30/05/2025

AMPS Workshop: Unlocking the Potential of SOC Technologies for a Decarbonized Future

Integrated DRI-SOEC systems for green steel - HySteel project

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Industrial sector - Energy demand and CO_2 emissions

Table A.2a: World final energy consumption

	Stated Policies (EJ)							Shares (%)			CAAGR (%) 2023 to:	
	2010	2022	2023	2030	2035	2040	2050	2023	2030	2050	2030	2050
Total final consumption	377	437	445	485	499	509	533	100	100	100	1.3	0.7
Industry	143	170	173	193	200	204	209	100	100	100	1.6	0.7
Electricity	27	38	39	47	50	53	58	22	25	28	3.0	1.5
Liquid fuels	29	34	34	40	41	42	43	20	20	20	2.1	0.8
Oil	29	34	34	40	41	42	42	20	20	20	2.1	0.8
Gaseous fuels	24	32	33	36	38	40	42	19	19	20	1.6	0.9
Biomethane	0	0	0	0	1	1	2	0	0	1	16	12
Hydrogen	-	0	0	0	0	0	0	0	0	0	44	20
Unabated natural gas	21	28	29	32	33	34	34	17	17	16	1.4	0.6
Natural gas with CCUS	0	0	0	0	0	0	0	0	0	0	13	8.0
Solid fuels	58	58	59	60	60	59	57	34	31	27	0.3	-0.1
Modern solid bioenergy	8	11	11	13	14	15	16	6	7	8	2.3	1.5
Unabated coal	48	44	45	44	43	41	38	26	23	18	-0.3	-0.6
Coal with CCUS	-	0	0	0	0	0	0	0	0	0	29	8.8
Heat	5	8	8	10	10	10	9	5	5	4	1.8	0.3
Chemicals	37	49	50	58	61	63	63	29	30	30	2.1	0.9
Iron and steel	31	36	37	37	37	37	36	21	19	17	0.2	-0.1
Cement	9	12	12	12	12	12	12	7	6	6	0.0	0.0
Aluminium	5	7	7	7	8	8	8	4	4	4	0.7	0.3
Transport	101	118	122	132	133	134	140	100	100	100	1.1	0.5
Buildings	111	125	124	132	137	141	153	100	100	100	0.9	0.8

21.4%

8.3%

Table A.4a: World CO_2 emissions

	Stated Policies (Mt CO_2)							CAAGR (%) 2023 to:	
	2010	2022	2023	2030	2035	2040	2050	2030	2050
Total CO_2*	32 805	37 230	37 723	36 170	33 285	31 185	28 636	-0.6	-1.0
Electricity and heat sectors	12 513	14 943	15 262	13 311	10 968	9 469	7 757	-1.9	-2.5
Other energy sector**	1 441	1 616	1 579	1 585	1 567	1 539	1 490	0.1	-0.2
Final consumption**	18 590	20 410	20 604	21 106	20 601	20 043	19 288	0.3	-0.2
Coal	4 686	4 243	4 302	4 096	3 927	3 760	3 400	-0.7	-0.9
Oil	9 020	9 909	10 108	10 359	9 893	9 421	9 008	0.4	-0.4
Natural gas	2 854	3 559	3 521	3 888	3 952	3 995	3 991	1.4	0.5
Bioenergy and waste	71	123	124	120	116	112	103	-0.5	-0.7
Industry**	8 313	9 183	9 207	9 491	9 532	9 468	9 098	0.4	-0.0
Chemicals**	1 163	1 344	1 343	1 449	1 457	1 421	1 306	1.1	-0.1
Iron and steel**	2 111	2 730	2 800	2 774	2 737	2 686	2 509	-0.1	-0.4
Cement**	1 916	2 408	2 356	2 366	2 417	2 452	2 458	0.1	0.2
Aluminium**	175	248	250	263	266	265	266	0.7	0.2
Transport	6 965	7 944	8 213	8 537	8 198	7 840	7 557	0.6	-0.3
Road	5 181	6 028	6 137	6 221	5 799	5 378	5 027	0.2	-0.7
Passenger cars	2 658	3 083	3 168	3 011	2 668	2 376	2 137	-0.7	-1.4
Heavy-duty trucks	1 518	1 873	1 898	2 136	2 168	2 154	2 190	1.7	0.5
Aviation	746	800	941	1 158	1 266	1 363	1 491	3.0	1.7
Shipping	792	836	856	900	883	854	806	0.7	-0.2
Buildings	2 873	2 842	2 747	2 666	2 468	2 345	2 275	-0.4	-0.7
Residential	1 961	1 974	1 904	1 772	1 611	1 500	1 380	-1.0	-1.2
Services	912	867	842	894	857	846	895	0.9	0.2
Total CO_2 removals**	-	1	1	21	24	30	50	48	14
Total CO_2 captured**	16	43	40	122	192	261	395	17	8.8

*Includes industrial process and flaring emissions.

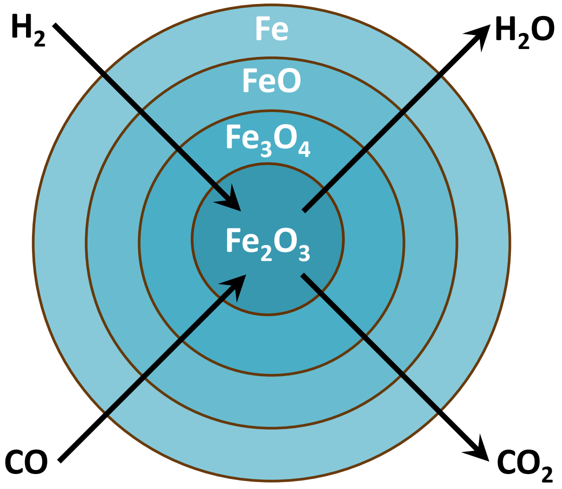
**Includes industrial process emissions.

30.4%

7.4%

Source: IEA, "World Energy Outlook 2024", 2024

Direct Reduced Iron (DRI)



Reduction with H_2

$3\ Fe_2O_3 + H_2 \rightarrow 2\ Fe_3O_4 + H_2O$
$Fe_3O_4 + H_2 \rightarrow FeO + H_2O$
$FeO + H_2 \rightarrow Fe + H_2O$

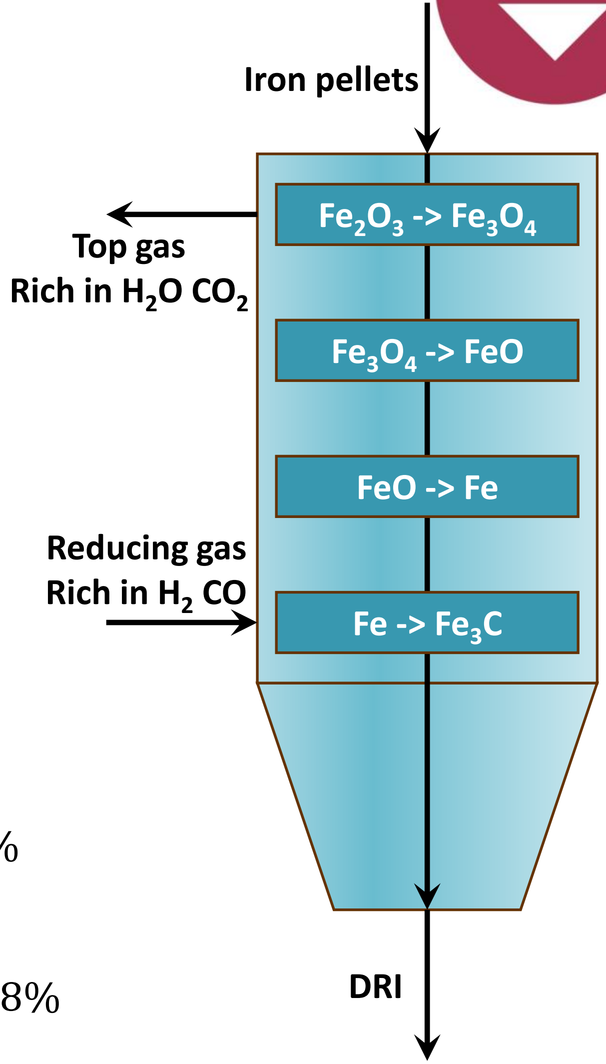
Reduction with CO

$3\ Fe_2O_3 + CO \rightarrow 2\ Fe_3O_4 + CO_2$
$Fe_3O_4 + CO \rightarrow FeO + CO_2$
$FeO + CO \rightarrow Fe + CO_2$

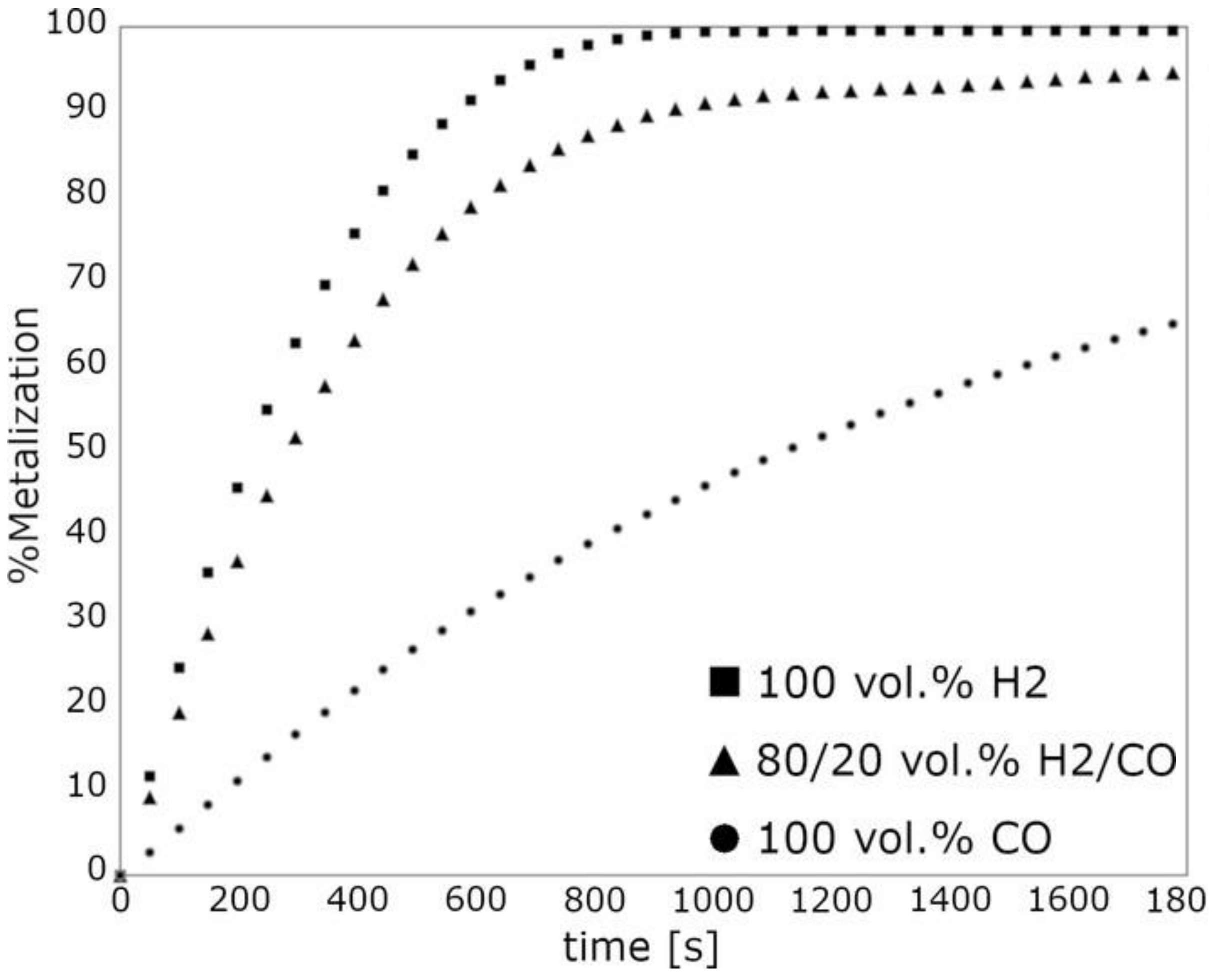
- **70%** of world steel production is based on the **BF-BOF** process
- **10%** of the world iron production is based on the **DRI** process
- Switching **from BF to DRI** can **decrease CO_2 emissions by 50%**
  - MIDREX: 16 GJ/t_{DRI} and 630 kg_{CO2}/t_{DRI}
  - Energirion: 15 GJ/t_{DRI} and 490 kg_{CO2}/t_{DRI}
- **Goal: 1.4 -> 0.5 $t_{CO2}/t_{crude\ steel}$**
  - Material and process efficiency
  - CCUS and hydrogen
  - Fuel shift

$$\textit{Metallization}: \ M[\%] = \frac{Fe_0\ [kg]}{Fe_{tot}[kg]} \quad 90\% < M < 96\%$$

$$\textit{Carbon content}: \ C[\%] = \frac{C_{steel}\ [kg]}{Steel_{tot}[kg]} \quad 0.3\% < C < 0.8\%$$



Reduction process

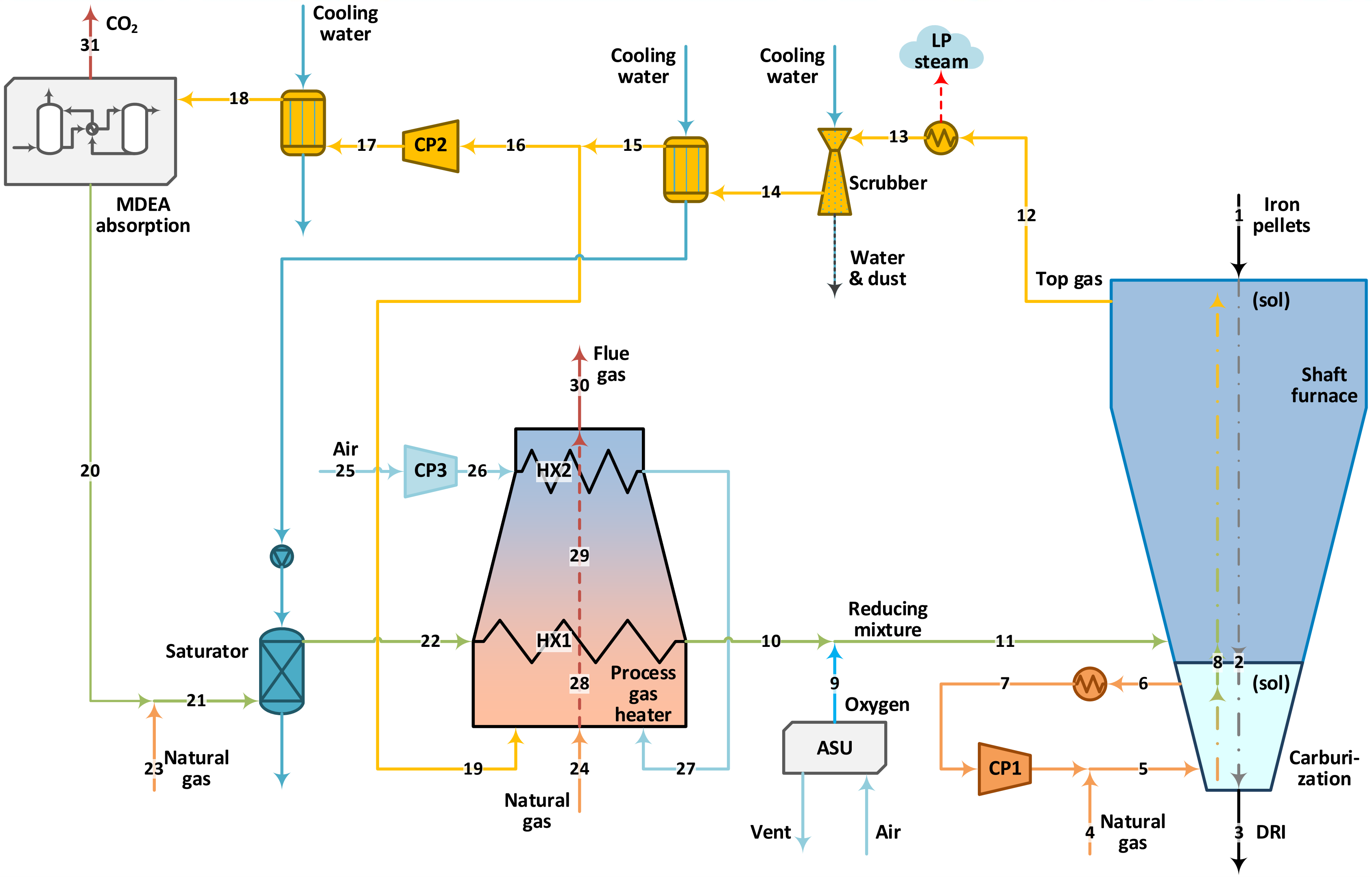


- Different reducing gas composition affects the kinetics of the reducing process
- Reducing reaction with H_2 have slower kinetics compared to CO, but the diffusion of the chemical species in the iron pellet is faster -> **faster reduction of the iron pellet with H_2**
- The overall reducing reaction with H_2 is endothermic while with CO it is exothermic -> **the reducing gas inlet temperature has to increase with the concentration of H_2**
- Low concentration of CO and CH_4 in the reducing gas can lead to low carbon content in the DRI

$$\frac{\partial X_O}{\partial t} = D\left(X_{H_2}, X_{CO}, D_{H_2}, D_{CO}\right) \cdot \frac{1}{r^2} \cdot \frac{d}{dr}\left(r^2 \frac{dX_O}{dr}\right)$$

Source: C. Mapelli et al., "A Simplified Approach Based on Cellular Automata for Describing Direct Reduced Iron Production in Different Reducing Conditions", steel research int. 95, 2024, 2300411, DOI: 10.1002/srin.202300411

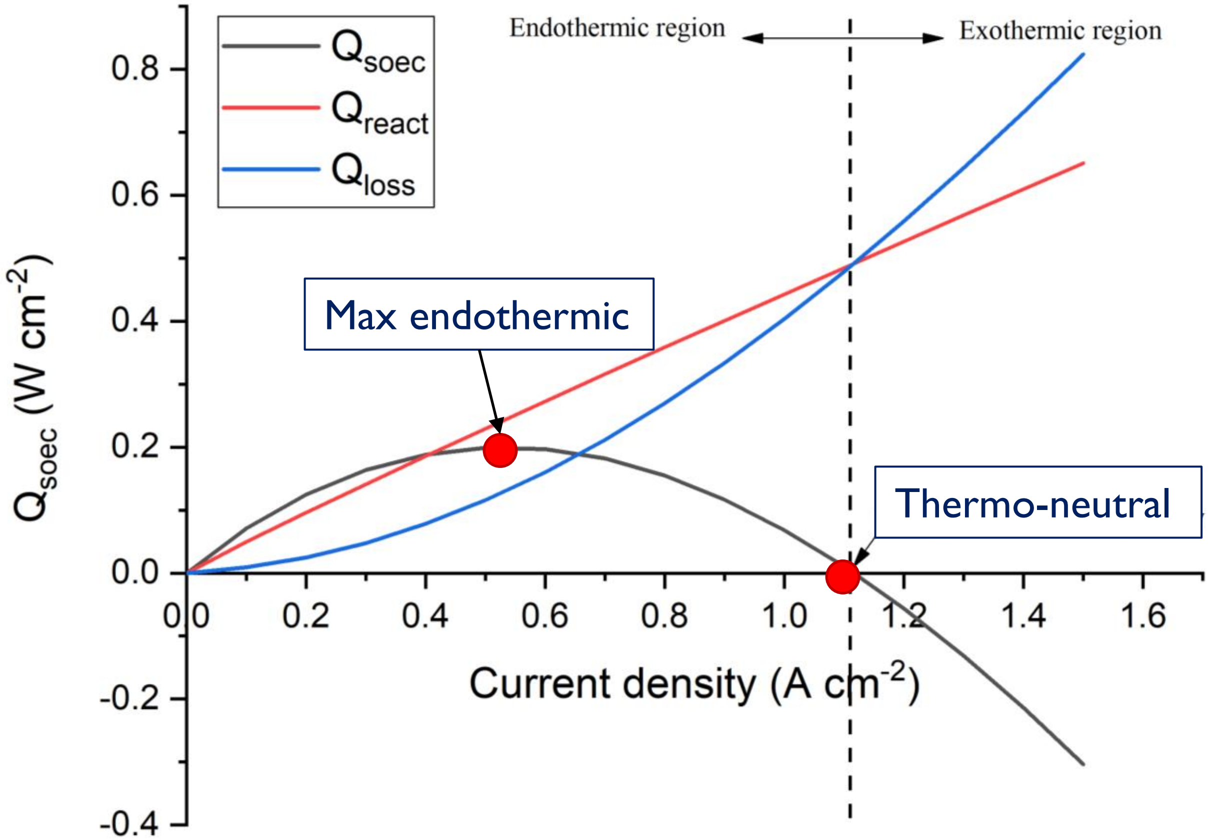
Energiron process



- **Natural gas reforming** occurs directly in the shaft furnace
- Natural gas is used as:
  - **Make-up** of the reducing gas
  - **Cooling agent** at the bottom of the furnace
  - **Fuel** of the process gas heater
- **~270 kg_{CO2}/t_{DRI}** are removed from the top gas with a dedicated process (CO_2 **ready to capture**)

Source: R. Scaccabarozzi et al., "Technical analysis of high-efficiency and flexible direct reduced iron plants integrated with high-temperature electrolysis", Journal of Cleaner Production 489, 2025, 144681, DOI: 10.1016/j.jclepro.2025.144681

SOEC thermodynamic principles



$$\Delta G = \Delta H - Q = \Delta H - T\Delta S$$

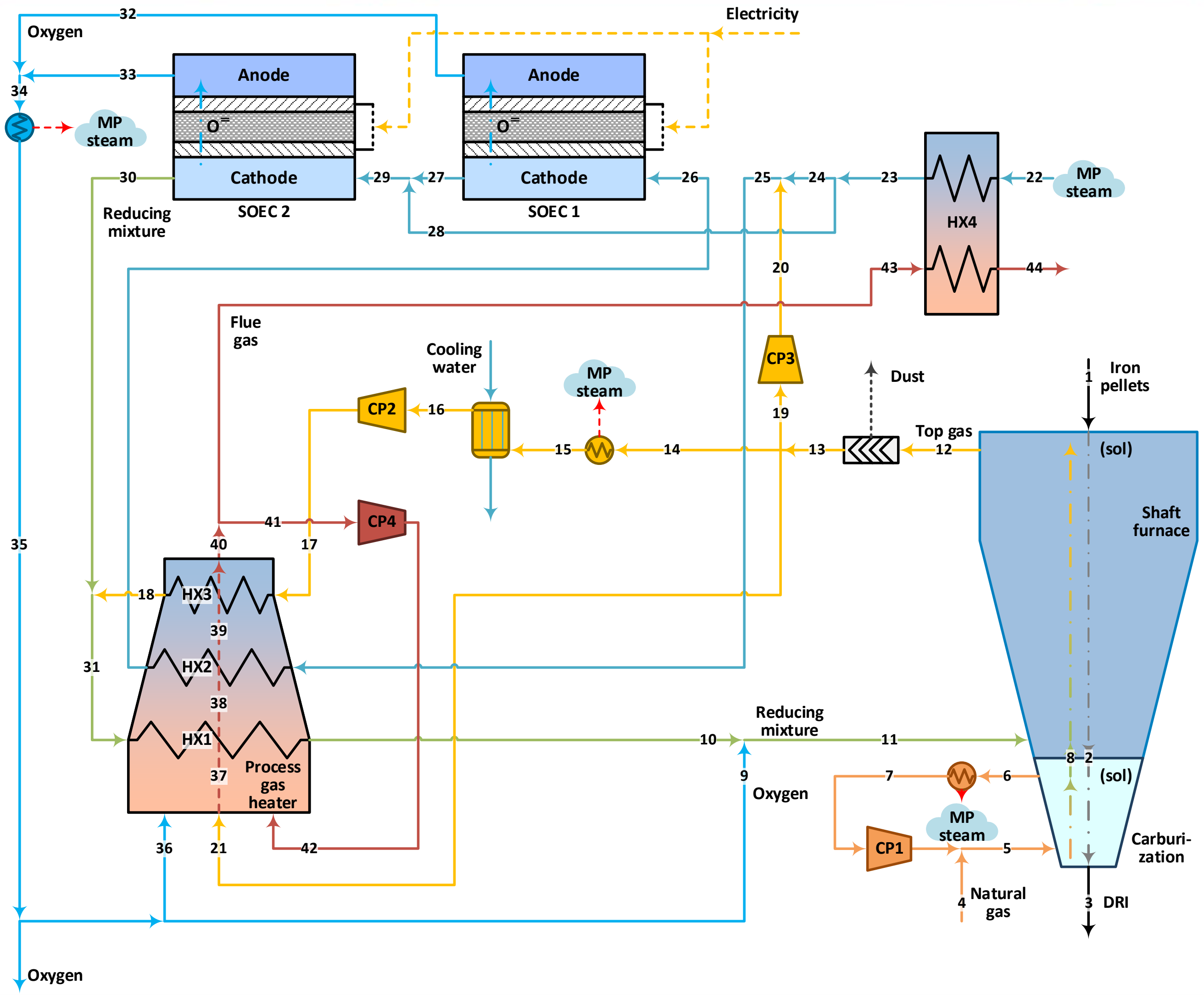
- It is possible to use the **thermal power generated by the losses** to provide part of the energy required by the electro-chemical reaction (ΔG), defining the thermoneutral voltage:

$$V_{tn} = \frac{\Delta H}{2 \cdot F}$$

- Integration strategy:
  - Use the **hot H_2O/CO_2-rich gas at the exit of the shaft furnace to feed the SOEC cathode** side avoiding the need of generating steam
  - Use the **hot cathode outlet stream as reducing gas make-up**

Source: L. Mastropasqua et al., "Solar hydrogen production: Techno-economic analysis of a parabolic dish-supported high-temperature electrolysis system", Applied Energy 261, 2020, 114392, DOI: 10.1016/j.apenergy.2019.114392

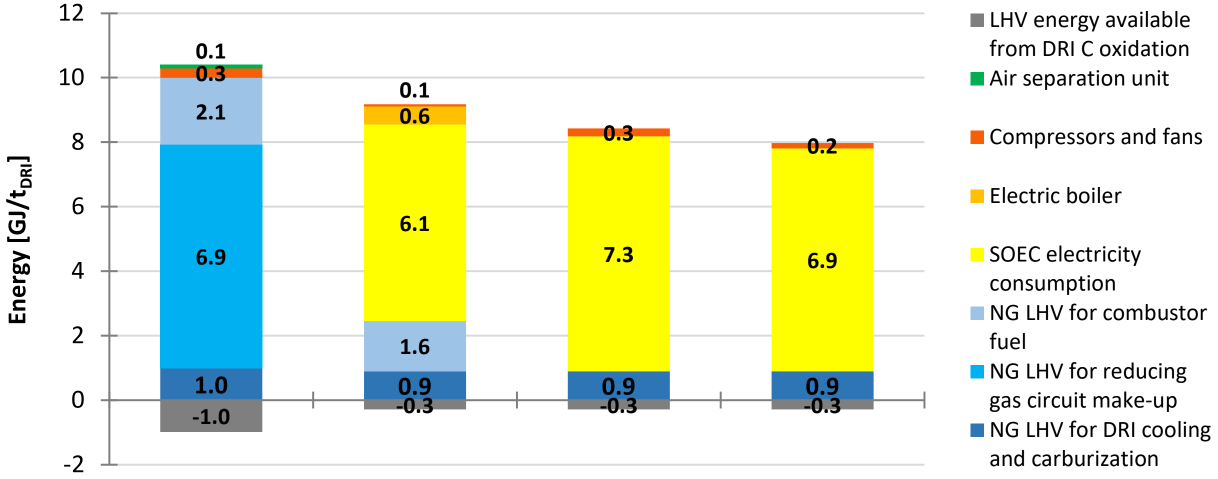
SOEC integration in DRI process

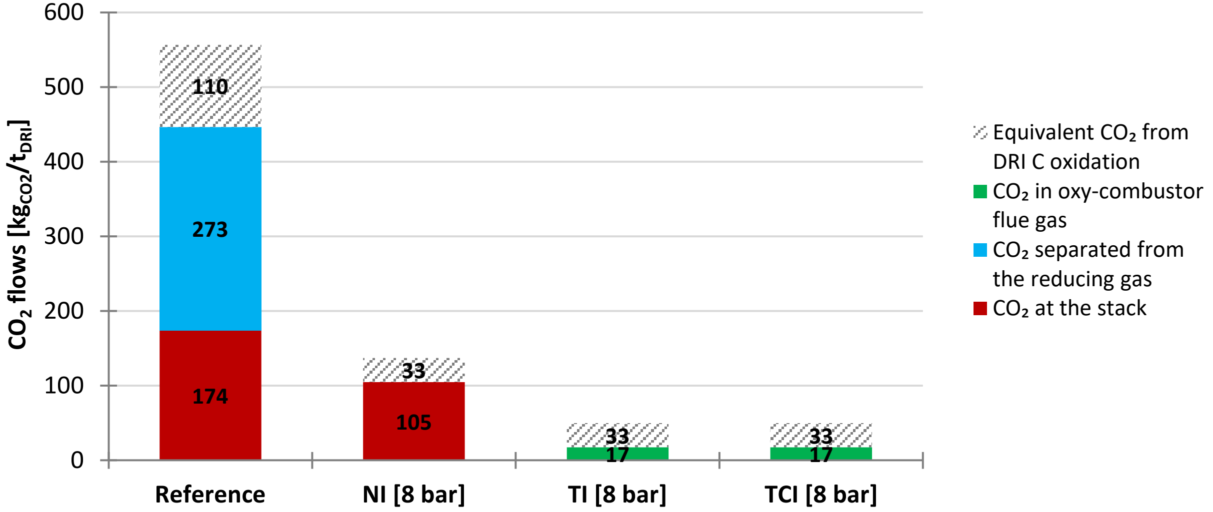


- Three configurations:
  - **Non-integrated**: SOEC completely separated from the DRI plant
  - **Thermally integrated**: the heat for the SOEC steam generation is produced in the process gas heater of the DRI plant
  - **Thermally and chemically integrated**: part of the shaft furnace top gas is directly feed to the SOEC cathode
- **Oxygen from the SOEC anode side** used for the final **partial oxidation** of the reducing gas and as **oxidant** in the process gas heater
- **Oxy-combustion** in process gas heater for **easy CO_2 capture** at the stack

Source: R. Scaccabarozzi et al., "Technical analysis of high-efficiency and flexible direct reduced iron plants integrated with high-temperature electrolysis", Journal of Cleaner Production 489 (2025) 144681, DOI: 10.1016/j.jclepro.2025.144681

SOEC integration in DRI process





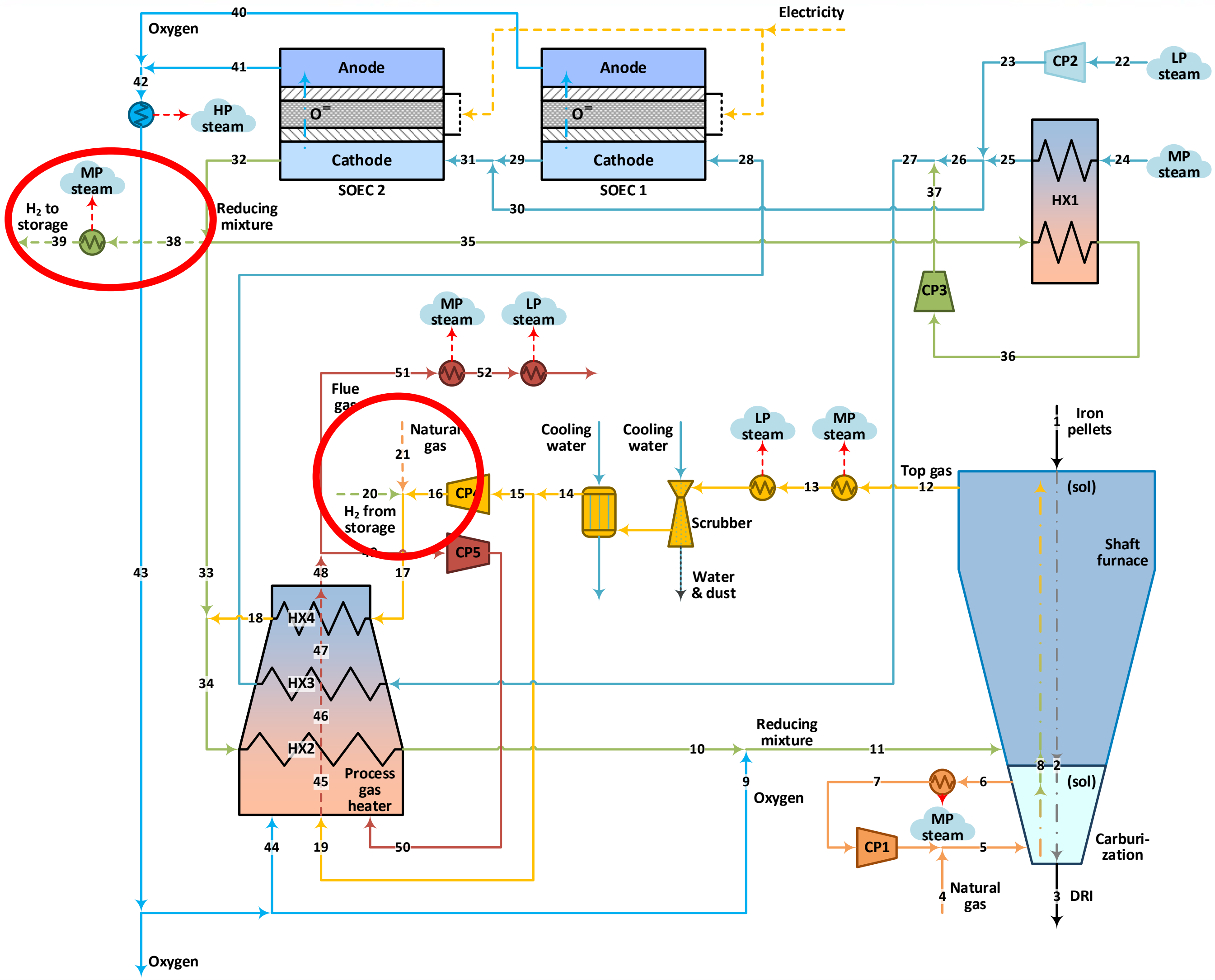
Energy and CO_2 balances of the reference case and three proposed configurations with a SOEC operating pressure of 8 bar

Case	Reference	IN [8 bar]	TI [8 bar]	TCI [8 bar]
SOEC (1 & 2) voltage [V]		1.29 1.32	1.29 1.34	1.23 1.27
SOEC efficiency (LHV basis)		96.1%	96.0%	97.0%
Metallization degree	95.0%	95.0%	95.0%	95.0%
DRI carbon content	3.0%	0.9%	0.9%	0.9%

- It is assumed to design the shat furnace to meet the **metallization requirement of 95%**
- Due to the low concentration of carbon in the reducing gas the **carbon content of the DRI decreases to 0.9%$_{wt}$**
- The thermally and chemically integrated case decreases the **specific energy consumption below 8 GJ/t$_{DRI}$**

Source: R. Scaccabarozzi et al., "Technical analysis of high-efficiency and flexible direct reduced iron plants integrated with high-temperature electrolysis", Journal of Cleaner Production 489 (2025) 144681, DOI: 10.1016/j.jclepro.2025.144681

Plant flexible operation



- **Thermally integrated case** analyzed for flexible operation with **H_2 production/consumption, NG make-up**, and **part-load DRI production**
- Operational mode:
  - **Natural gas import (NG_{in})**
  - **Hydrogen import ($H_{2\ in}$)**
  - **Hydrogen export ($H_{2\ out}$)**
  - **Natural gas import + hydrogen export ($NG_{in}H_{2\ out}$)**
  - **DRI production load 100% and 60%**

Source: R. Scaccabarozzi et al., "Technical analysis of high-efficiency and flexible direct reduced iron plants integrated with high-temperature electrolysis", Journal of Cleaner Production 489, 2025, 144681, DOI: 10.1016/j.jclepro.2025.144681

Plant flexible operation

Table: Energy and emission performance and DRI quality estimation (metallization and carbon content) of the thermally integrated DRI production plant with SOEC off-design operation, both considering full and 60% DRI production capacity.

		Product quality		Energy					CO_2 emission
		Metallization	C content	Natural gas (ID 4 + 21)	H_2 input (ID 20)	Electric consumption	Total energy consumption	H_2 output (ID 39)	CPU (ID 52)
		%	%	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	kg_{CO2}/t_{DRI}
DRI full load - 100%	Base	95,0%	0,9%	0,9	-	7,6	8,4	-	17
	NG_{in}	93,8%	1,1%	2,9	-	5,9	8,8	-	120
	$H_{2\ in}$	95,2%	0,9%	0,9	2,1	4,8	8,2	-	16
	$H_{2\ out}$	95,1%	0,9%	0,9	-	8,5	9,4 (8,6)	0,8	16
	$NG_{in}H_{2\ out}$	93,8%	1,1%	2,9	-	8,5	11,4 (9,2)	2,2	122
DRI part load - 60%	Base	97,3%	1,3%	1,2	-	7,4	8,6	-	22
	NG_{in}	96,8%	1,5%	3,3	-	5,8	9,1	-	127
	$H_{2\ in}$	97,4%	1,3%	1,2	2,5	4,7	8,4	-	22
	$H_{2\ out}$	97,3%	1,2%	1,2	-	14,2	15,4 (9,5)	5,9	23
	$NG_{in}H_{2\ out}$	96,1%	1,5%	3,3	-	14,1	17,4 (10,1)	7,3	128

- Operational mode:
  - **Natural gas import (NG_{in})**
  - **Hydrogen import ($H_{2\ in}$)**
  - **Hydrogen export ($H_{2\ out}$)**
  - **Natural gas import + hydrogen export ($NG_{in}H_{2\ out}$)**
  - **DRI production load 100% and 60%**

Source: R. Scaccabarozzi et al., "Technical analysis of high-efficiency and flexible direct reduced iron plants integrated with high-temperature electrolysis", Journal of Cleaner Production 489, 2025, 144681, DOI: 10.1016/j.jclepro.2025.144681

Optimal sizing and operation

Method

- Mixed-Integer Linear Programming (MILP)

Time window

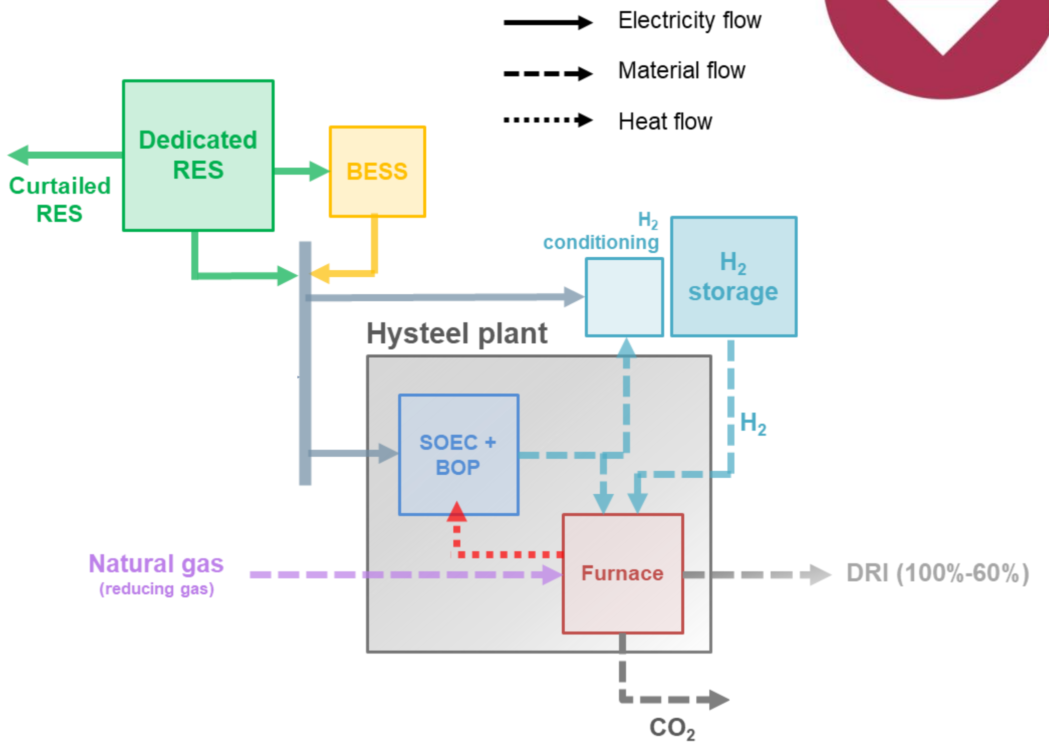
- One year horizon with 1-hour resolution

Objective function

- Minimization of the total annual cost (TAC)

Constraints

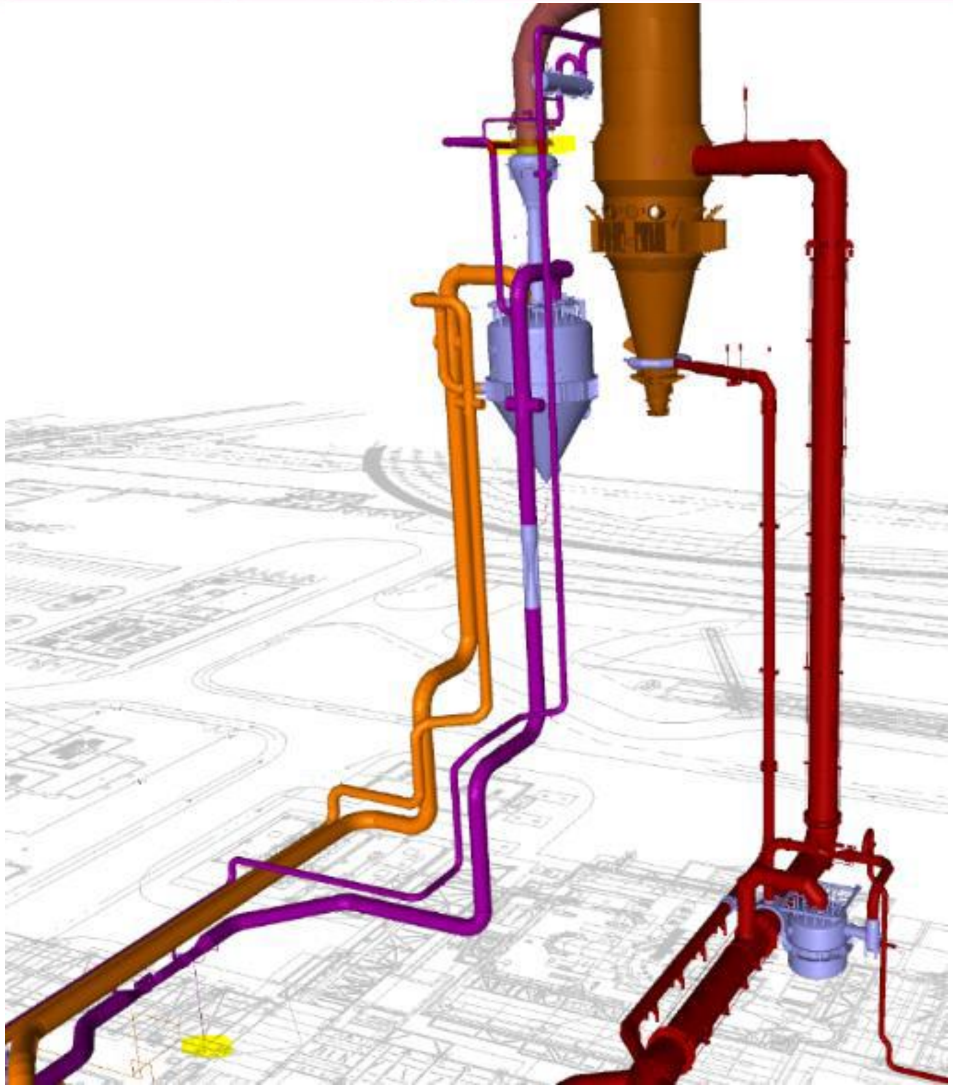
- Energy and material balances from system process analysis → Operational maps
- Fixed DRI production of 2 Mt/y

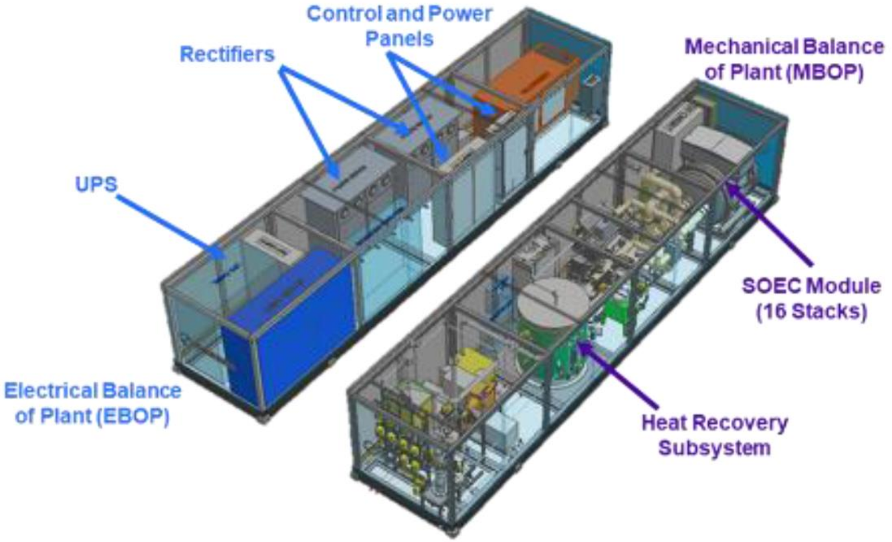


Flexibility option	Inflex.	fS	fS+fD	fS+NG	fS+fD+NG
SOEC flexibility and hydrogen storage		✓	✓	✓	✓
DRI shaft furnace flexibility			✓		✓
Natural gas as reducing gas				✓	✓

Soon to be published

HySteel II - Demonstration of a SOEC Hydrogen Direct Reduction (HDR) at the Toledo, Ohio Steel Plant





38' L x 7'-10" W x 7'-7" H (x 2 skids)

- Design and demonstrate iron Hydrogen Direct Reduction (HDR) and Hybrid-HDR systems at **TRL 6**
- Install and demonstrate the operation for at least **3600 hr** of a **250 kW_{el} SOEC** system at the existing **1.6 Mt_{DRI}/y facility in Toledo, OH**
- Demonstrating the potential to reduce specific CO_2 emissions from ironmaking plants to **<20 kg_{CO2}/t_{DRI}**, and specific primary energy consumptions **<8 GJ/t_{DRI}**

Conclusions

- The current average DRI production plant requires around 10 GJ/t_{DRI}, mainly as chemical energy (LHV) of natural gas, to operate the DRI production unit while emitting 450 kg_{CO2}/t_{DRI}
- Even considering a **non-integrated case** (SOEC case), where the SOEC unit is completely separated from the DRI production system, the use of an electrolyzer to generate the reducing gas make-up stream and replacing the fuel for the preheating section can reduce the **overall energy consumption to 9.4 GJ/t_{DRI}**, and simultaneously reduce the **CO_2 emission to 150 kg_{CO2}/t_{DRI}**
- If the **SOEC is integrated in the DRI production system** (SOEC & CCS case), so that the furnace top gas is directly fed to the cathode side of the electrolyzer and the oxygen generated is used as oxidant by the combustor of the pre-heating section, the **overall energy consumption can decrease to 8.0 GJ/t_{DRI}**, and the **greenhouse gas emission to 17 kg_{CO2}/t_{DRI}**
- The integration of the SOEC electrolyzer to generate the reducing gas requires to **substitute the largest part of the chemical energy** (NG input of the reference case) **with electricity**
- To respond to variability of renewable energy sources, **SOEC-DRI plants may adapt electricity consumption by increasing natural gas input, by importing/exporting hydrogen from/to a storage unit and by reducing DRI production**
- Key parameter to be economically competitive is the **sizing optimization of the various sections (RES, BESS, H_2 storage)** and the system flexibility in term of load and energy source
- **The HySteel II project will demonstrate the ability of the proposed system to achieve the decarbonization targets**

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Disclaimer: the views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government

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Thankyou for your attention

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RETE ALTA TECNOLOGIA EMILIA-ROMAGNA HIGH TECHNOLOGY NETWORK

TECNOPOLO PIACENZA

LEAP FOUNDED IN 2005 BY POLITECNICO DI MILANO