Solid Oxide Electrolysis Cells (SOEC) integrated with Direct Reduced Iron (DRI) plants for producing green steel

Kick-off and preliminary results

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November 4th, 2021

http://www.apep.uci.edu/H2GS/

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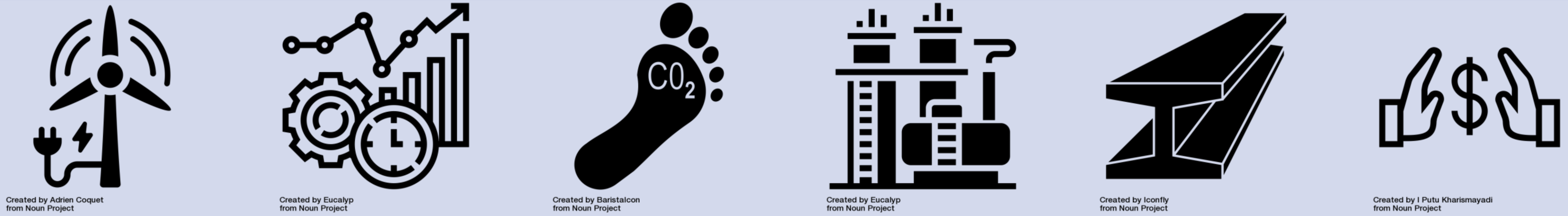
Project Goal and Milestones

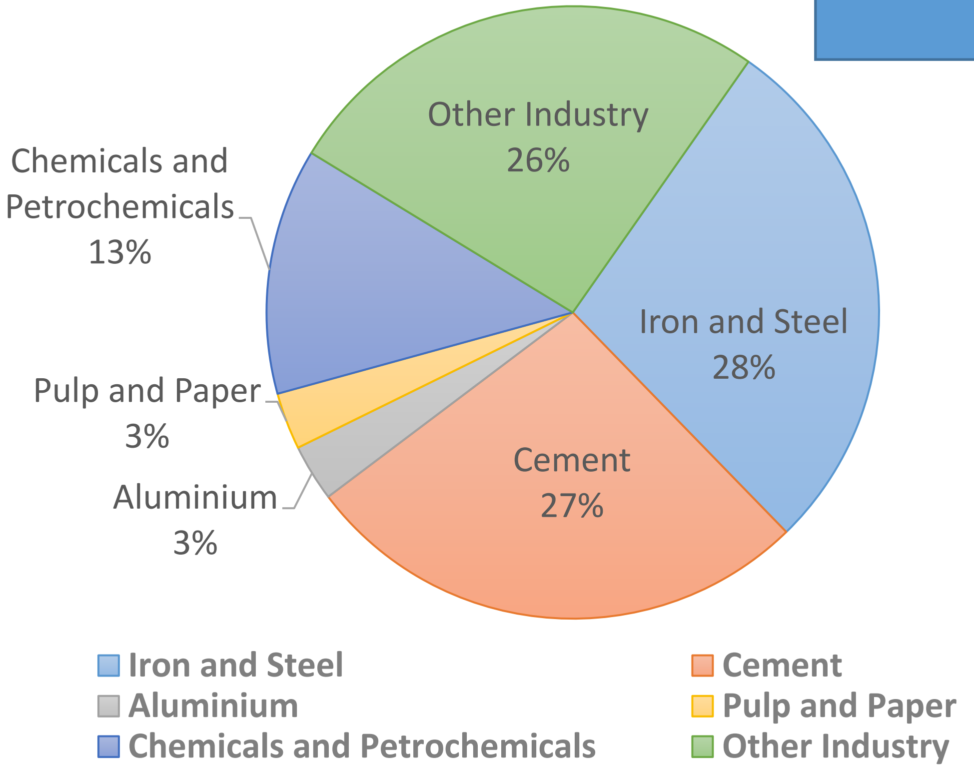
Advance, demonstrate and optimize a thermally and chemically integrated Solid Oxide Electrolysis Cell (SOEC) system, as co-producer of H_2 and O_2, with a Direct Reduction Iron (DRI) plant at 1 ton/week of product scale.



Specific primary energy consumption <8 GJ/t_{DRI}	**Electric-to-hydrogen efficiency for an SOEC stack of <35 kWh/kg of H_2 produced**	**Specific CO_2 emissions rate < 90 kg CO_2/ton DRI product w/o oxyfuel**	**Pilot system at production capacity of 1 ton/week and TRL 4**	**Scale-up design for a 2 Mton/year DRI product capacity**	**Total capital specific cost < $200/ton equivalent pig-iron per year**

Potential Impact

Direct Industrial CO2 emissions



WorldSteel association – World steel in figures 2020
International Energy Agency (IEA)

Steel industry:
World total 1869 $Mton_{steel}$
6-6.5% of total anthropogenic CO_2 emissions

Blast Furnace + Basic Oxygen Furnace (BF+BOF)
Hydrogen Direct Reduction (HDR)
Hybrid Hydrogen Direct Reduction (Hybrid HDR)

	Units	BF+BOF	HDR	Hybrid HDR
Energy intensity	$GJ/ton_{crude\ steel}$	19-22	<8	<9
Specific emissions	$ton_{CO2}/ton_{crude\ steel}$	1.8-2.1	<0.09	<0.09
Specific cost	$\$/ton_{eq\ pig\text{-}iron}\ yr$	210	200*	200*
Electric load	$GJ_{el}/ton_{crude\ steel}$	-	<7	<7
*At 2 Mton/yr scale				

	Units	Ref SOEC	HDR	Hybrid HDR
Hydrogen Eff.	kWh/kg	40	35	-
Syngas Eff.	kWh/kg	45	-	40
Oxygen Eff.	kWh/kg	6.5	<5	<5

Iron and Steel industry

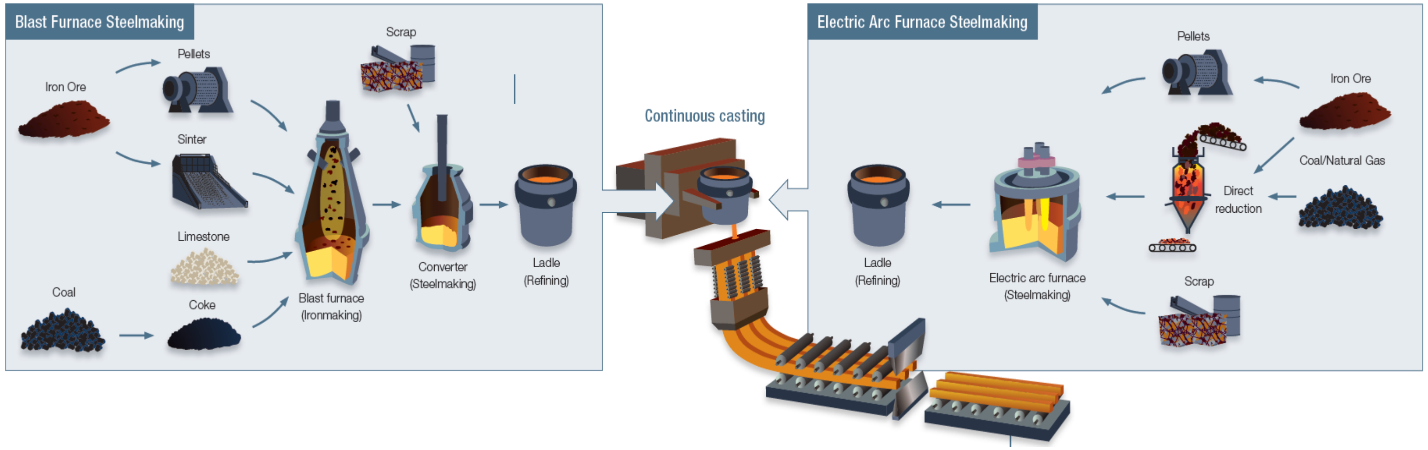
Technology Impact

Steel production is responsible for the 7% of global anthropogenic CO_2 emissions and a rise of 20% in steel production is predicted until 2040. BF-BOF steel production route produces 71% of total steel:

- Energy intensity: 19-20 GJ/$ton_{crude\ steel}$
- Specific emissions: 1.8-1.9 $ton_{CO2}/ton_{crude\ steel}$

Reference Integrated Steel Mill:

- **Capacity: 4 $Mton_{HRC}$/yr**
- **Total specific emission: 2.01 t_{CO2}/t_{HRC}**



BF/BOF Steelmaking ↔ **Coal** processing

Source of heat to melt the iron ores (Fe_2O_3)
Source of CO-reducing gas for ironmaking
Sustain charge (porosity and carrying capacity)

Carbon Capture and Storage

Alternative Steelmaking Routes

Noteworthy relevant projects:

- *2018: HYBRIT - SSAB site in Luleå, Sweden, with SEK 500 million ($51.88 million)*
- *ArcerlorMittal Hamburg DRI plant*
- *2019: thyssenkrupp Steel grant IN4climate.NRW*

L **Mastropasqua**, et al., International Journal of Greenhouse Gas Control 88, 195-208
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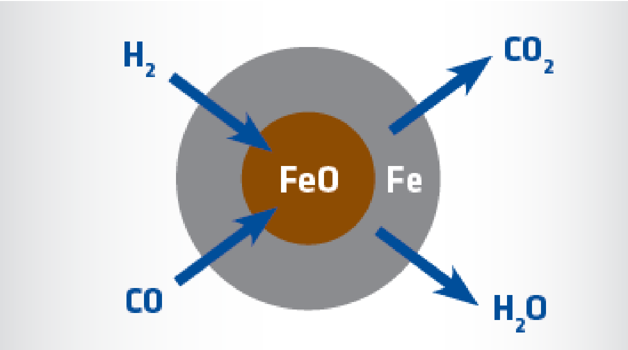
Background - Direct Reduced Iron



Reduction with H_2

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

Reduction with CO

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

Reduction with $C_{(s)}$

$CO_2 + C \rightarrow 2CO$

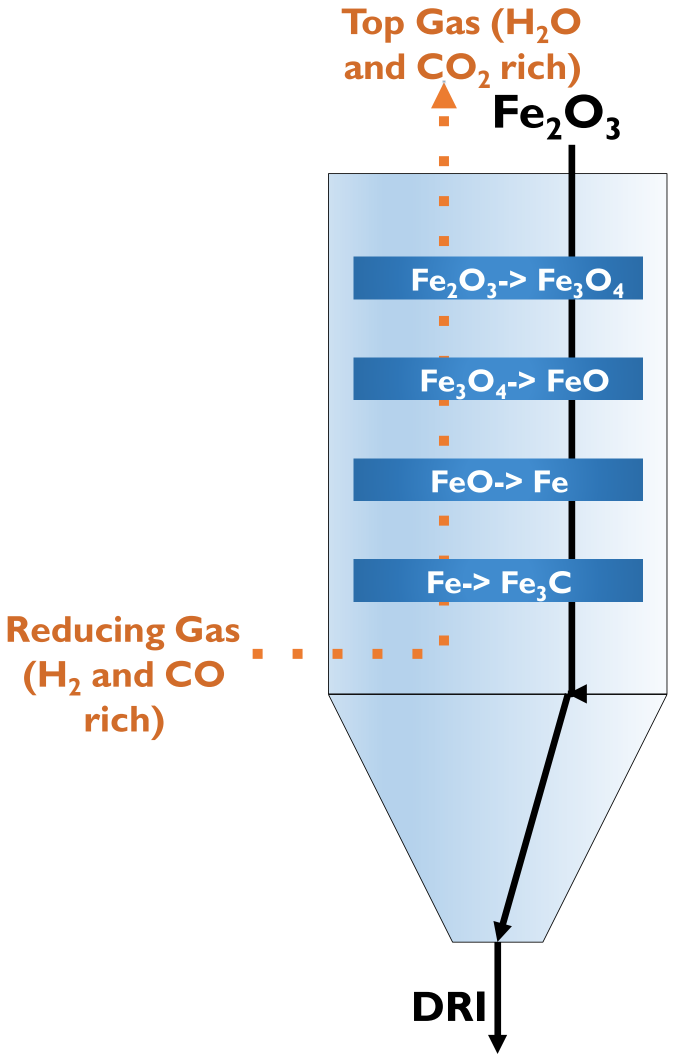
Fe_2O_3	**Hematite**	% Oxygen = 30.05 %
Fe_3O_4	**Magnetite**	% Oxygen = 27.64 %
FeO	**Wustite**	% Oxygen = 22.27 %
Fe	**Iron**	% Oxygen = 0 %

METALLIZATION:

$$M\ [\%] = \frac{Fe_0\ [kg]}{Fe_{tot}\ [kg]} \qquad 90\% < M < 96\%$$

CARBON CONTENT:

$$C\ [\%] = \frac{C_{Fe_0}\ [kg]}{C_{Fe_{tot}}\ [kg]} \qquad 0.3\% < M < 0.8\%$$



SOEC Steam electrolysis

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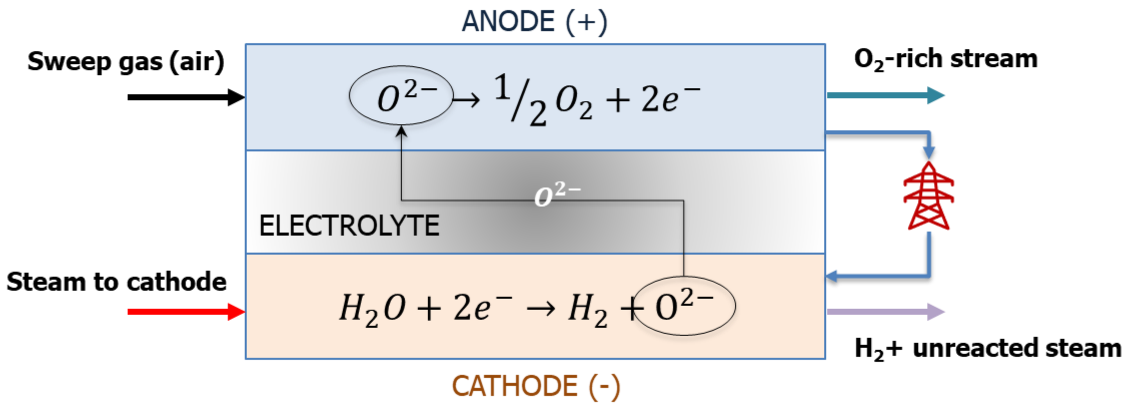


$$\eta_{el-H_2} = \frac{LHV_{H_2} \cdot \dot{m}_{H_2}}{\dot{W}_{el}} = \frac{LHV_{H_2} \cdot \left(\frac{jA}{2\mathcal{F}}\right)}{\dot{W}_{el}}$$

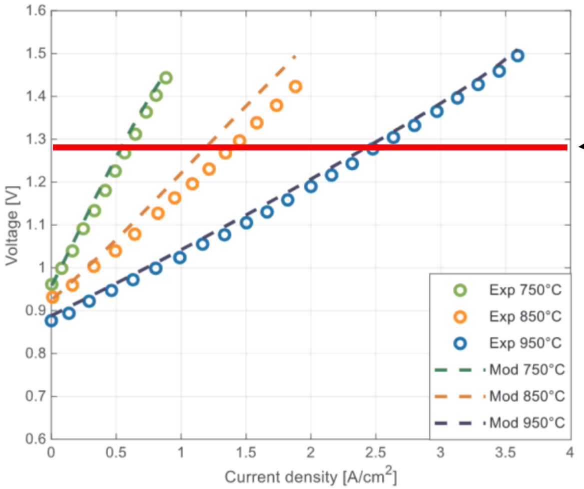
Electric-to-H_2 efficiency

$$\eta_I = \frac{LHV_{H_2} \cdot \dot{m}_{H_2} + \dot{Q}_{th}}{\dot{W}_{el} + \dot{Q}_{th}}$$

First law efficiency

Temperature range: **600-850°C**

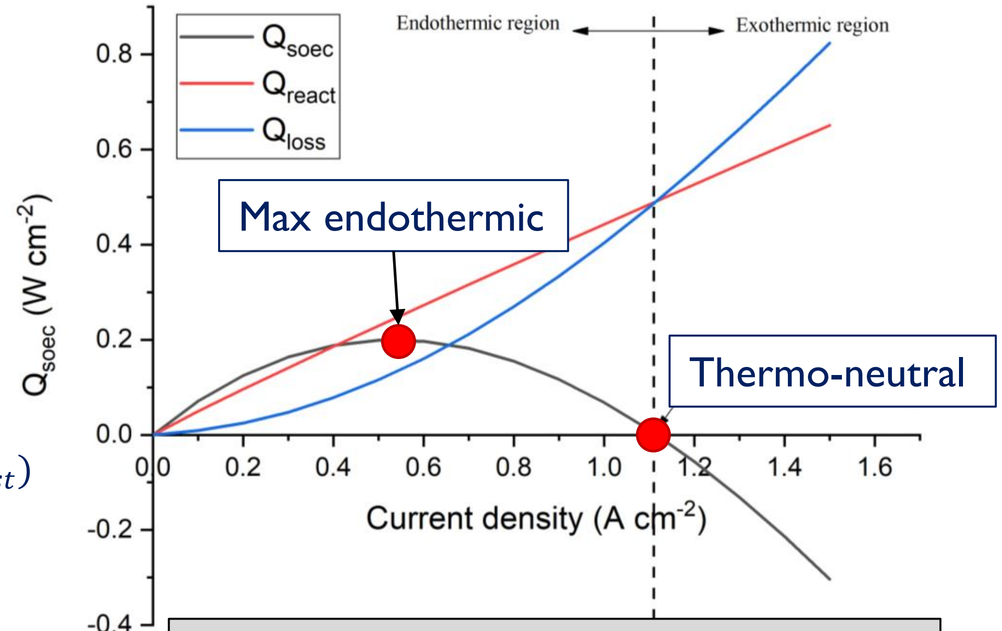
$$H_2O + \textbf{heat} \rightarrow H_2 + 1/2 O_2$$



Thermo-neutral voltage
V_{tn} = 1.285 V

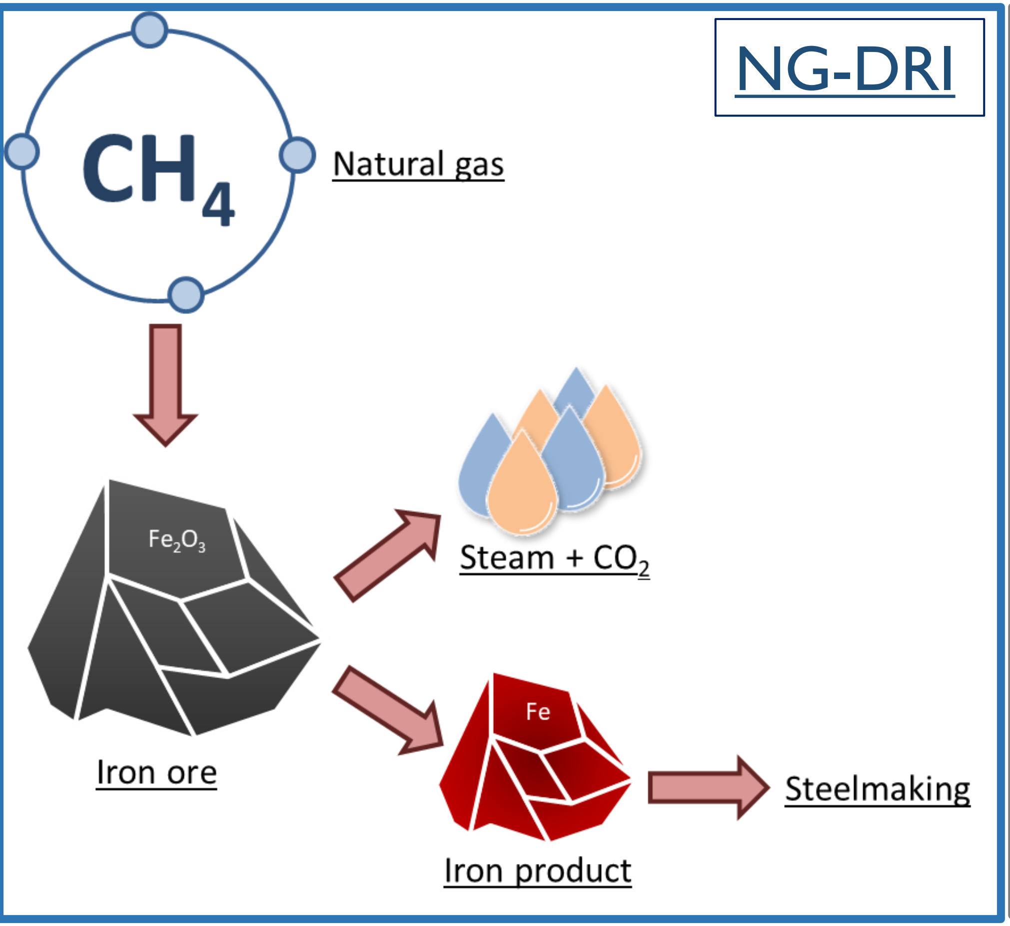
$$Q_{gen} = \frac{j}{2F} T\Delta S = \frac{j}{2F}(\Delta H_r - \Delta G) = j(V_{tn} - V_{Nernst})$$

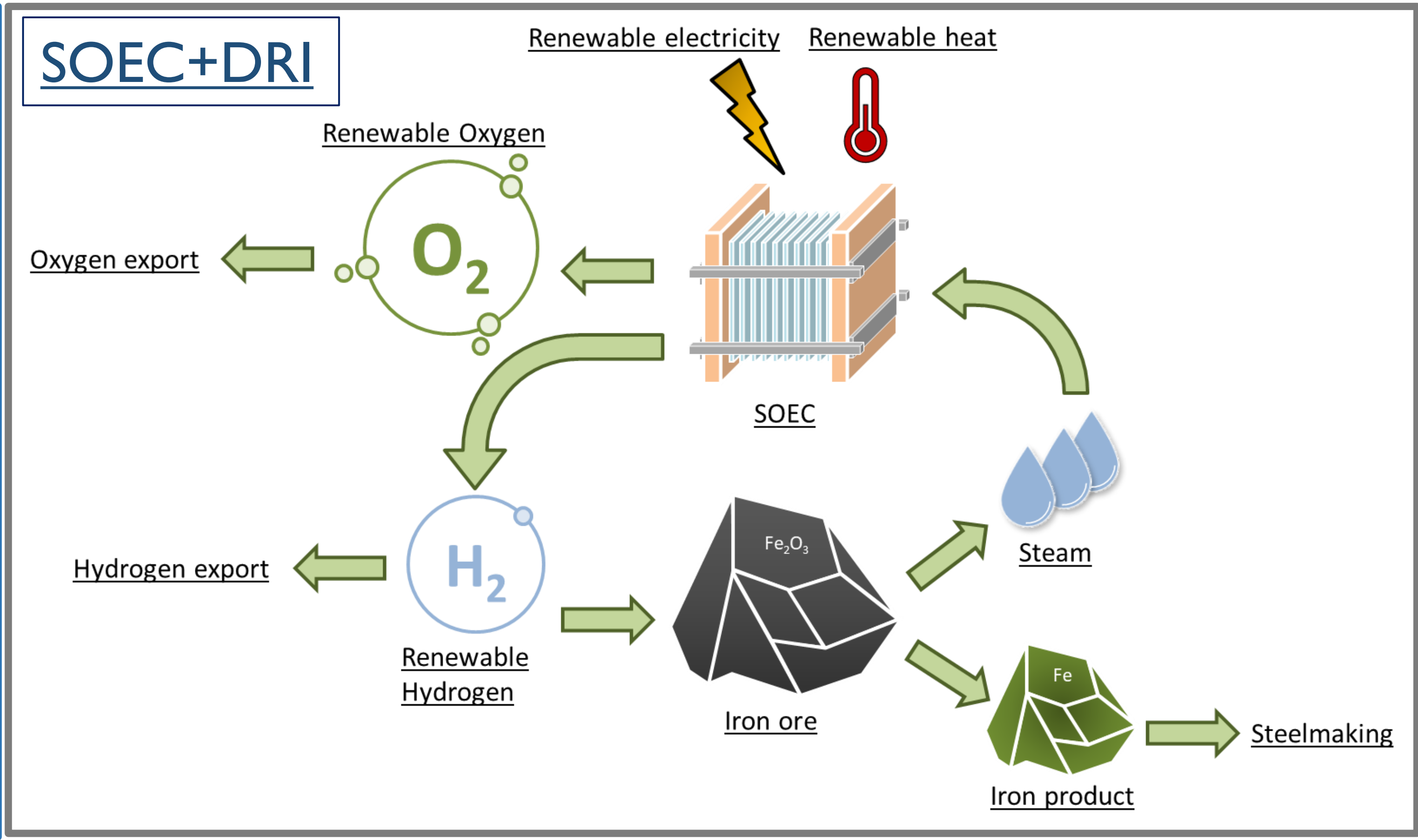
$$Q_{loss} = j(V - V_{Nernst}) = j(\sum \Delta V_{loss})$$



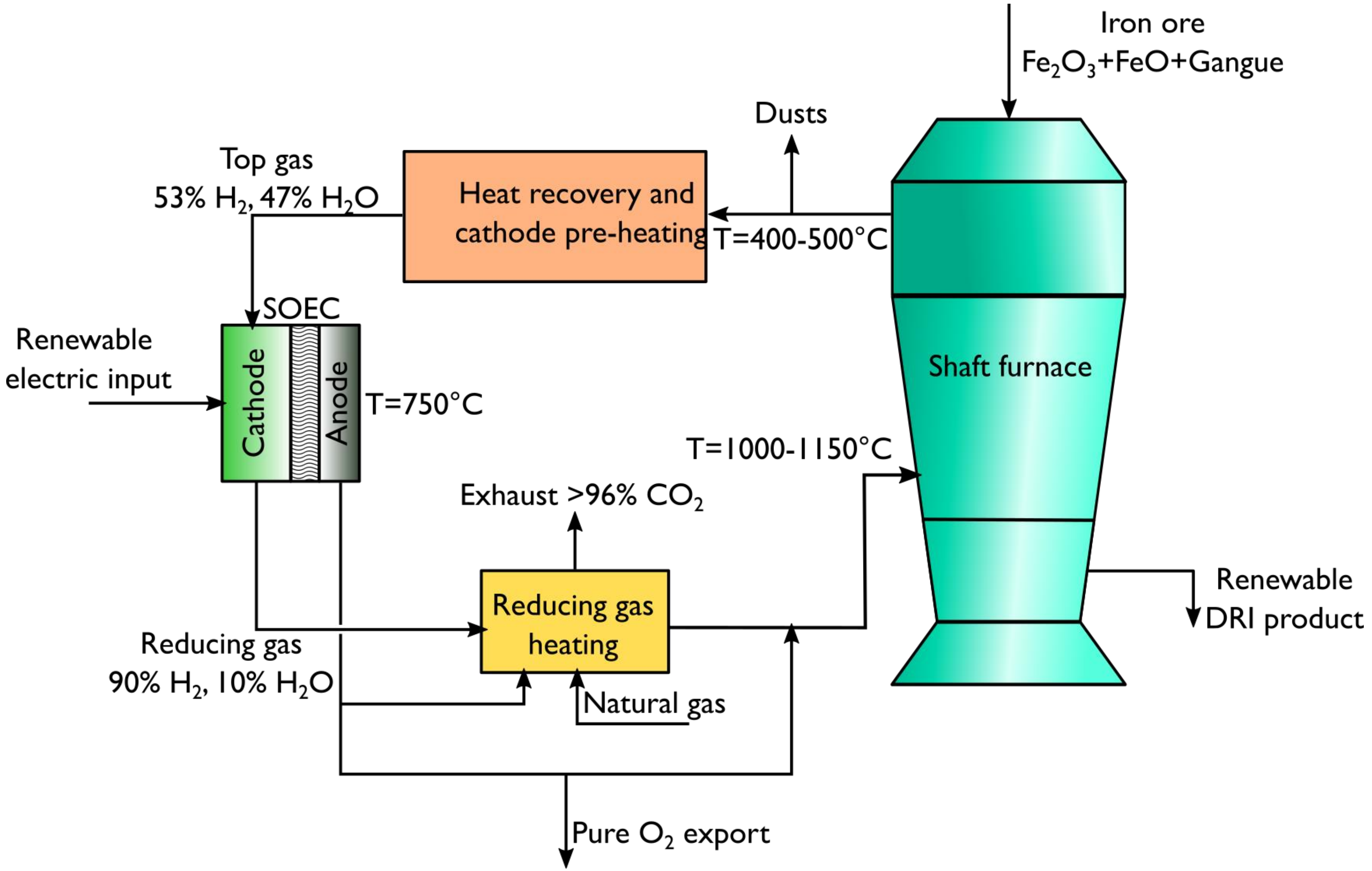
Mastropasqua et al., 2020, Applied Energy 261, 114392

State of the Art vs. SOEC+DRI





Hydrogen Direct Reduction (HDR)



- **SOEC** operates as oxygen pump to remove O_2 from **shaft furnace** top gas
- SOEC exploits the enthalpic content of top gases to perform part of the electrochemical process
- Iron ore is reduced mainly with hydrogen produced by the SOEC
- Carbon is introduced in the cycle only to provide carburization to DRI product
- Excess carbon is oxidised in pure oxygen (produced by SOEC) and captured

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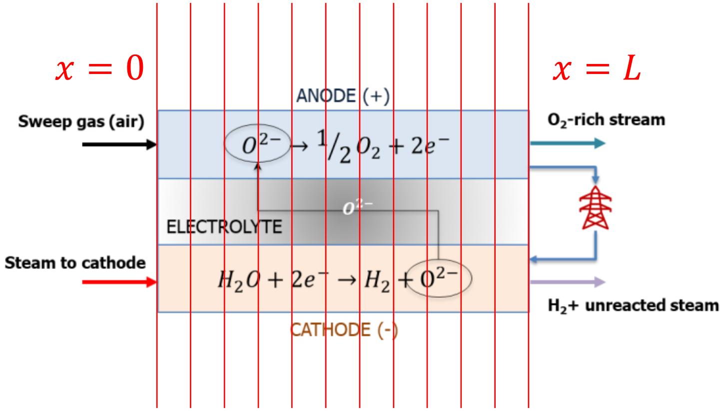
SOEC steam electrolysis design

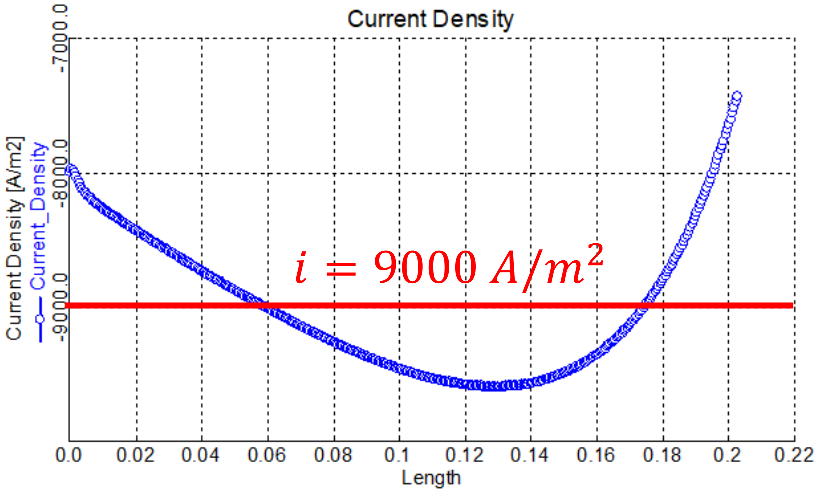


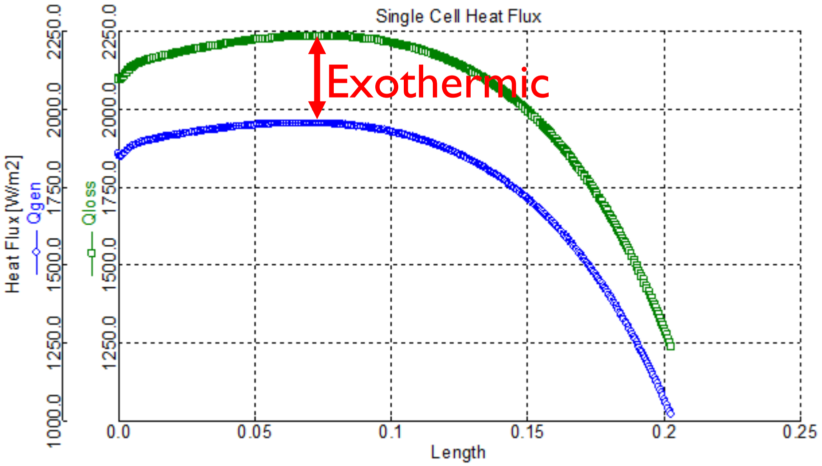
Current density	A/cm^2	0.9
Cell voltage	V	1.315
Power	MW	533
Steam utilization	-	0.85
Stack efficiency (LHV based)	%	95.35
Energy per kg of H_2	kWh/kg	34.98
Energy per kg of O_2	kWh/kg	4.406

Slightly exothermic
V_{tn} = 1.285 V

85% of inlet steam is converted

High H_2 and O_2 production efficiencies





$$\dot{m}_{H_2} = \left(\frac{I}{2\mathcal{F}}\right) \qquad \dot{m}_{H_2} = \qquad I =$$

$$i = \frac{I}{A} \uparrow \qquad A \downarrow$$

$$V \propto i \uparrow \quad \dot{W}_{el} \propto IV \uparrow \quad \eta_I \downarrow$$

$$CAPEX = c_{SOEC} \cdot A \left[\frac{\$}{m^2} \cdot m^2\right] \downarrow$$

$$c_{H_2} = \frac{CAPEX}{\dot{m}_{H_2}} \downarrow$$

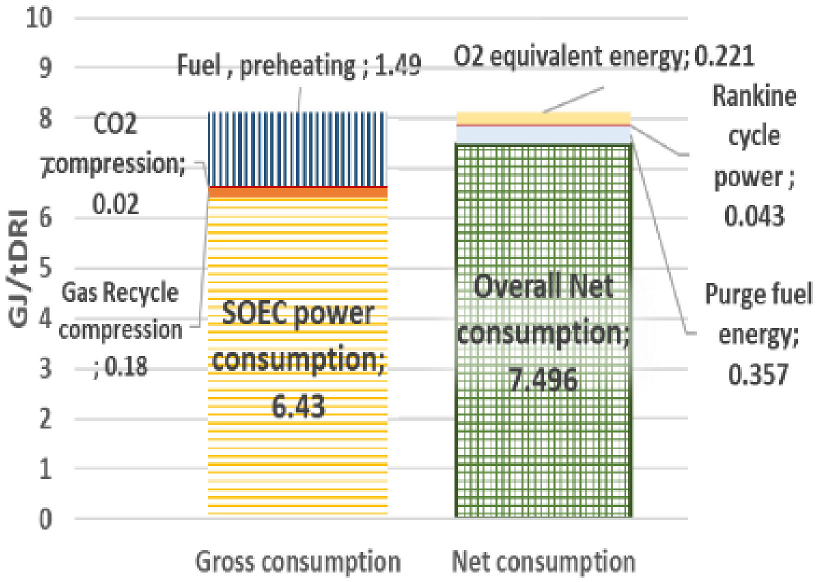
Preliminary thermodynamic performance

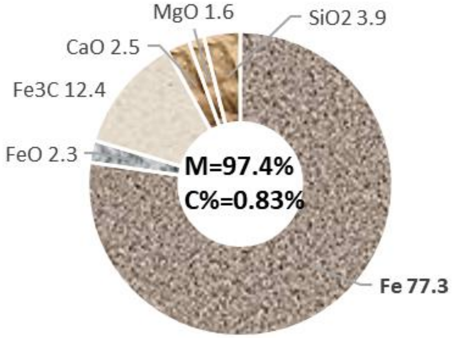
$$C\,[\%] = \frac{c_{Fe_0}\,[kg]}{c_{Fe_{tot}}\,[kg]}$$ = 0.85%mass Carburization

$$M = \frac{Fe_0}{Fe_{tot}}$$ = 97.5% Metallization factor

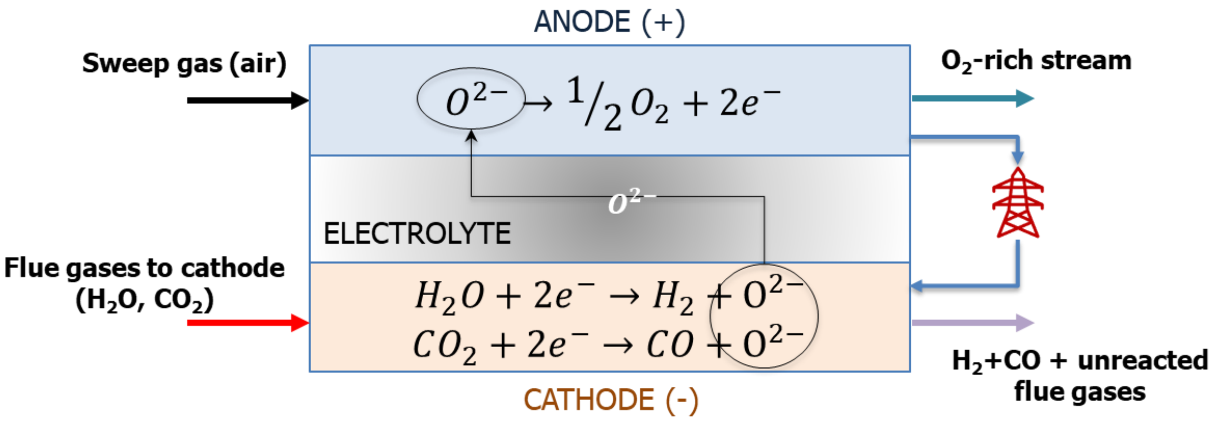
$$PE_{dir}^{HDR} = PE_{RES} + \dot{m}_{NG} \cdot LHV_{NG}$$ = 7.4−8.3 GJ/ton DRIhot

$$e_{CO_2} = \frac{E_{CO_2}^{HDR}}{m_{DRI}}$$ = 40-60 kg CO_2/ton DRI_{hot}





SOEC – CO_2 and co-electrolysis



Temperature range: **600-850°C**

REDOX

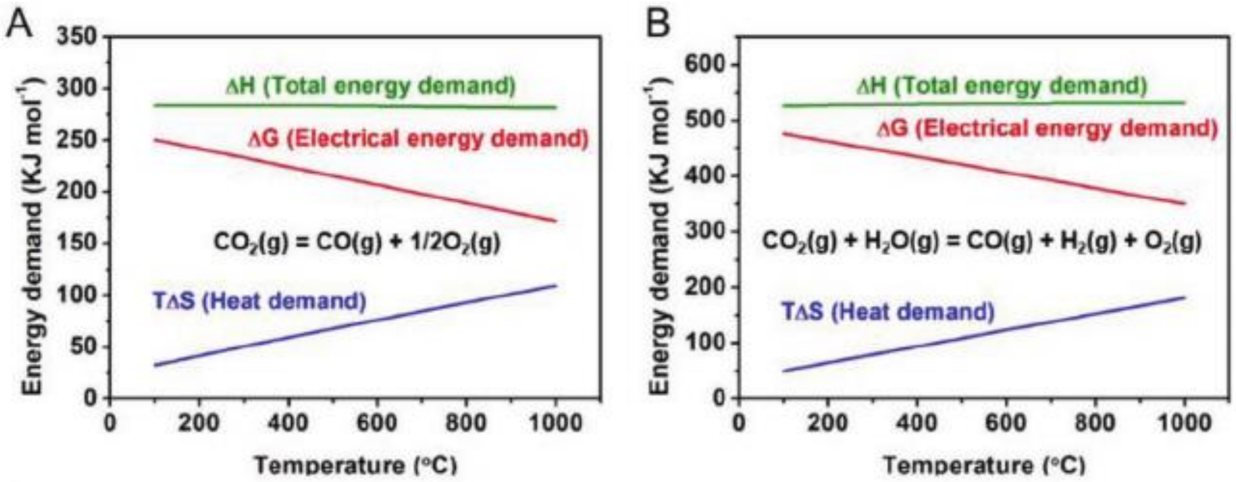
$$H_2O + \textbf{heat} \rightarrow H_2 + 1/2O_2$$

$$CO_2 + \textbf{heat} \rightarrow CO + 1/2O_2$$

$$C_nH_m + nH_2O + \textbf{heat} \rightleftharpoons \left(\frac{m}{2} + n\right) H_2 + nCO$$

$$CO + H_2O \rightleftharpoons H_2 + CO_2 + \textbf{heat}$$

$$E_{Nernst} = \frac{\Delta G_{mix}}{nF} + \frac{RT}{nF} ln\left(\frac{x_{H_2O,cat}\, x_{CO_2,cat}}{x_{H_2,cat} x_{CO,cat}\, x_{O_2,an}}\right)$$

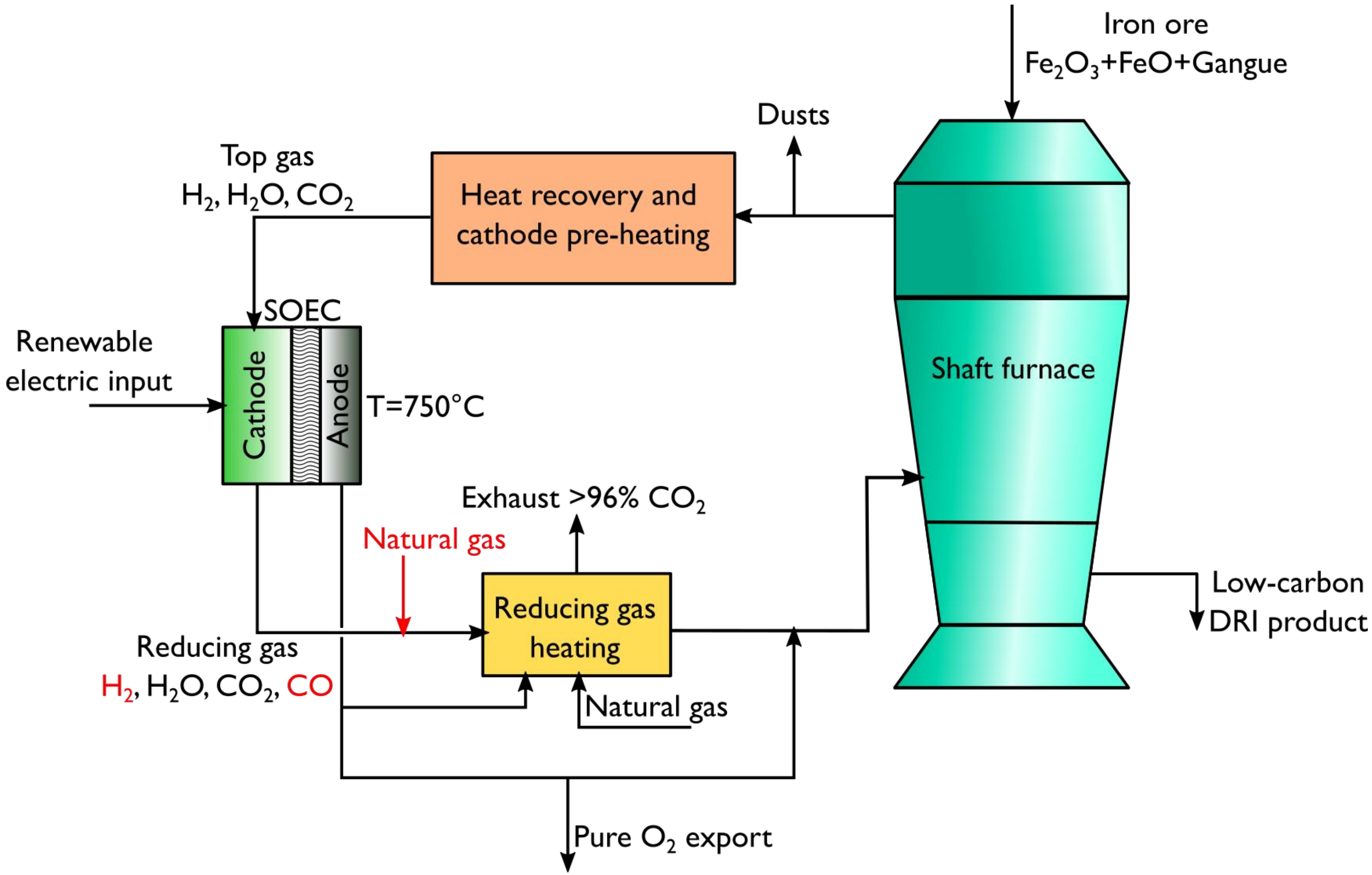


Summary

- Mixture of steam and CO_2 can be electrochemically reduced to produce a syngas and pure oxygen
- Depending on the operating conditions of the SOEC, methane and other longer hydrocarbon species can be produced inside the cell cathode
- The endo or exothermicity of the stack is determined by the current density and internal chemical reactions yield

Song et al., Adv. Mater. 2019, 31, 1902033

Hybrid HDR concept – co-electrolysis



- **SOEC** operates in co-electrolysis mode. Both H_2O and CO_2 are directly converted into H_2 and CO
- Methane can also be formed in co-electrolysis – thermodynamically favored by high pressure, and kinetically enabled by high temperature
- Hybrid HDR enables regulating the DRI carbon content without increasing natural gas make-up
- High-pressure co-electrolysis will be demonstrated

Hardware-in-the-Loop (HIL) SOEC+DRI simulator

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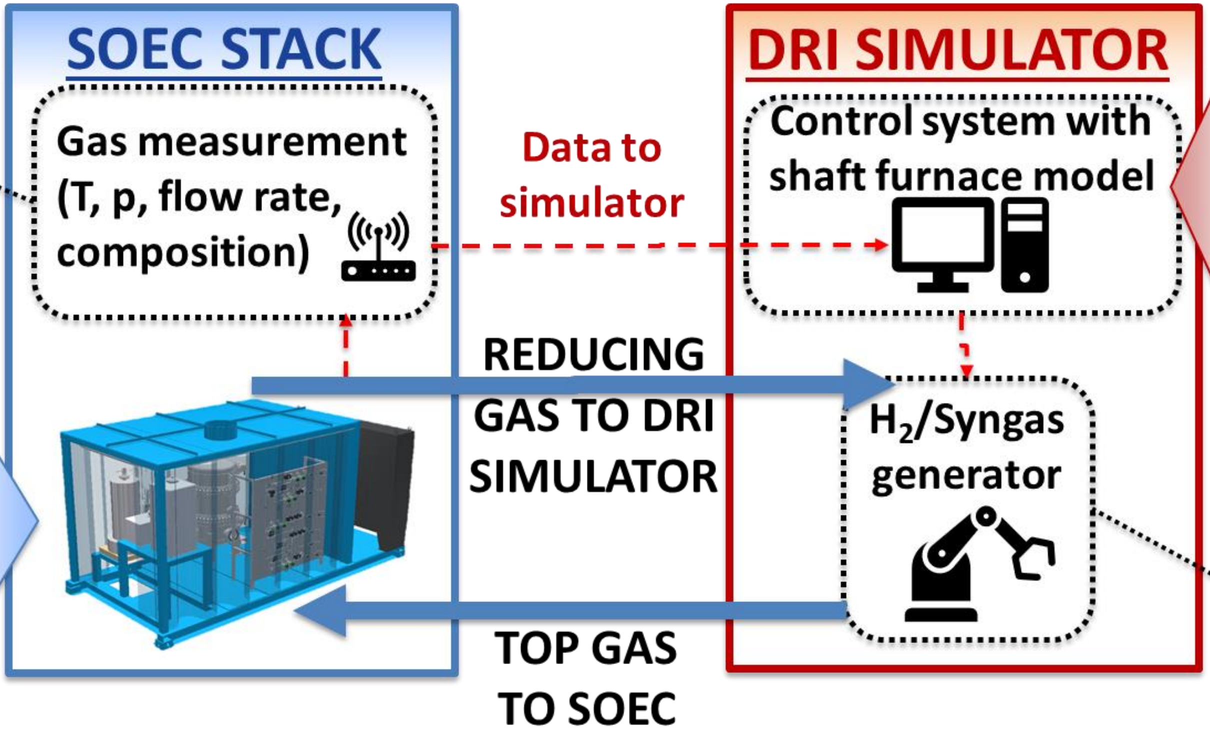
Physical sensors
- Flowmeters
- Thermocouples
- Pressure gauge
- GC

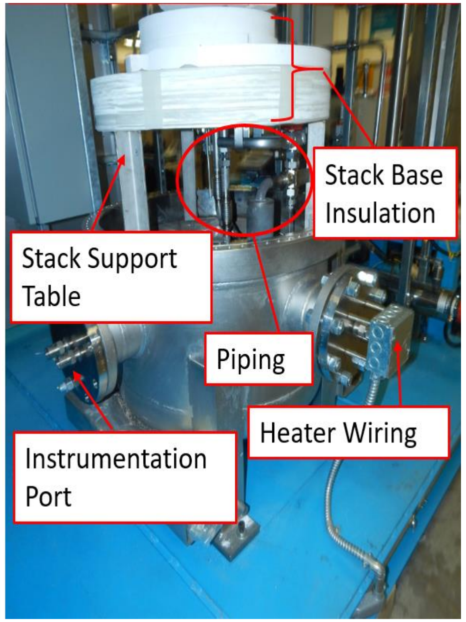
SOEC Physical Inputs:
- Power supply profile
- Current density
- Temperature
- Flow

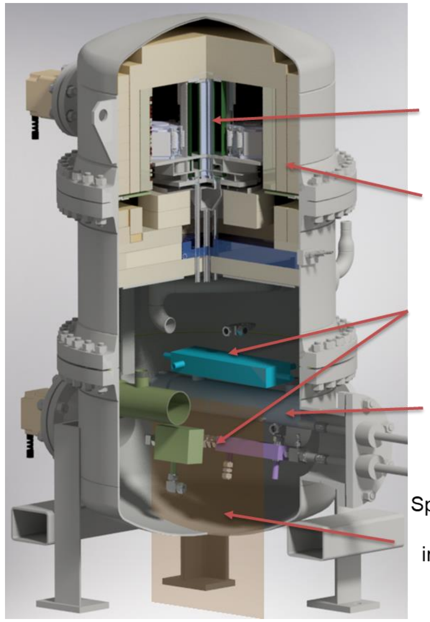


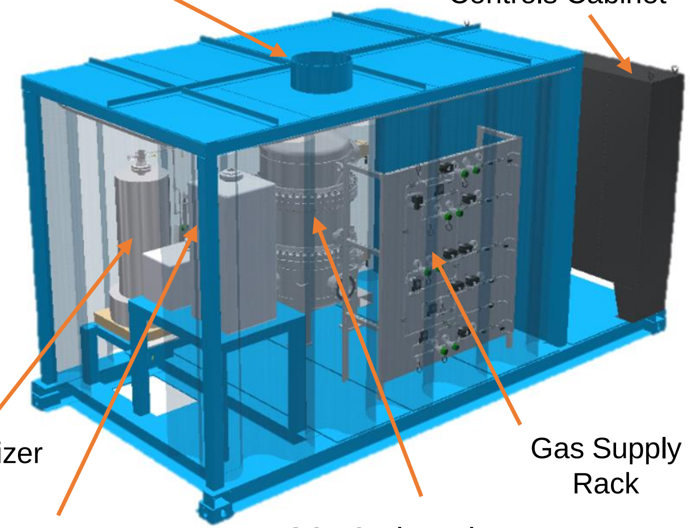
DRI Virtual Inputs:
- Iron ore composition
- Gangue content
- Pellet coating
- Residence time
- Operating temperature
- Size, furnace configuration

Physical actuators + hardware
- Calibrated gas tanks
- Heat exchangers
- Vessels /Piping /Valves

Demonstration System Design







125 psig (8.6 barg) design pressure

Accommodates 1x150-cell stack or 4x45-cell stacks with adapter

Three thermal zones:

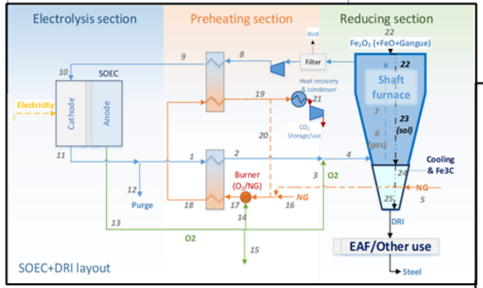
- Hot zone for the electrolyzer stack
- Mid-temp zone for BOP components such as electric heaters and heat exchangers
- Cool Instrument termination zone

Vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature.

Project Work Packages

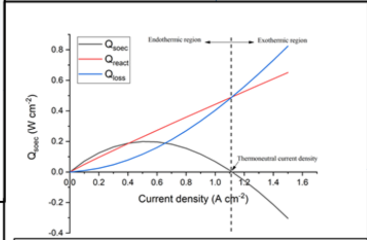
WP1: System integration and thermodynamic analysis

- *Plant conceptualization and thermodynamic analysis*
- *DRI kinetics at high H_2 concentrations*
- *Assessment of product quality*



WP2: SOEC module design and control

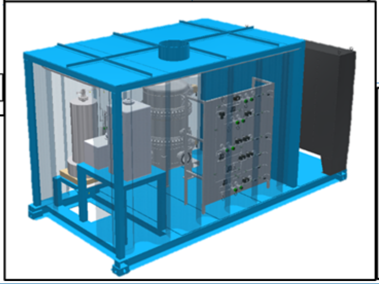
- *SOEC module sizing and nominal load design*
- *SOEC thermal management*
- *SOEC control strategy development*



Mastropasqua et al., 2020, Applied Energy 261, 114392

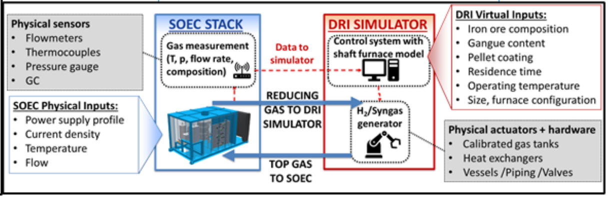
WP3: SOEC prototype design, construction and testing

- *Testing in relevant conditions for DRI operation*
- *SOEC prototype design*
- *SOEC prototype fabrication*



WP4: Design and characterization of pilot-scale SOEC+DRI process

- *Design and commissioning of DRI simulator*
- *Integration and commissioning of SOEC module into DRI test bench*
- *Characterization and testing of integrated SOEC+DRI system*



WP5: Techno-economic optimization of full scale SOEC+DRI layouts

- *Economic and market background build-up*
- *Design and Techno-economic assessment of full-scale system*
- *Comparative assessment with state-of-the-art*
- *Sector coupling assessment*

1 ton/week demo at TRL = 4

Design for full commercial scale plant

Collaborations and Coordination

Project Partner		Project Role
	University of California, Irvine	Coordination; SOEC modelling and control design; Design of DRI+SOEC HIL demo
	FuelCell Energy	Design of SOEC prototype; Construction, testing of DRI+SOEC HIL demo
	Laboratorio Energia Ambiente Piacenza	Thermodynamic analysis and layout definition
	Politecnico di Milano	DRI modelling and support on HIL demo
	Hatch	Design scale-up and techno-economic analysis
	Southern California Gas Company	Market insight partner and co-sponsor
	Nucor Corporation	Advisor
	Tenova Inc.	Advisor
	Arcelor Mittal	Advisor
	Midrex	Advisor

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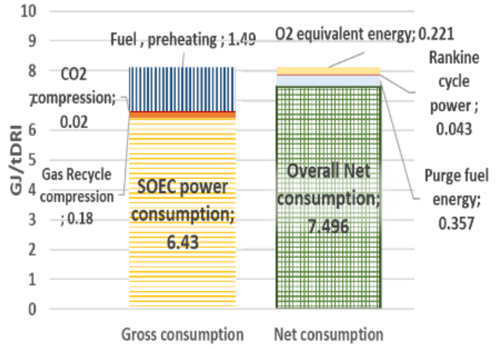
Summary

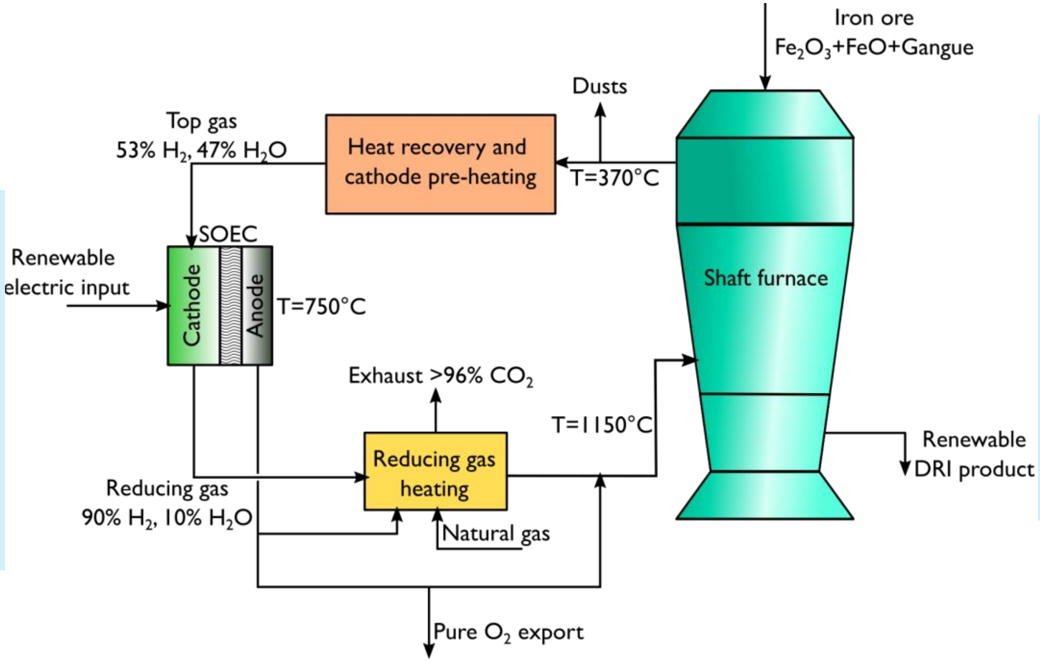


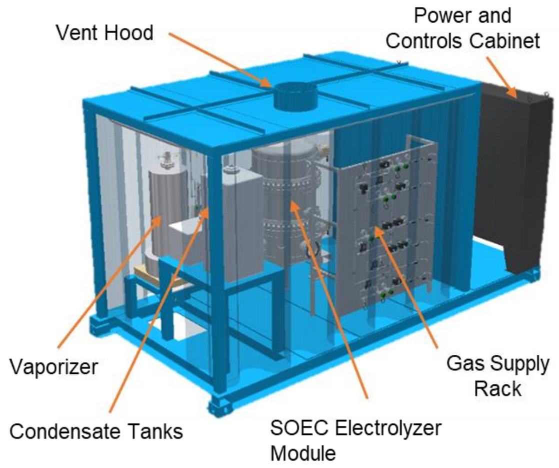
Preliminary performance

- Preliminary results show the potential to reduce the primary energy consumption of steelmaking by **>64%**
- Direct CO_2 emissions can be reduced by **>97%**

Key takeaways

- **SOEC** systems can be thermally and chemically integrated with high temperature industrial processes
- Both **hydrogen** and **renewable syngas fuels** can be directly produced by SOEC with renewable electricity and thermal energy inputs





Future steps

- Demonstration of SOEC operation at pressure in both steam and co-electrolysis
- Thermodynamic and kinetic analysis of H2+DRI
- **This project** will demonstrate the HDR and Hybrid HDR scenarios at a TRL = 4 in Danbury (CT)
- Stay tuned for more…

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Acknowledgements

LEAP Laboratorio Energia e Ambiente Piacenza

Dr. Maurizio Spinelli

Dr. Roberto Scaccabarozzi

Dr. Manuele Gatti

POLITECNICO MILANO 1863

Prof. Matteo C. Romano

Prof. Stefano Campanari

Prof. Stefano Consonni

Prof. Carlo Mapelli

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