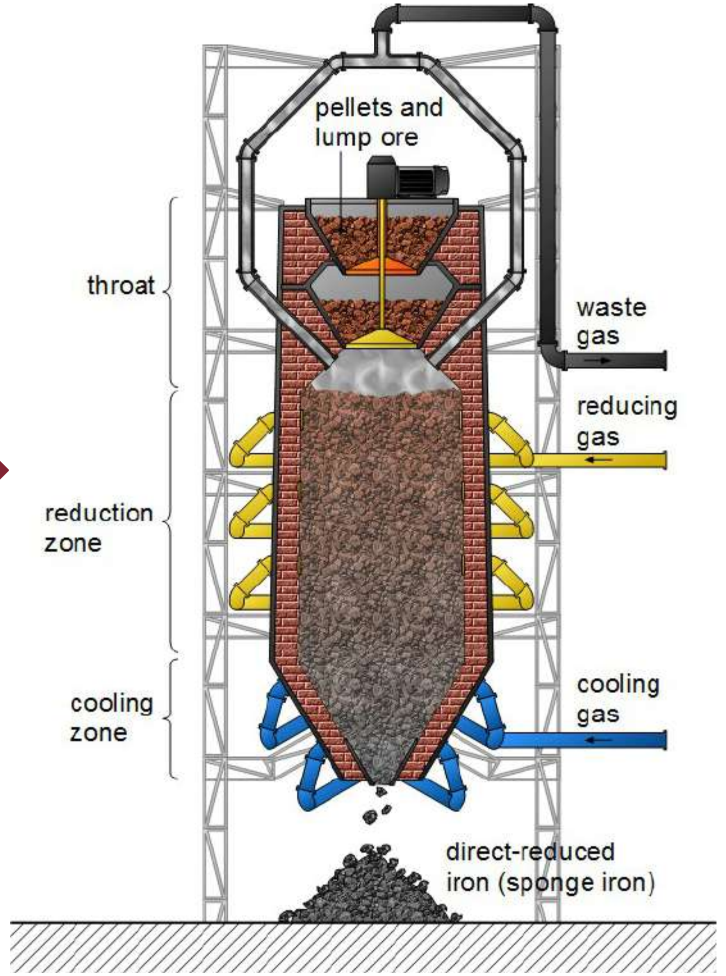
- Natural Gas
- Coal

- Biomass
- Waste

- Water

CO

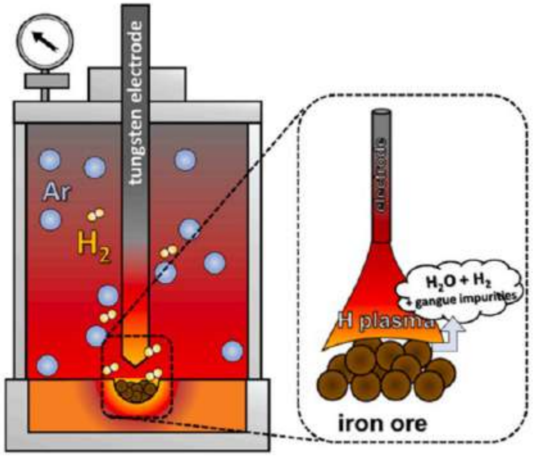
H_2



Alternative BF/BOF production

- **Hydrogen Smelting Reduction**

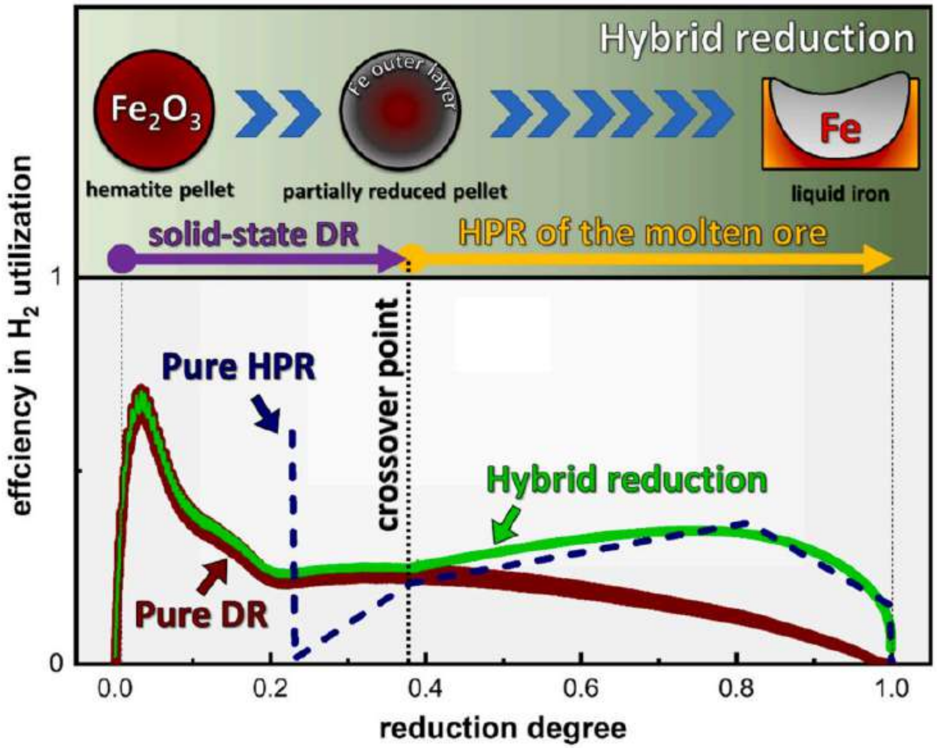
- Simultaneous reduction and melting
- Reduction potential of atomic and ionic H_2 present in H_2 plasma is, respectively, **3** and **15** times higher than molecular H_2
- **2000-2600 °C** at the interface between the plasma arc and the oxide melt
- Close to **100% reduction**

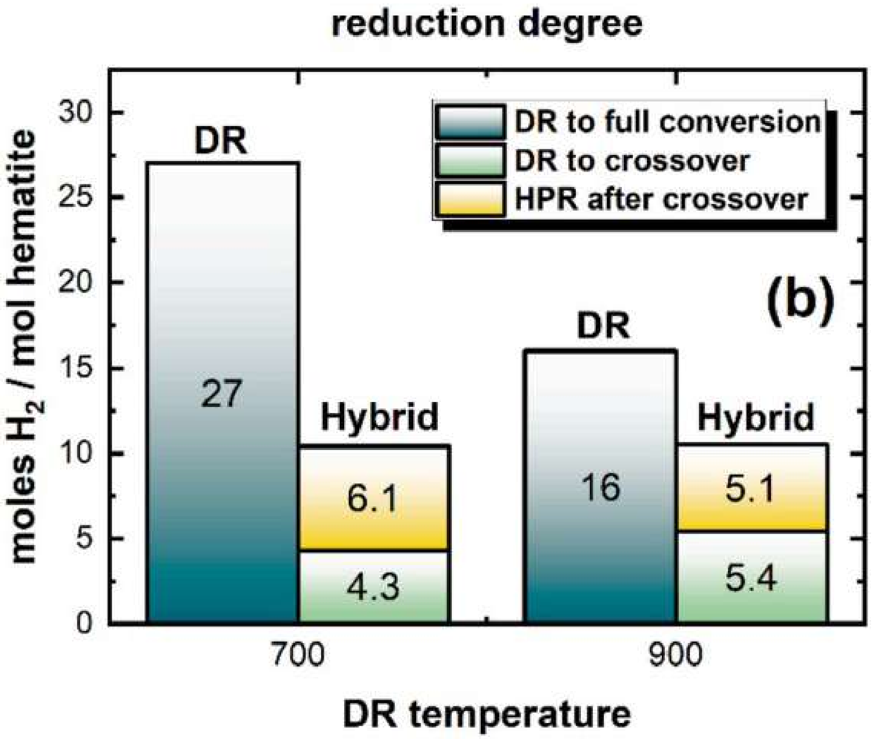


- Souza Filho, I. R., Springer, H., Ma, Y., Mahajan, A., da Silva, C. C., Kulse, M., & Raabe, D. (2022). Green steel at its crossroads: Hybrid hydrogen-based reduction of iron ores. Journal of Cleaner Production, 340, 130805.
- Behera, P.R., Bhoi, B., Paramguru, R.K. et al. Hydrogen Plasma Smelting Reduction of Fe2O3. Metall Mater Trans B 50, 262–270 (2019). https://doi.org/10.1007/s11663-018-1464-8

Alternative BF/BOF production

- **Hydrogen Smelting Reduction**





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Carbon Capture in the Steel Industry

Carbon Capture in the Steel Industry

- CO_2 removal consists of:
  - PSA, VPSA
  - VSPA/PSA + Cryogenic Separation
  - Chemical Absorption

	PSA	VPSA	PSA+cryogenic separation+ compression	VPSA+compression + cryogenic separation	Amines+ compression
CO_2-rich gas captured					
CO_2 (% vol)	79.7	87.2	100	96.3	100
Suitable for transport and storage?	no	no	yes	yes	yes
CCS Process					
Electricity consumption (kWh/tCO_2)	100	105	310	292	170
Capture Process (kWh/tCO_2)	100	105	195	160	55
Compression to 11 MPa for storage (kWh/tCO_2)	-	-	115	132	115
Steam consumption (GJ/tCO_2)	0	0	0	0	3.2
Total energy consumption (GJ/tCO_2)	**0.36**	**0.38**	**1.12**	**1.05**	**3.81**

Carbon Capture in the Steel Industry

COURSE 50 Programme

CAT-1 & CAT-10

at Nippon Steel Kimitsu Works

CAT-1
1 t/d CO_2 for solvent testing

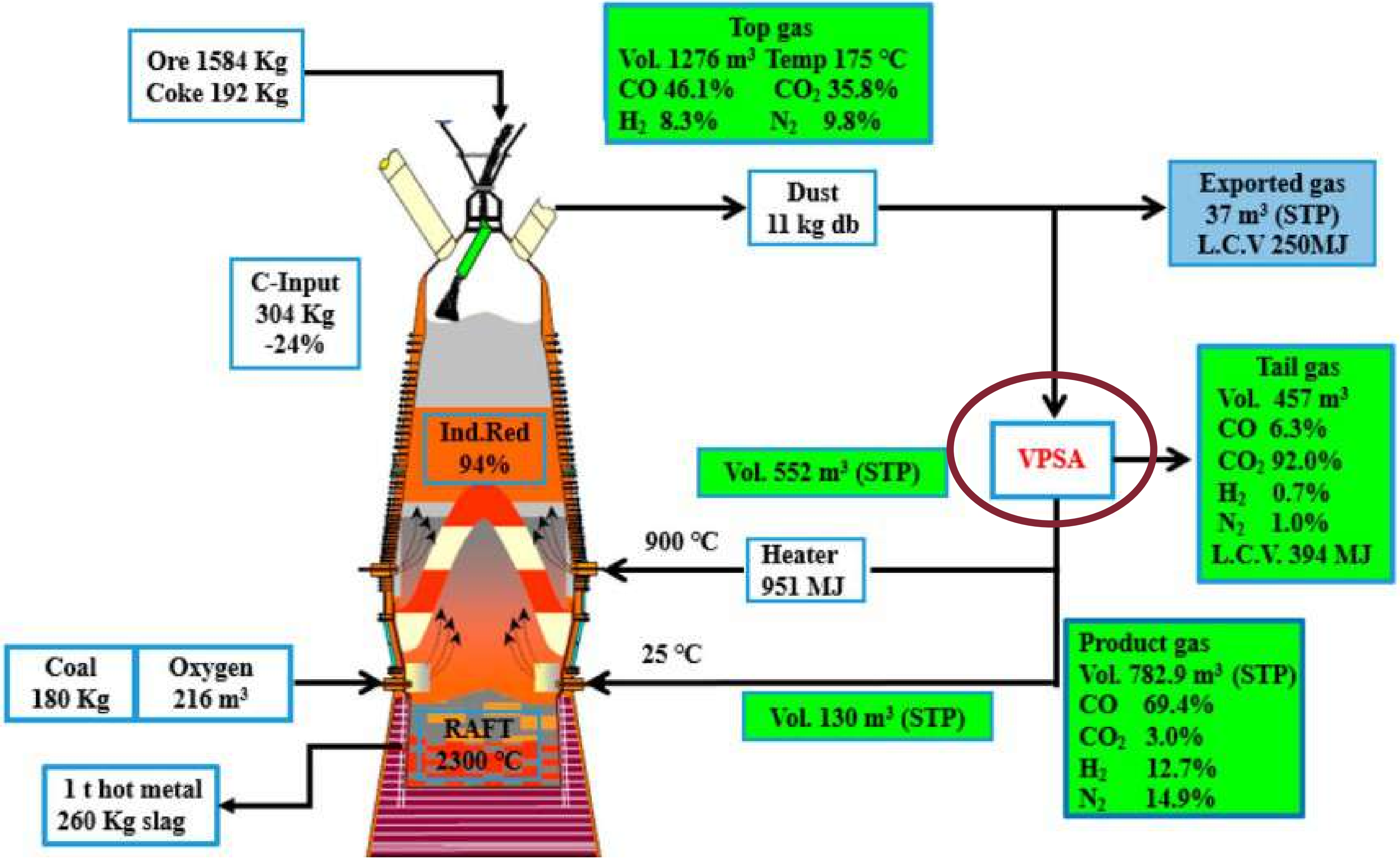
CAT-30
30 t/d CO_2 for process improvement evaluation

ASCOA

at JFE Steel Fukuyama Works

Carbon Capture in the Steel Industry

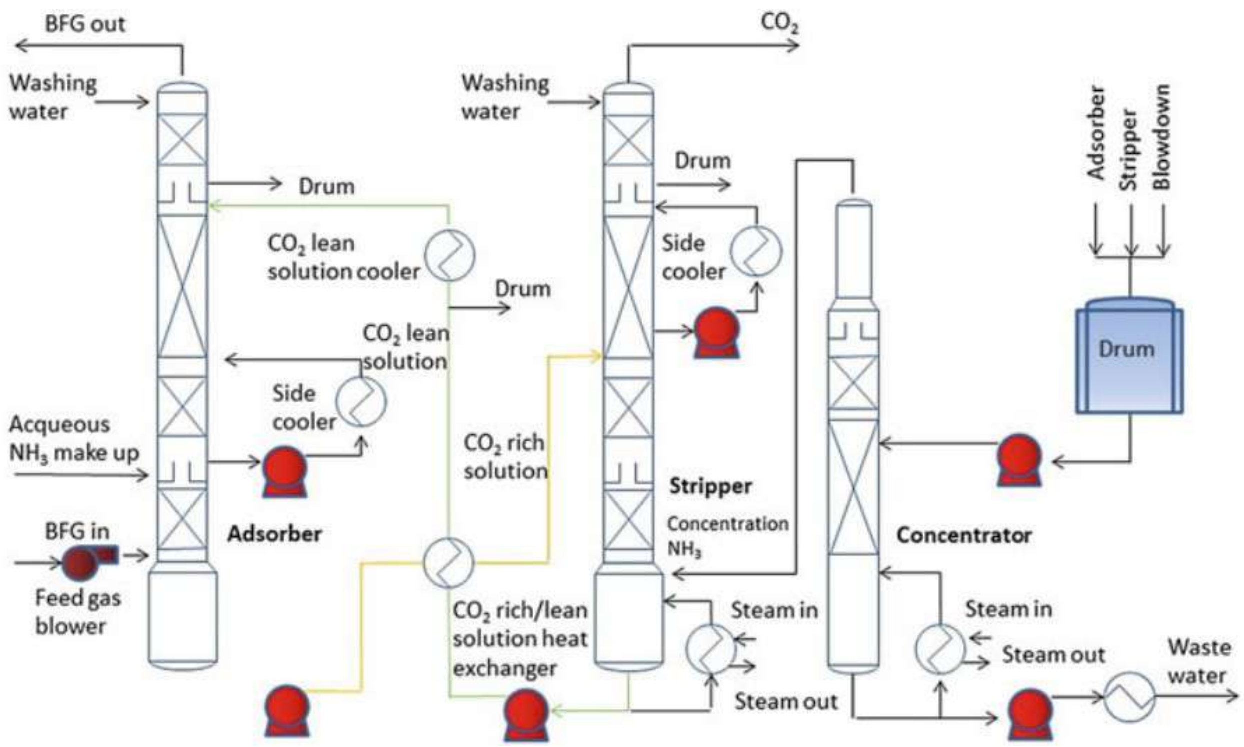
Ultra-Low CO_2 Steelmaking (ULCOS) Programme



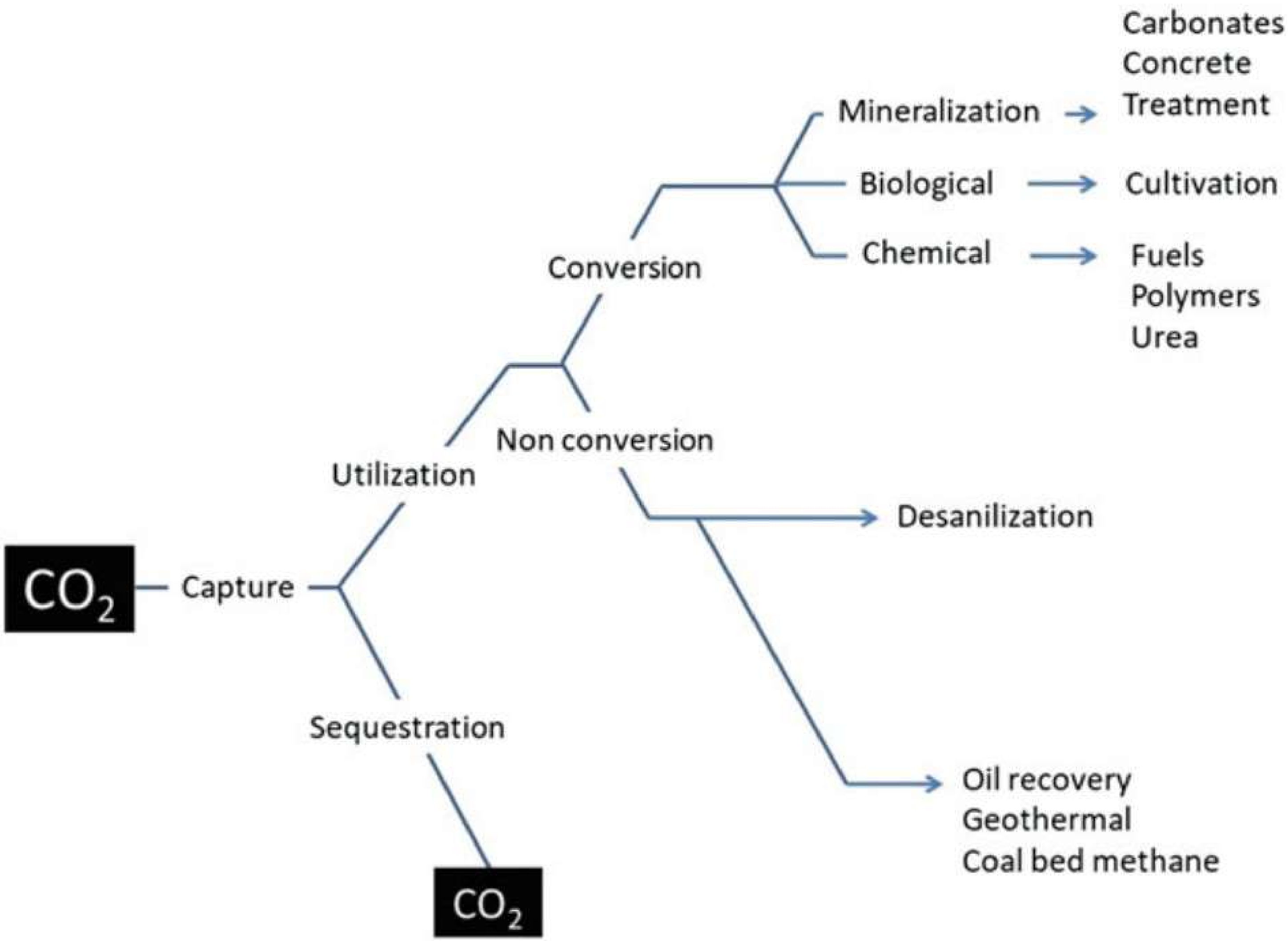
Carbon Capture in the Steel Industry

POSCO Programme

Feed Gas	**BFG (CO_2-22%)**
Flow Rate	1000 Nm_3/h
Absorbent Solvent	10% NH_3
CO_2 Absorption	10 tCO_2/d
Purity	> 99.5%
Recovery	**> 90%**



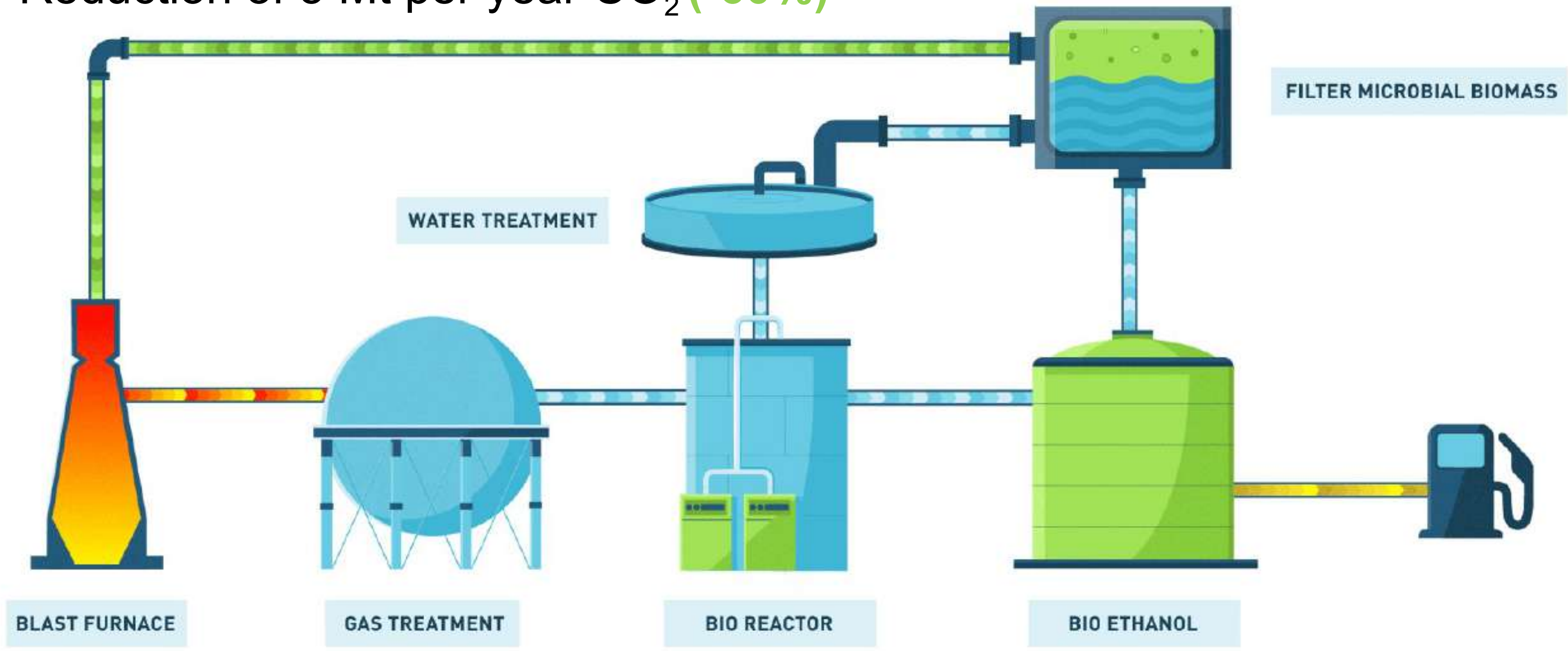
Carbon Capture in the Steel Industry



Carbon Capture in the Steel Industry

Steelanol Programme

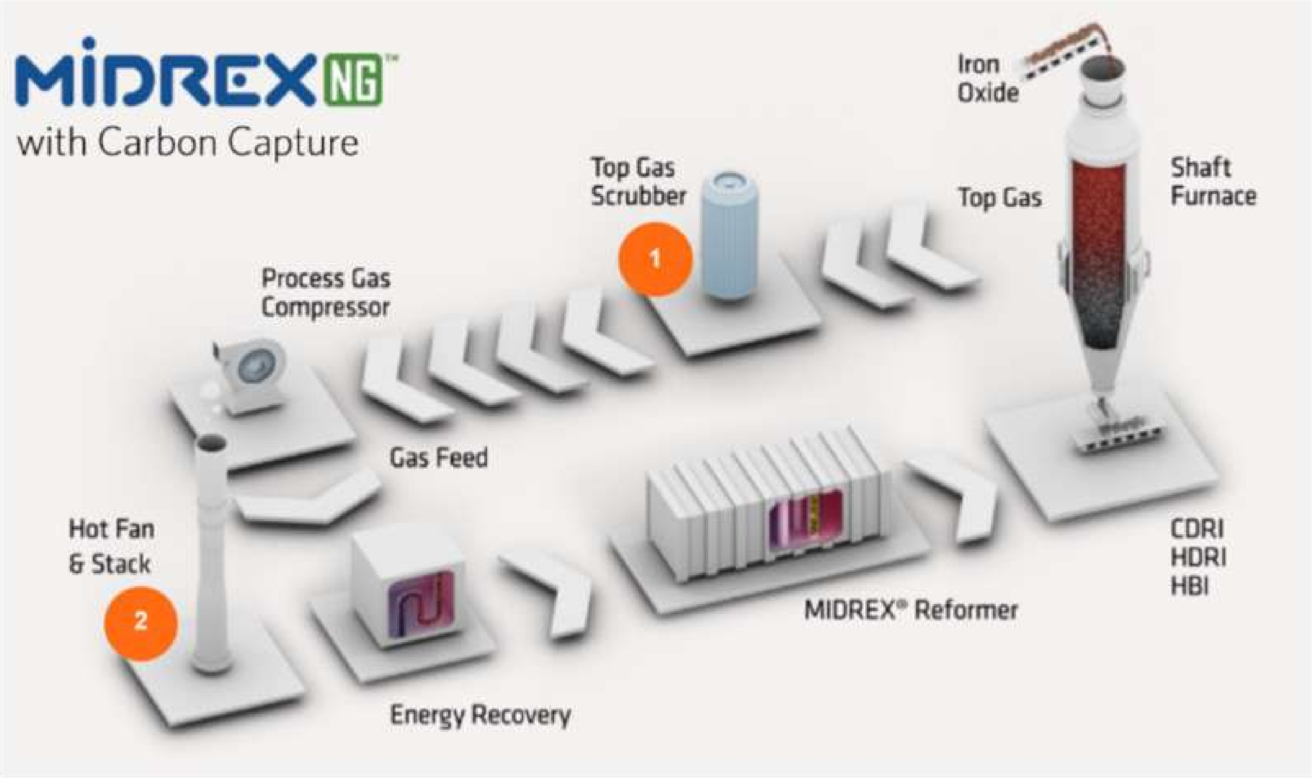
- 165 M€ investment
- 80 million liters of bioethanol annually
- Every 2.3 tons of CO_2 captured equals one ton of ethanol
- Reduction of 5 Mt per year CO_2 **(-60%)**



Carbon Capture in DRI

MIDREX Process

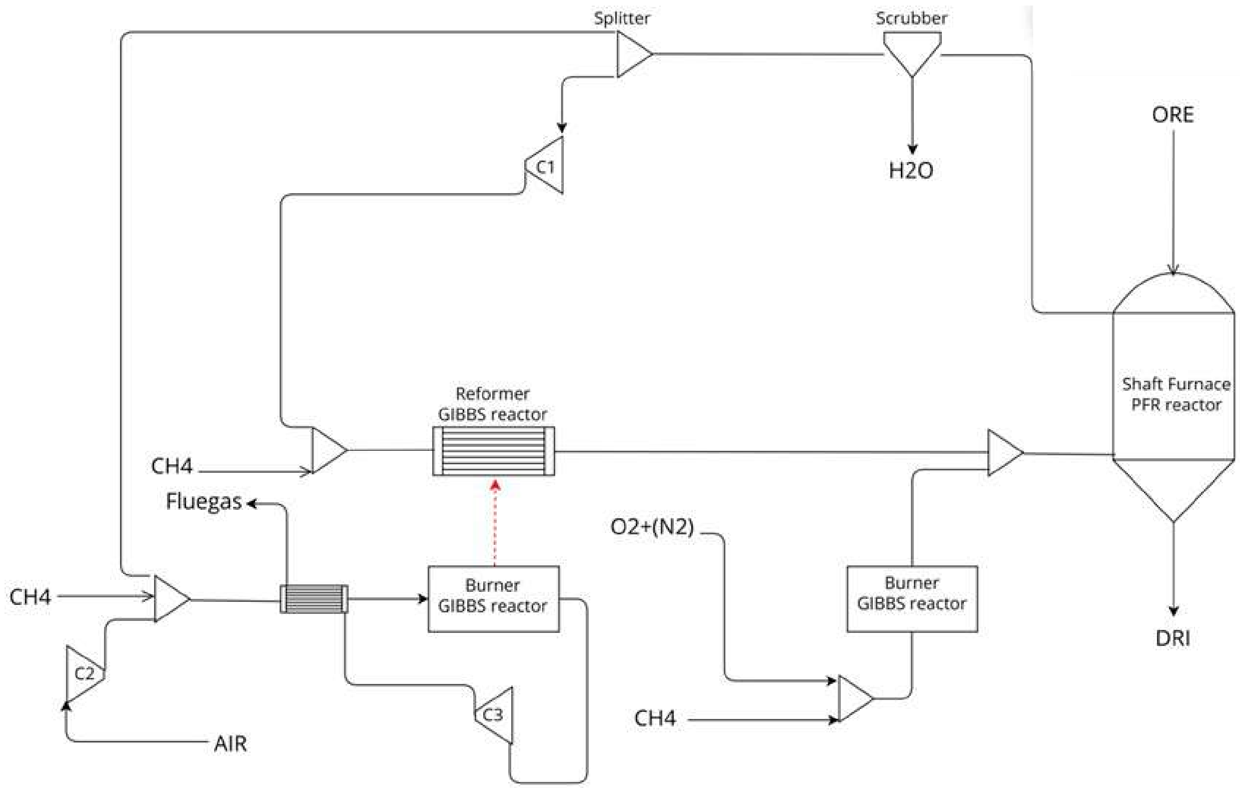
- No standalone Midrex Plant that removes CO_2 from the DRI shaft reactor's off-gas.



Carbon Capture in DRI

MIDREX Process

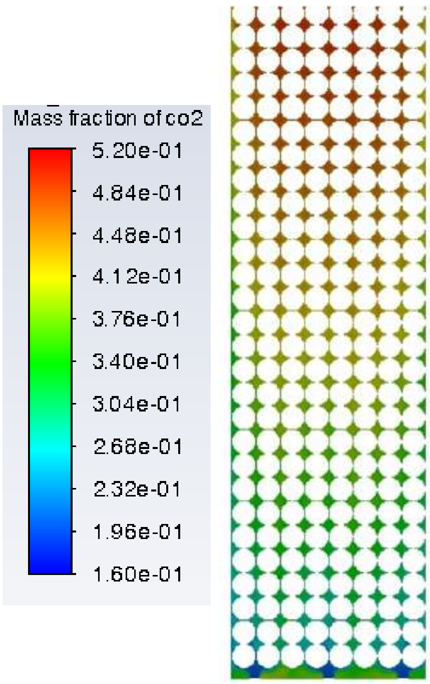
Gilmore Steel Corporation (U.S.A.)

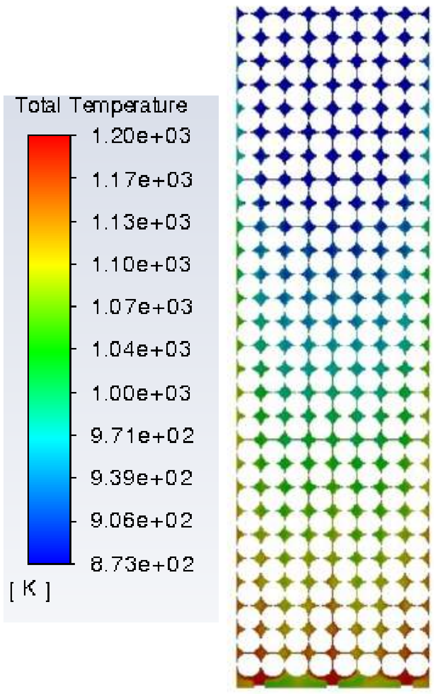


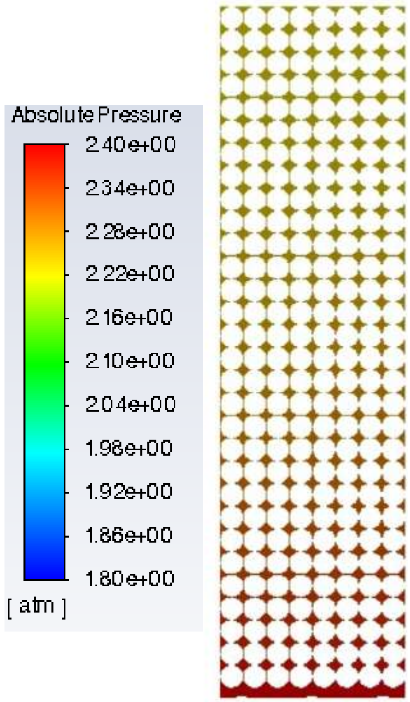
Carbon Capture in DRI

MIDREX Process

Gilmore Reduction Shaft

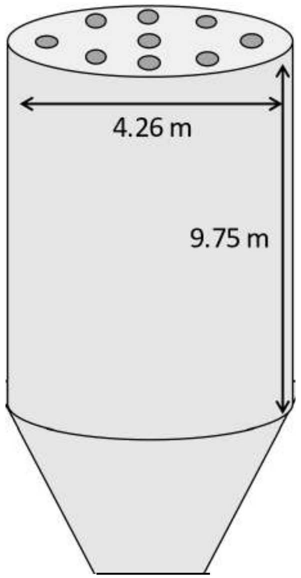


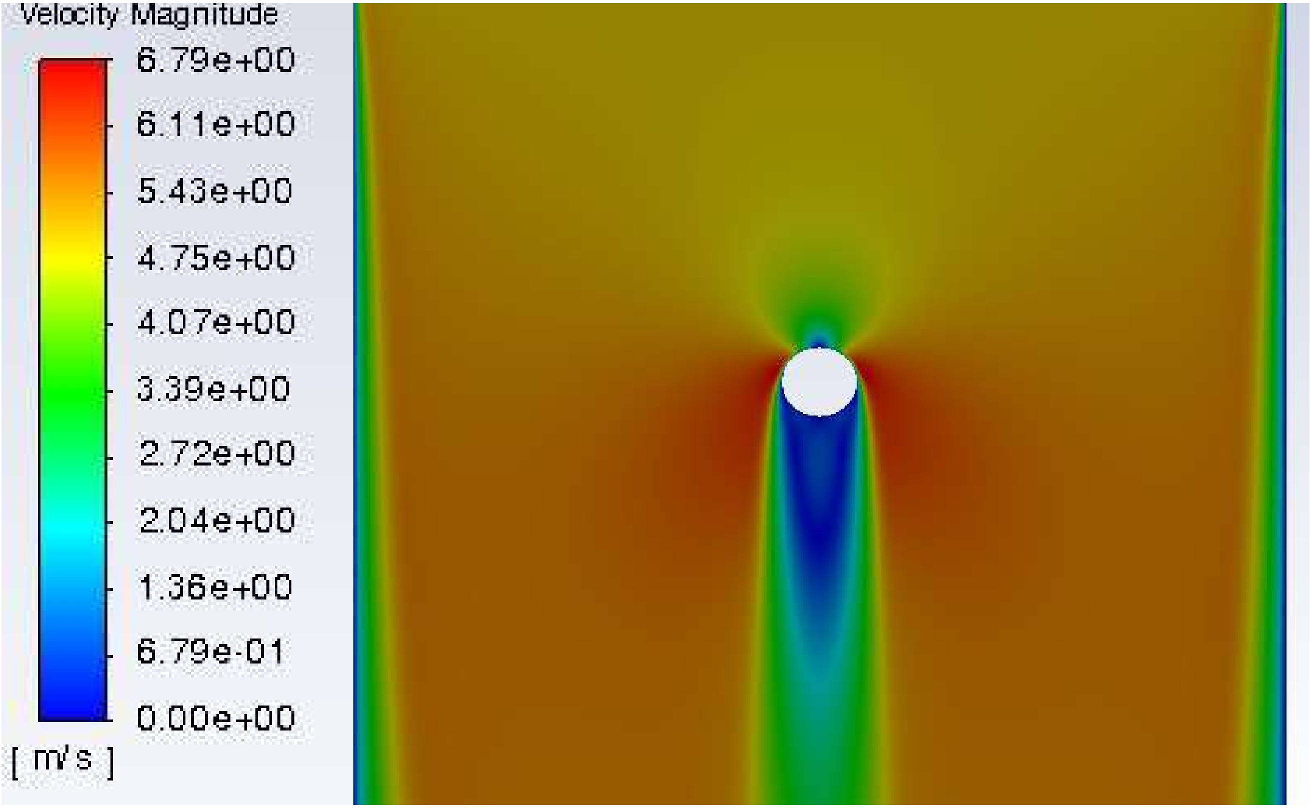




Carbon Capture in tDRI

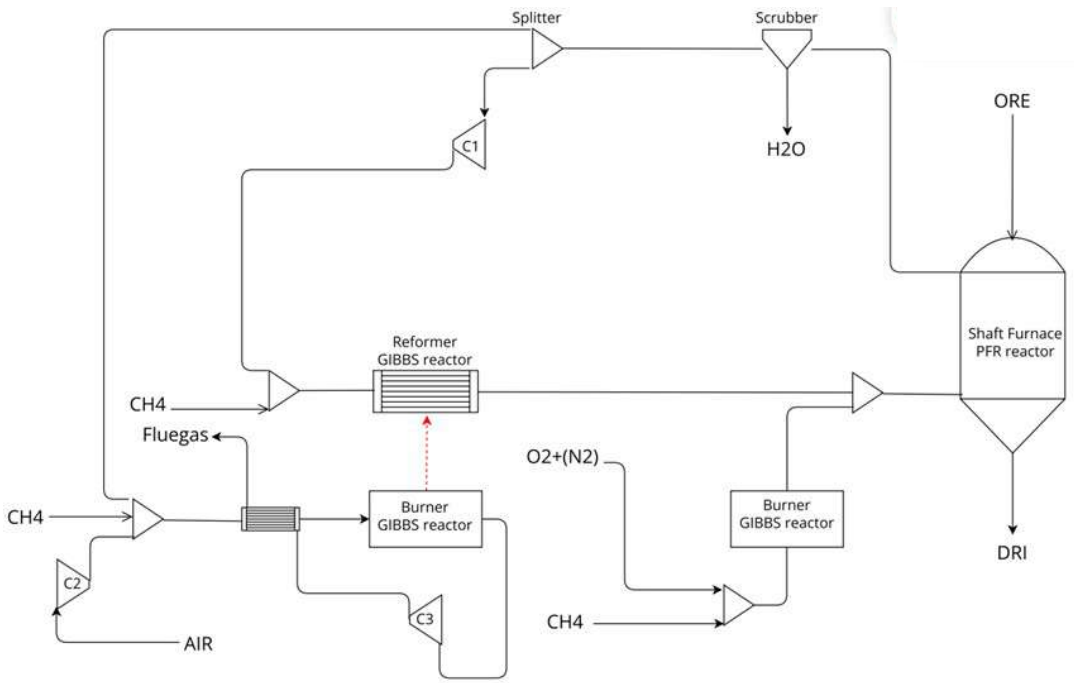
MIDREX Process





Carbon Capture in the Steel Industry

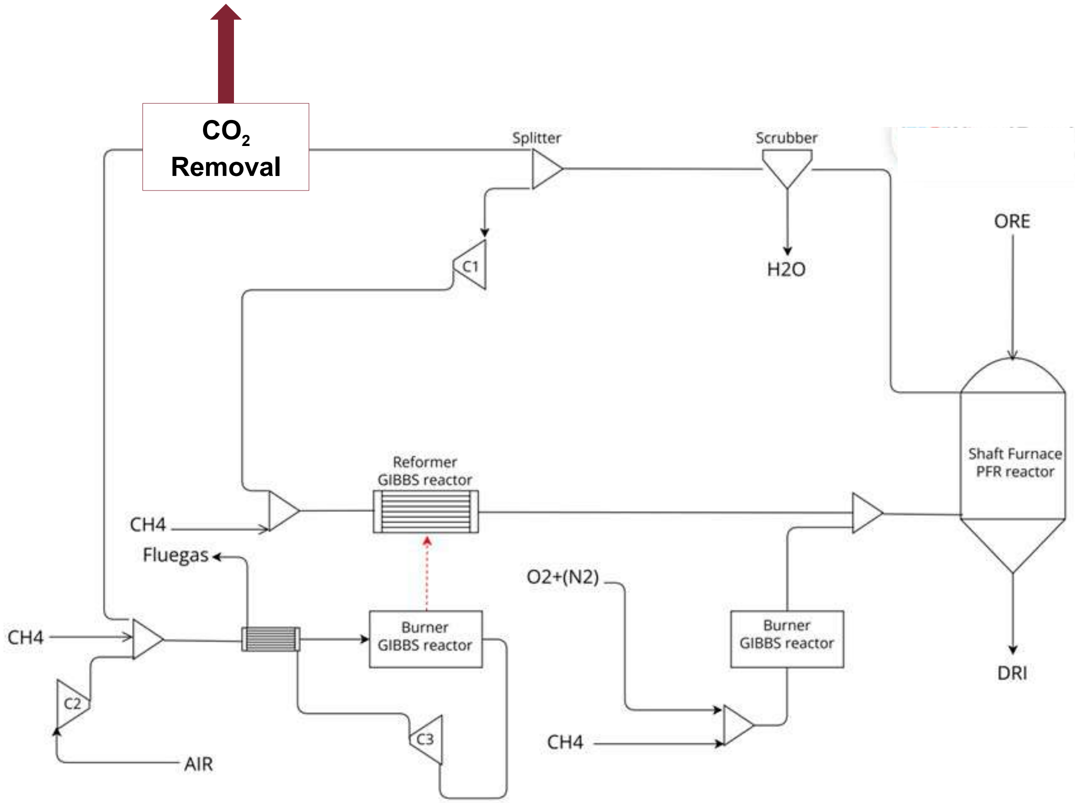
MIDREX Process



Inlet reducing gas		
Flow rate	Nm^3/h	53,862.31
Temperature	°C	930
Pressure	bar	2.4
	Composition	
H_2	%	48.19
CO	%	25.40
H_2O	%	13.85
CO_2	%	5.43
N_2 (+CH_4)	%	7.13
	Outlet gas	
Flowrate	Nm^3/h	53,799.74
Temperature	°C	660
	Composition	
H_2	%	37.04
CO	%	12.80
CO_2	**%**	**17.98**
H_2O	%	25.13
N_2 (+CH_4)	%	7.01

Carbon Capture in the Steel Industry

MIDREX Process



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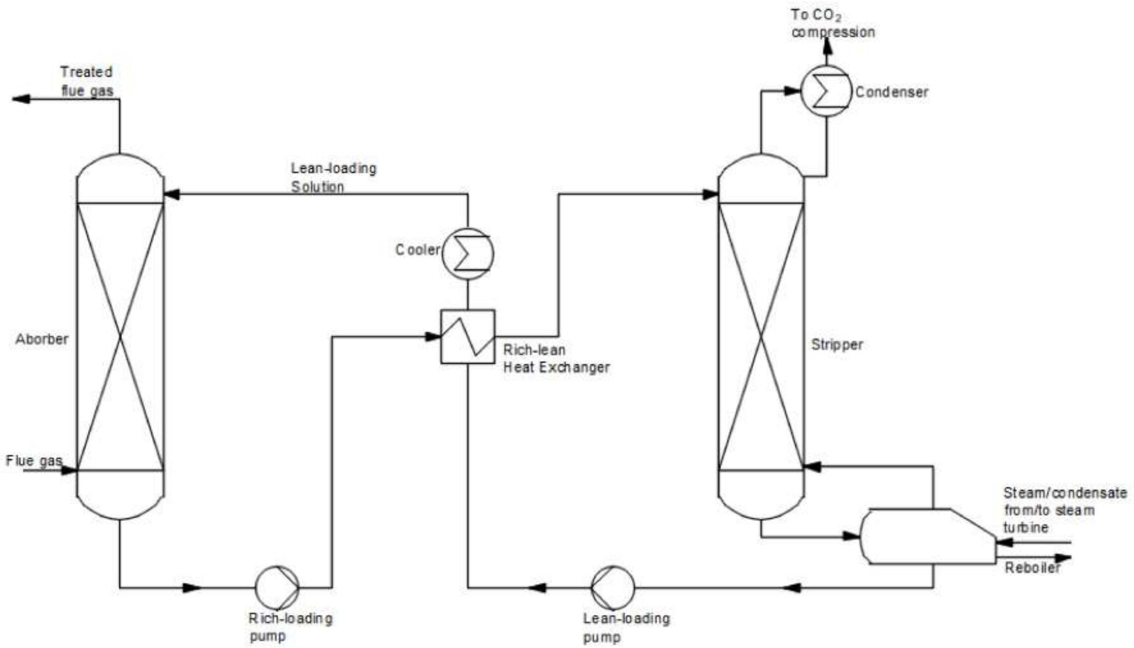
	Composition	
H_2	%	37.04
CO	%	12.80
CO_2	**%**	**17.98**
H_2O	%	25.13
N_2 (+CH_4)	%	7.01

Carbon Capture in the Steel Industry

MIDREX Process

Feed Gas	CO_2-30% (dry)
Flow Rate	13017.80 kg/h
Absorbent Solvent	30% MEA
Purity	96.6%
Recovery	95%



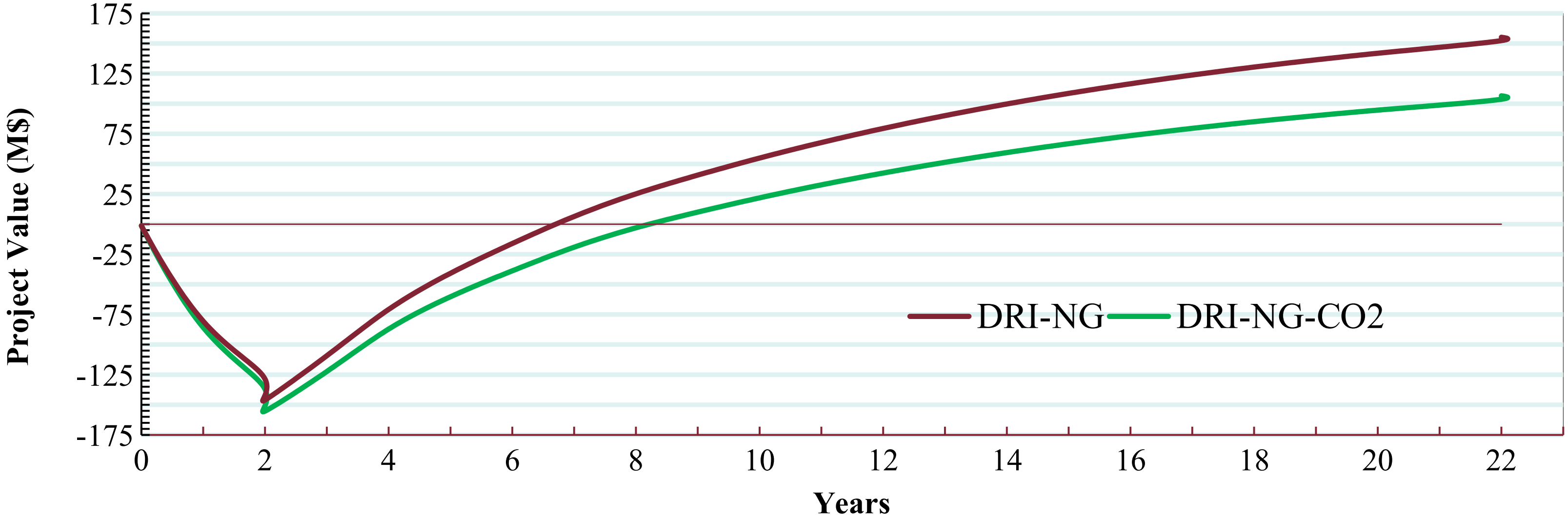
Specific Emission (t_{CO2}/t_{STEEL})		
	DRI-NG	**DRI-NG+Carbon Capture**
Direct	0.46	0.19
Equivalent	0.14	0.15
Total	0.60	0.34

Carbon Capture in the Steel Industry

MIDREX Process

Production cost ($/t):

- Chemical Absorbtion: **+ 8.7%**
- Chemical Absorption + Storage/Transport: **+10.5%**



	Unit	DRI-NG	DRI-NG CO_2
NPV	M$	155.11	106.55
ROI	%	23.62	19.27
PBT	y	3.90	4.98

Decarbonization of steel production: alternative Direct Reduced Iron and CCS

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