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

University of California, Irvine
DOE project award #DE-EE0009249
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DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

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H2GS
UCI ADVANCED POWER AND ENERGY PROGRAM

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 Reduced 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

Overview

Timeline and Budget

- Project Start Date: 03/10/21
- Project End Date: 03/10/24
- Total Project Budget: $5,664,862.00
  - Total DOE Share: $4,043,993.00
  - Total Cost Share: $1,620,869.00
  - Total DOE Funds Spent*: $2,081,875.78
  - Total Cost Share Funds Spent*: $1,061,486.56

* As of 01/31/2024

Advisory Board

- Tenova
- Arcelor Mittal
- Nucor
- Midrex
- Snam
- Cleveland Cliffs
- EPRI

Barriers

- F. Capital Cost
- G. System Efficiency and Electricity Cost
- J. Renewable Electricity Generation Integration

Partners

- University of California, Irvine (UCI) - Project lead
- University of Wisconsin-Madison (UW-Madison)
- FuelCell Energy (FCE)
- Versa Power Systems (VPS)
- Hatch Associates Consultants, Inc. (HATCH)
- Politecnico di Milano (PoliMi)
- Laboratorio Energia Ambiente Piacenza (LEAP)
- Southern California Gas Company (SoCalGas)

Potential Impacts

Technology Impact

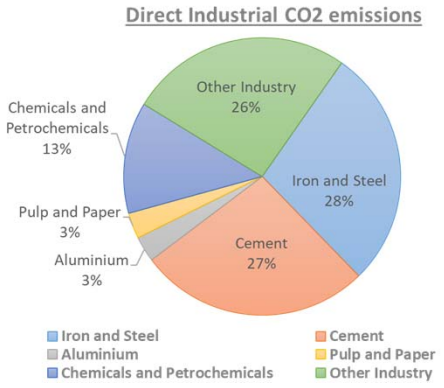
Steel production is responsible for the 7% of global anthropogenic CO_2 emissions and a rise of 20% in steel production is predicted until 2040.

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}**



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

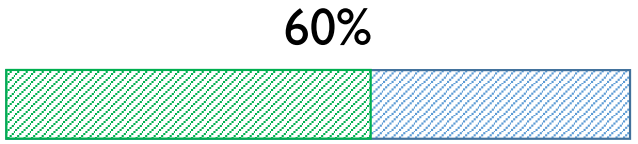
Blast Furnace + Basic Oxygen Furnace (BF+BOF)
Hydrogen Direct Reduction (HDR)
Hybrid Hydrogen Direct Reduction (Hybrid HDR)

	Units	BF+BOF	HDR	Hybrid HDR
Energy intensity	$GJ/ton_{crude\ steel}$	19-20	<8	<9
Specific emissions	$ton_{CO2}/ton_{crude\ steel}$	1.8-1.9	<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

Progress toward DOE Targets

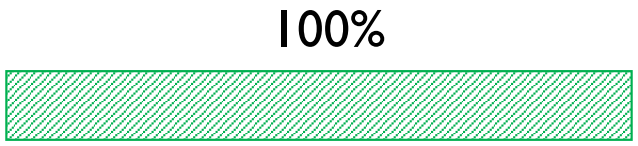
Bench-scale verification of at least one approach to iron reduction at a scale of 1 tonne/week



Project targets:

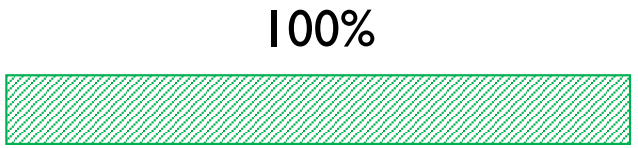
1 ton/week

Concepts proposed should be ultimately scalable to capacities of at least 5,000 tonnes/day



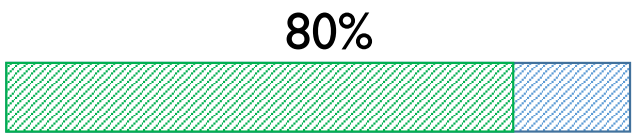
2 Mton/yr

Concepts should also target achieving an energy consumption no higher than that of current state-of-the-art DRI plants, which are baselined at approximately 11 gigajoule (GJ)/tonne steel



8 GJ/ton

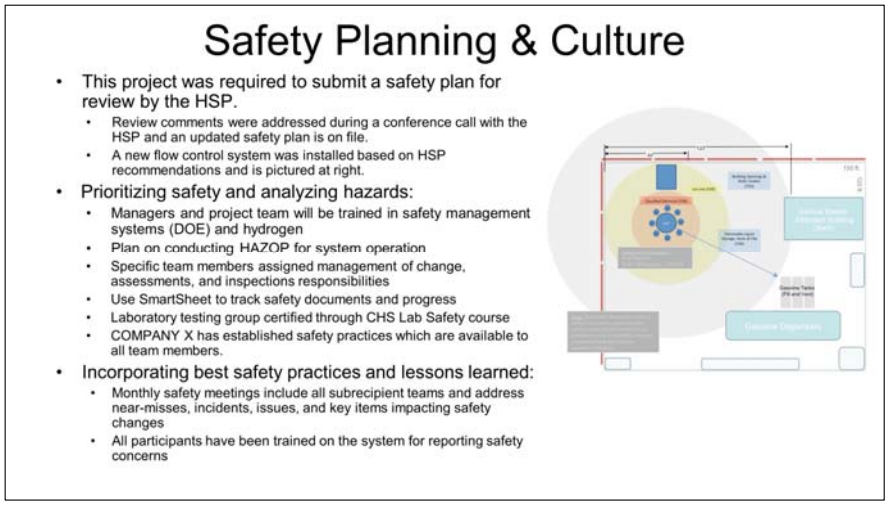
Concepts should also target achieving capital costs no higher than those of conventional blast furnaces, which are baselined at approximately $210/tonne-pig iron/year*.



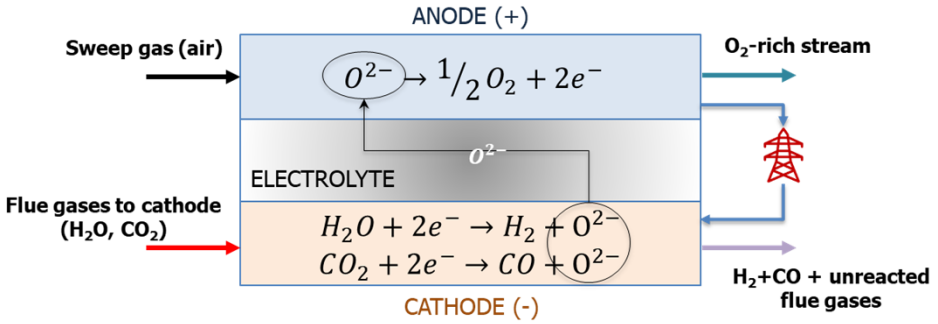
$200/ton*

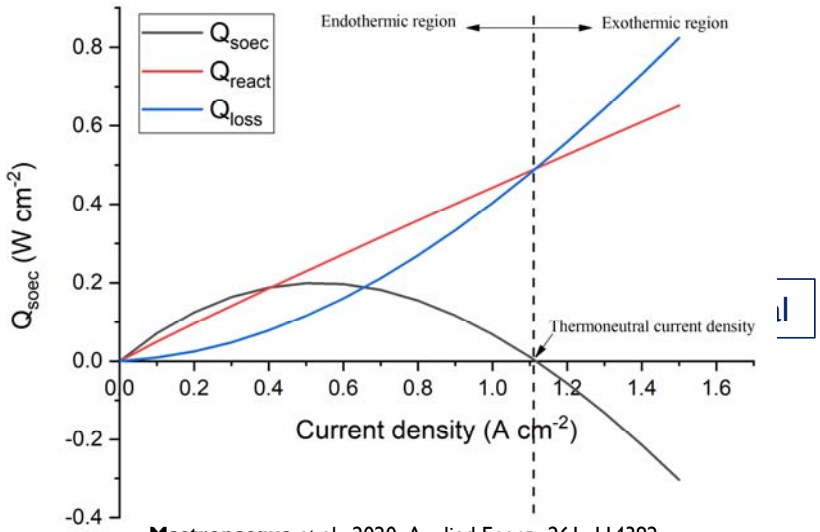
Safety Planning & Culture

- This project was required to submit a safety plan for review by the HSP
- We are prioritizing safety and analyzing hazards
- We are incorporating best safety practices and lessons learned

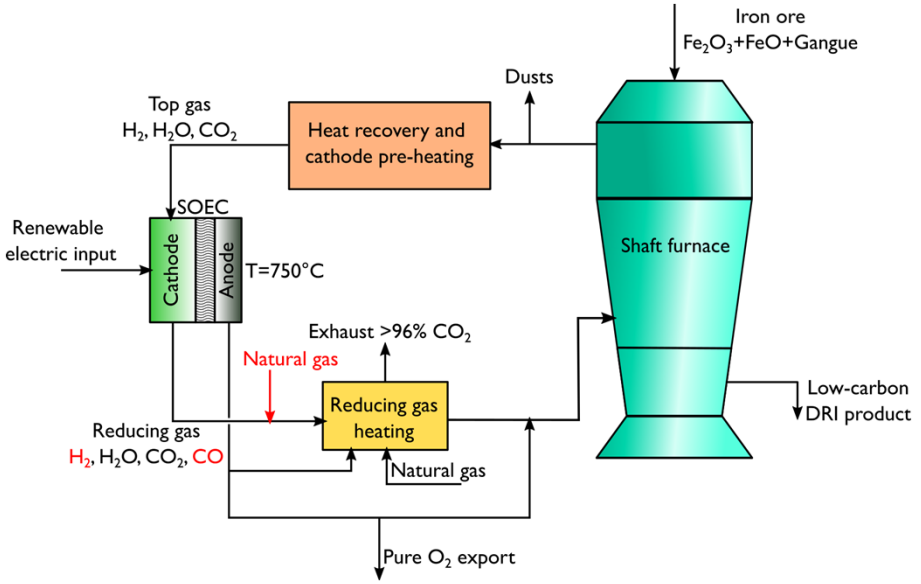


Approach: SOEC HDR





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



Summary

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

Approach: Work Packages and major milestones & Go/no-Go decisions

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*

WP3: SOEC prototype design, construction and testing

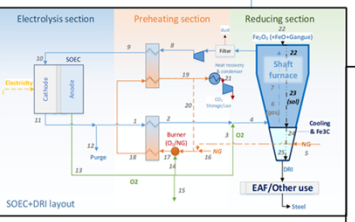
- *Testing in relevant conditions for DRI operation*
- *SOEC prototype design*
- *SOEC prototype fabrication*

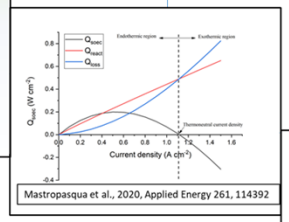
WP4: Design and characterization of pilot-scale SOEC+DRI process

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

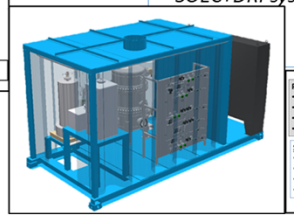
WP5: Techno-economic optimization of full scale SOEC+DRI layouts

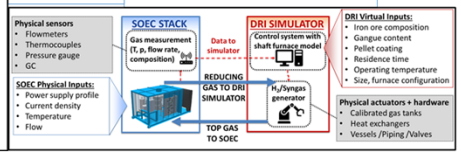
- *Economic and market background build-up*
- *Design and Techno-economic assessment of full-scale system*
- *Comparative assessment with state-of-the-art*
- *Sector coupling assessment*





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





1 ton/week demo at TRL = 4
Design for full commercial scale plant

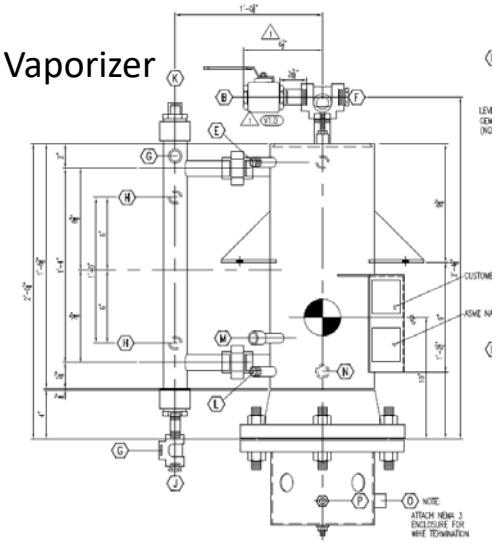
- Predicted DRI primary energy <8 GJ/ton (100%) – Go/no-GO BP1
- Testing of pressurized cell / stack system from 1 bar up to 8 bar (100%)
- **SOEC** Predicted H2 efficiency <35 kWh/kg (100%) – Go/no-GO BP1
- Furnace model of kinetics for H_2 concentrations up to 95%v (100%)
- Assessment of SOEC thermal management with 2D model (100%)
- Market analysis on DRI and competitive technologies (100%)
- Measured H_2 production <35 kWh/kg – Go/no-Go BP2
- Prototype ready for commissioning – Go/no-Go BP2

Demonstration Unit Design

Task 3.2: SOEC Prototype Design:

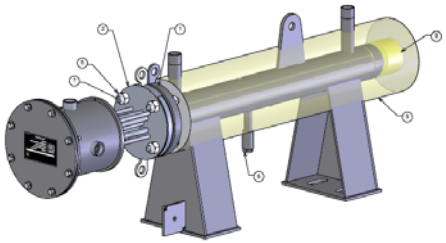
- Major process equipment designs complete and purchase orders have been issued
- Electrical design in progress. Long lead time equipment such as the PLC and the power supplies have been ordered
- Milestone 3.2.2 complete

Vaporizer





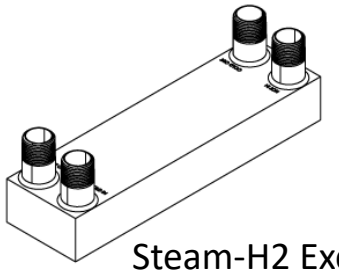
DC Power Supply



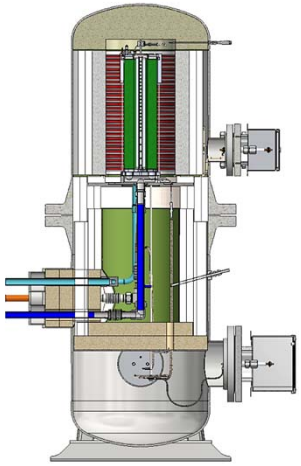
Feed Gas Heater



Water Supply Pump



Steam-H2 Exchanger



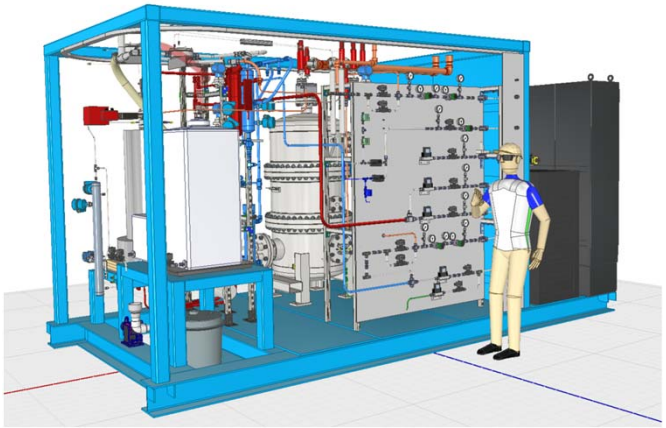
SOEC Module Vessel

FuelCell Energy

Demonstration Unit Fabrication

Task 3.3: SOEC Prototype Fabrication

- FCE process deliverables complete
- FCE electrical deliverables are evaluated at 90% complete
- FCE has selected two vendors to provide bids for the final skid fabrication.
- Milestone 3.3.1 evaluated at 70% complete

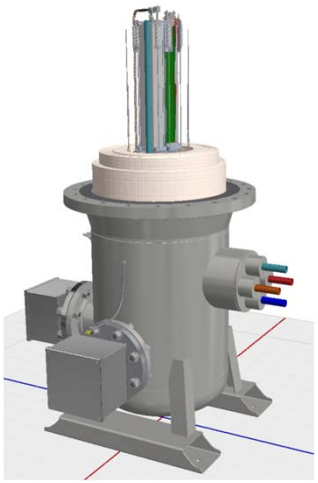


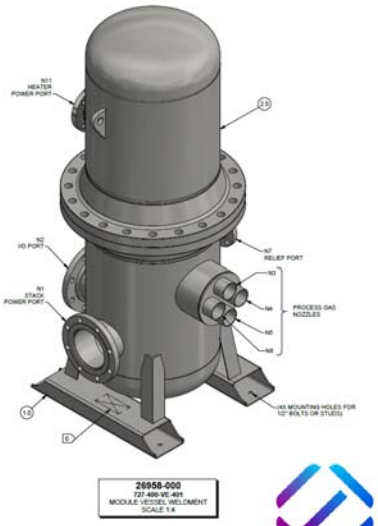
Equipment currently in Fabrication:

- Heat exchangers
- Electric Heaters
- Control Valves
- Vaporizer
- Oxygen Recycle Blower

Module Pressure Vessel:

FCE has completed the design of the pressure vessel that will house the SOEC stack. A purchase order was issued, and the vessel is in fabrication

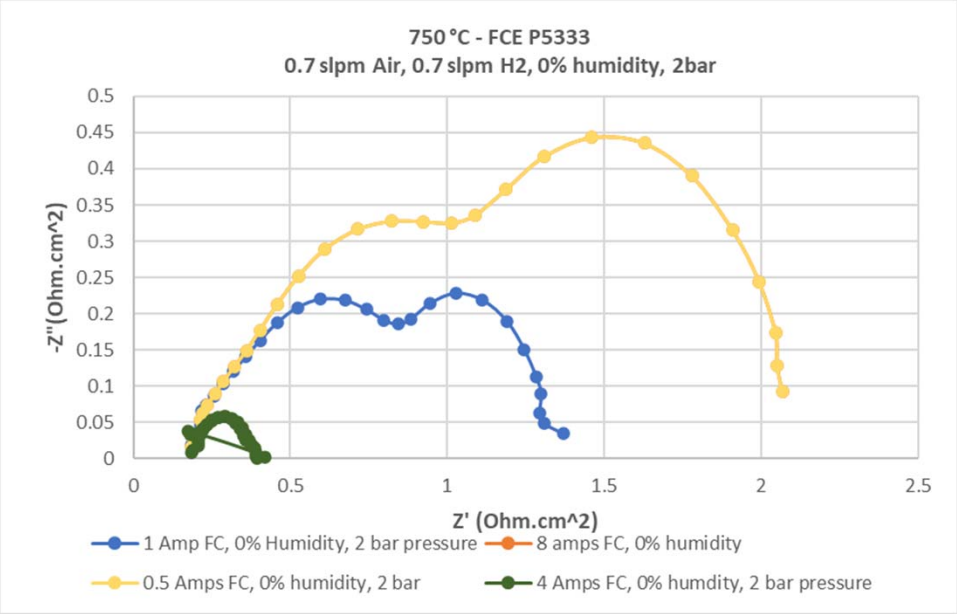




FuelCell Energy

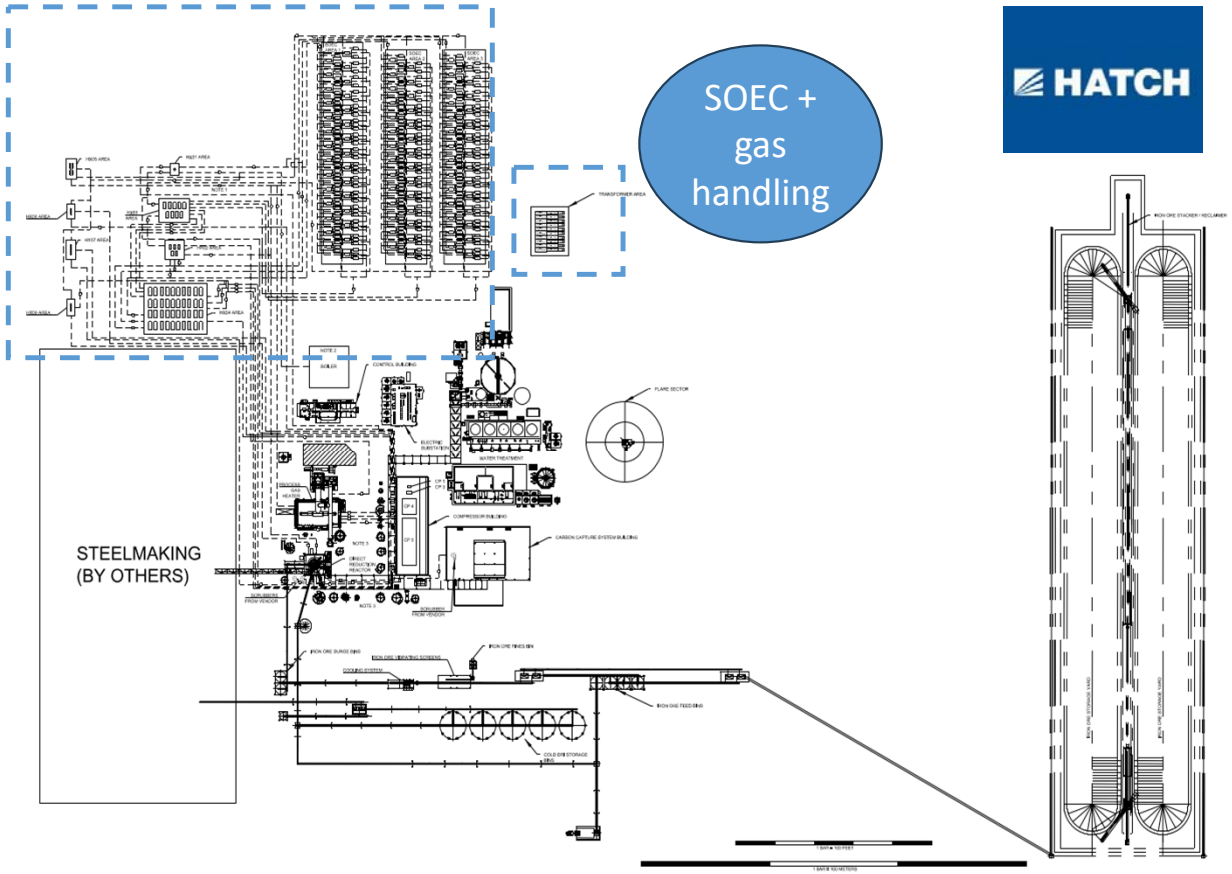
Electrochemical Impedance Spectroscopy Testing (EIS)

- FCE has completed the electrochemical impedance spectroscopy (EIS) testing over a wide range of operating conditions
- Two test stands were used to confirm the observed trends
- Data collected from 1 kHz to 1 MHz over an amplitude of 50mA
- Milestone 3.1.2 evaluated at 100% complete



Example Fuelcon EIS Measurements at 2 bar, 0% Humidity

Scaled-up design and energy balance summary



Raw Material	Unit	Typical HYL ZR	HySteel Project Plant w/ NG boiler	HySteel Project Plant w/ Electrode Boiler	Compliance/ Comment
Feed material	t/t DRI	1.45	1.45	1.45	From Hatch Calculations
Natural gas	GJ/t DRI	10.9	1.90	0.752	Heating value of 40.7 MJ/kg for NG
Electric power	kWh/t DRI	60 – 90	2163 – 2193	2571 – 2601	Based on 250 t DRI/h production
Make up water	m3/t DRI	0.5 – 1.5	1.01 – 2.01	1.01 – 2.01	

CAPEX summary

HATCH	USD MM$		
	Base DR plant	SOEC + Top gas handling	SOEC+DR plant
Equipment	515.38	267.59	
Material	183.67	59.47	
Labor	375.37	96.76	
Total Direct Costs	1074.42	437.26	
Total Indirect Costs	255.22	133.00	
Total Direct + Indirect	1329.65	570.25	
Owner's Cost	53.72	21.86	
Contingency	20%	35%	
Total Installed Cost	1649.30	791.70	$ 2,441.00

- The Base DR plant represents the HYL shaft furnace and associated auxiliary equipment.
- This includes raw material handling costs to receive and transport iron ore to the direct reduction shaft furnace. Cold DRI storage and handling costs have also been included.
- The CAPEX doesn't include any costs related to steelmaking or utilization/ processing of the DRI product.
- The base DR plant costs were scaled based on Hatch experience on other projects.
- The costs associated with SOEC + Top gas handling portion of the CAPEX are a blend of factored (where applicable) and budgetary quotes received from vendors. A higher contingency has been applied to this portion of the CAPEX to account for the less mature H_2 generation technology and associated gas handling equipment.
- The primary MTO's for this plant consist of the piping, and electrical equipment.
- Budgetary bids were received for the scrubbers, compressors, electrode boilers, heat exchangers, amine system, de-aerators, water treatment, and solid oxide electrolysis equipment. The HYL core plant costs were scaled from previous Hatch references.

Off-design simulations

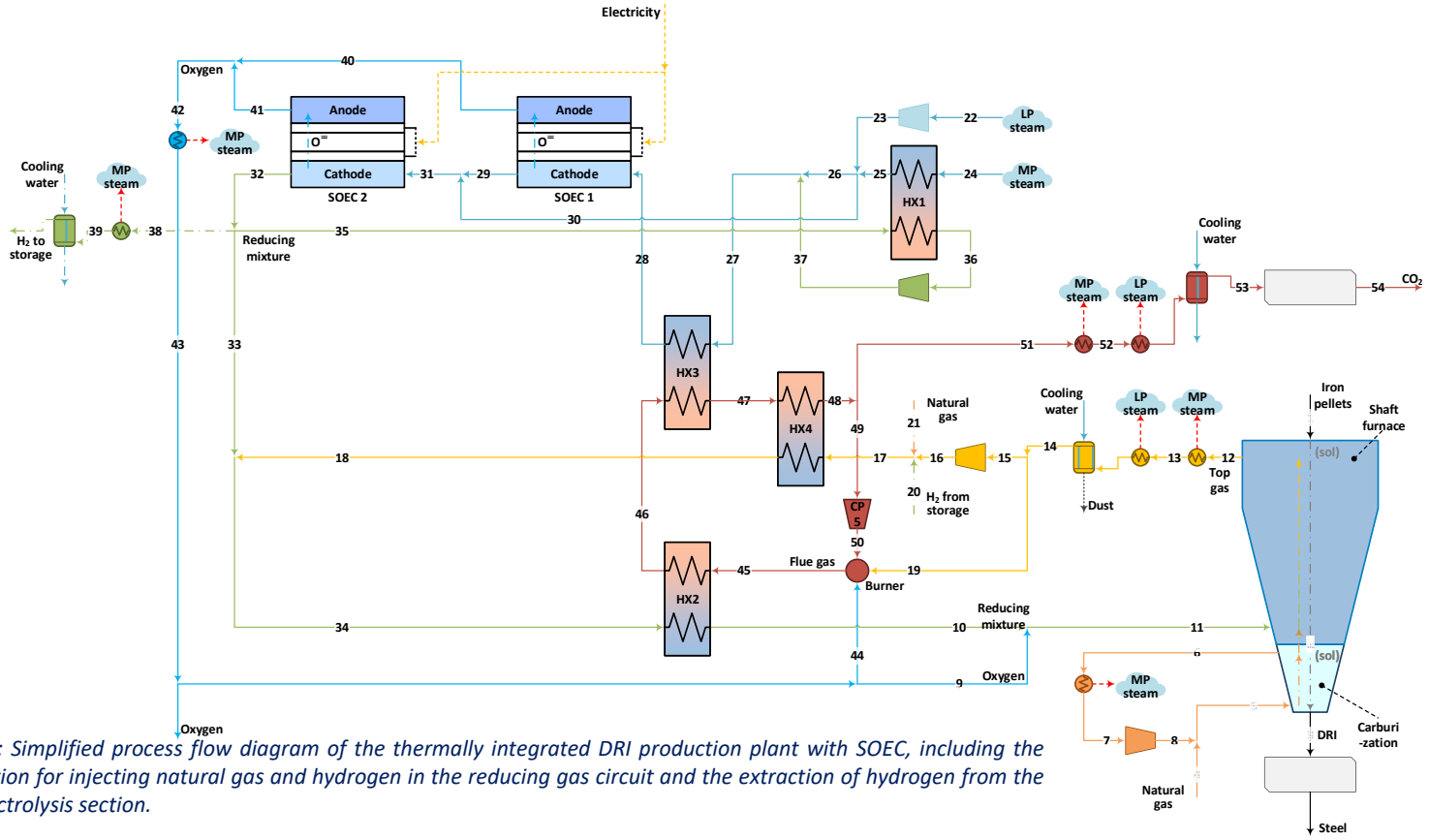


Fig: Simplified process flow diagram of the thermally integrated DRI production plant with SOEC, including the option for injecting natural gas and hydrogen in the reducing gas circuit and the extraction of hydrogen from the electrolysis section.

- **Several off-design simulations of the thermally integrated DRI production plant with SOEC were carried out** to assess the energy and emission performances of the proposed system operating with different electricity consumption levels:
- Although thermally integrated scheme is characterized by a slightly higher energy consumption with respect to the chemically integrated case (8.4 GJ/t_{DRI} vs. 8.0 GJ/t_{DRI}), **it has been chosen because of its higher simplicity**

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Off-design simulations

- The considered operating modes are the following:
  - **Base case (Base)**
  - **Natural gas injection (NG_{in})**: part of the reducing gas stream is provided by an injection of natural gas (stream 21)
  - **Hydrogen injection ($H_{2\ in}$)**: part of the reducing gas stream is provided by an injection of stored hydrogen (stream 20)
  - **Hydrogen production ($H_{2\ out}$)**: electricity consumption of the SOEC unit is increased to reach 120% of the nominal electric usage producing an additional hydrogen stream
  - **Natural gas injection + hydrogen production ($NG_{in}H_{2\ out}$)**: this combined operating mode aims at maximizing hydrogen production
- **All the scenarios were simulated at 100% and 60% load**

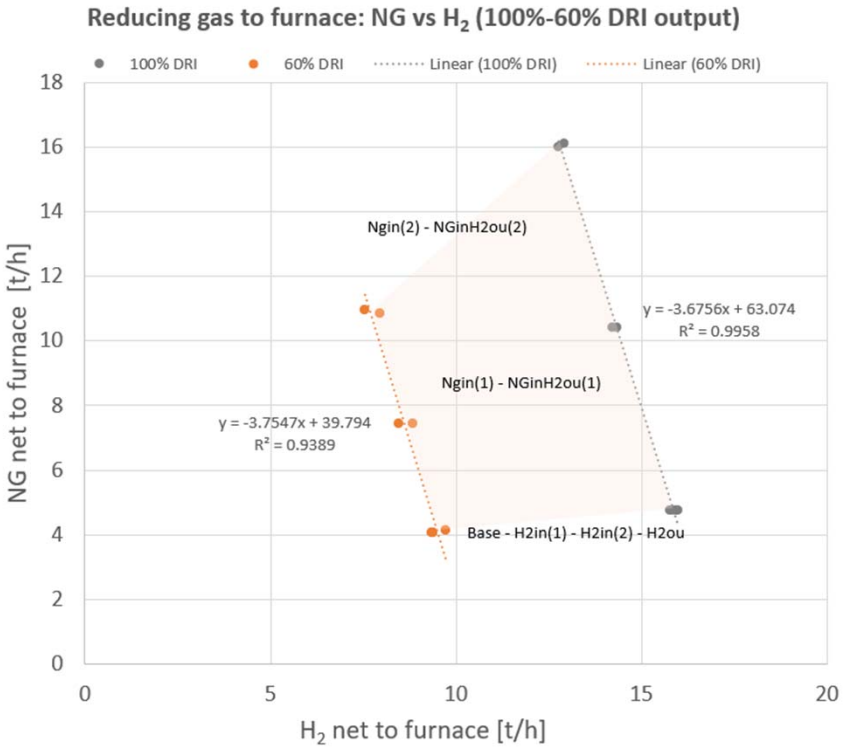
Table: Energy and emission performance and DRI quality estimation (metallization and carbon content) of the thermally integrated DRI production plant with SOEC off-design operation, both considering full and 60% DRI production capacity.

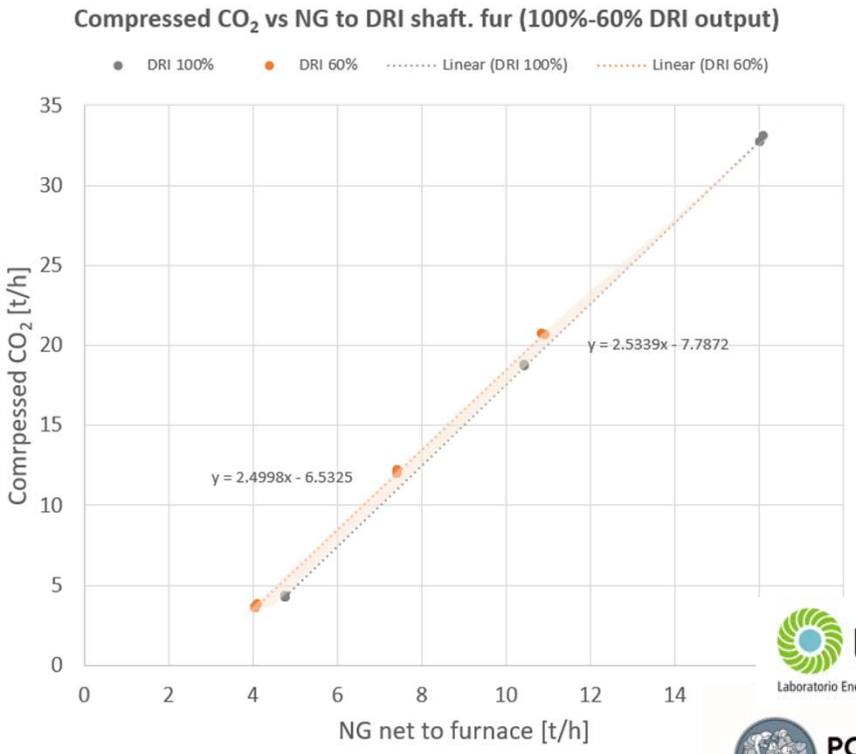
		Product quality		Energy					CO_2 emission
		Metallization	C content	Natural gas (ID 4 + 21)	H_2 input (ID 20)	Electric consumption	Total energy consumption	H_2 output (ID 38)	CPU (ID 54)
		%	%	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	GJ/t_{DRI}	kg_{CO2}/t_{DRI}
DRI full load - 100%	Base	95,1%	0,9%	0,9	0,0	7,6	8,4	0,0	15,8
	NG_{in}	93,8%	1,1%	2,9	0,0	6,0	8,9	0,0	120,4
	$H_{2\ in}$	95,2%	0,9%	0,9	2,6	4,8	8,2	0,0	15,8
	$H_{2\ out}$	95,1%	0,9%	0,9	0,0	8,5	9,4	0,8	15,8
	$NG_{in}H_{2\ out}$	94,4%	1,0%	1,9	0,0	8,5	10,4	1,5	69,2
DRI part load - 60%	Base	97,3%	1,3%	1,2	0,0	7,4	8,6	0,0	22,1
	NG_{in}	96,8%	1,5%	3,3	0,0	5,8	9,1	0,0	126,9
	$H_{2\ in}$	97,4%	1,3%	1,2	2,5	4,7	8,5	0,0	22,1
	$H_{2\ out}$	97,3%	1,2%	1,2	0,0	14,1	15,4	5,9	23,5
	$NG_{in}H_{2\ out}$	97,1%	1,3%	2,2	0,0	14,1	16,4	6,6	75,0

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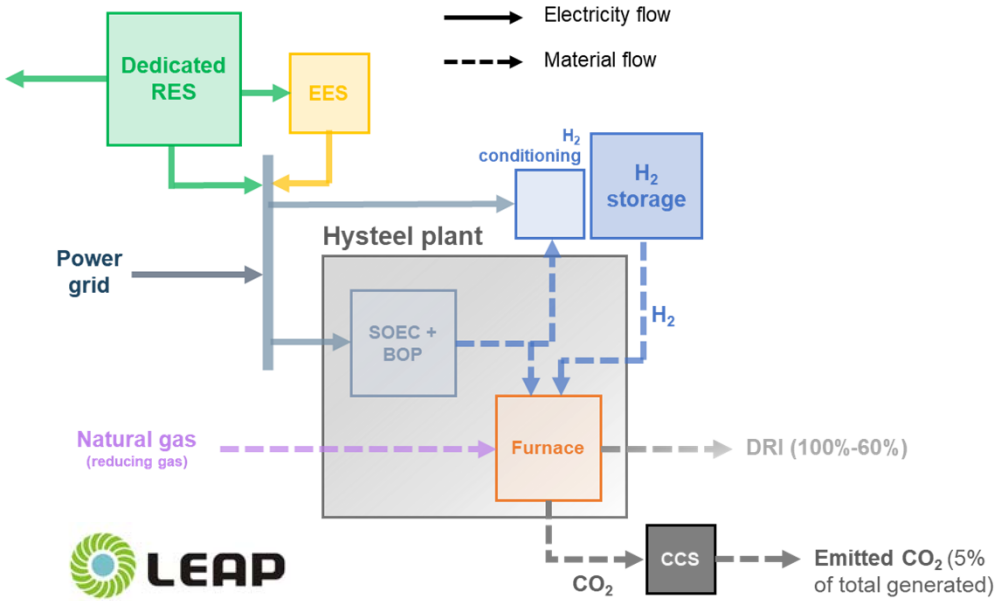
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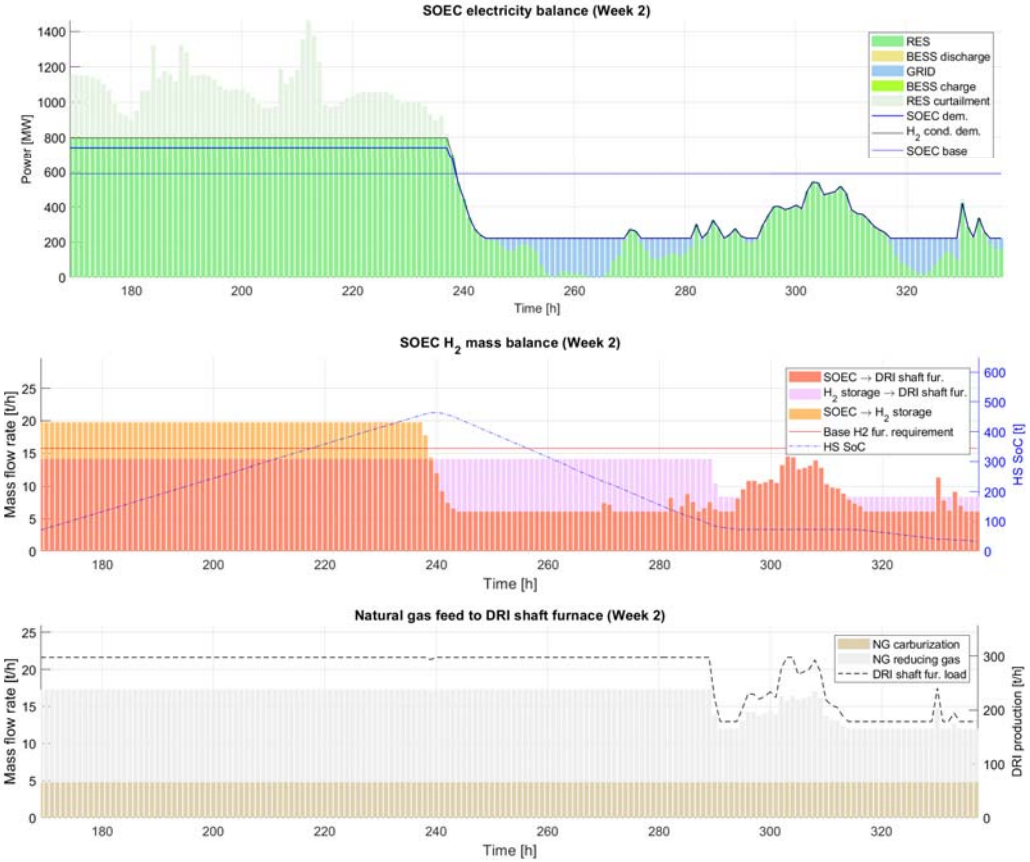
NG-H2-DRI and NG-CO_2-DRI maps (1)





SOEC HDR annual operation





Installed capacities, costs, CO_2 emissions

Parameter	DRI fix 95%RESel	DRI flex 95%RESel	DRI fix 100%RESel	DRI flex 100%RESel
%RES penetration (electricity)	95%	95%	100%	100%
%RES penetration (primary en.)	67%	68%	70%	69%
PV plant capacity, MW	713	544	1391	1358
WIND plant capacity, MW	1140	1160	1069	1016
BESS capacity, MWh	0	0	4502	4554
H_2 tank capacity, t	4055	617 ↓↓	1945	205
H_2 cond. plant capacity, t/d	151	136	45.2	15.4
SOE capacity, MW	685	709 ↑	525	525
DRI max. prod, t/h	269.0	297.8 ↑	269.0	296.6
%RES curtailment	14%	12%	23%	21%
LCOH, $/kg	2.03	1.89	2.98	2.90
DRI specific cost, $/$t_{DRI}$	289.8	284.5 ↓	334.9	331.3
CO_2 specific emissions*, kg_{CO2}/t_{DRI}	87.44	84.21 ↓	57.70	57.10
Natural gas consumption, kt/y	135.8	133.0	138.5	139.7
Compressed CO_2, kg_{CO2}/t_{DRI}	117	114	120	121

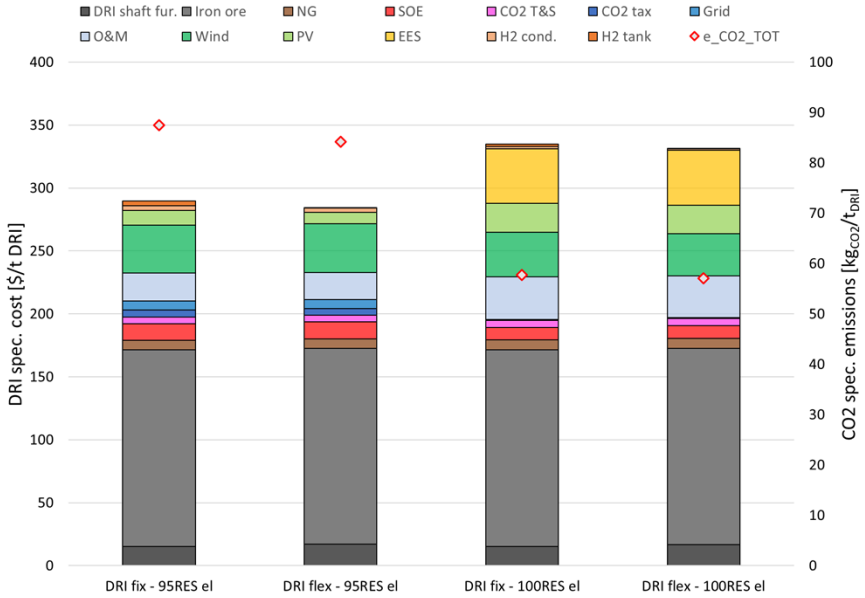
← *imposed*

← *result*

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SOEC system cost: 300 $/kW



* Including grid electricity generation, LCA emissions of PV, Wind, and BESS, direct emissions, and upstream NG leakage

Responses to Previous Year Reviewers' Comments

Review Comment 1:

Response 1:

Review Comment 2:

Response 2:

Review Comment 3:

Response 3:

Collaborations and Coordination

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

- The list of members of the Advisory Board has increased considerably compared to BP1, highlighting the relevance to the market and the interest from industrial actors
- Some of these members have already expressed interest in pursuing this concept at a larger scale and to secure more funding to achieve an industrially relevant demonstration

Challenges and Barriers

Construction of the SOEC prototype is lengthy	• Delayed final design and supply chain challenges • All parts (including long-lead items) should be available at start of summer • Construction will be completed by September – need for a 9-month extension
Hot gas handling & clean-up needs design	• High temperature (and pressure) oxygen materials of construction and piping distances • Maintaining thermal energy in top gas stream as it is cleaned (especially of particles) • Lockout methodology for maintenance of equipment
Transition of proven DRI technology to hydrogen DRI	• Assumed existing process gas heater (PGH) can accept oxy-fuel with minimal design change • Reaction rates, bed temperature, and overall energy balance of the shaft furnace will be affected • Carbon activity in the gas phase, may need more/less NG to achieve desired carbon content

Proposed Future Work

- Prototype hardware-in-the-loop (HIL) demonstration
  - Complete SOEC prototype fabrication at FCE and couple it with DRI simulator and control system
  - Test HIL system and measure performance targets
  - Garner information sufficient for design and implementation of a follow-on prototype demonstration at a steel plant (demonstration at Cleveland Cliffs Toledo Steel plant with funding support from the U.S. DOE Industrial Efficiency and Decarbonization Office)
- Submit current article drafts to peer-reviewed journals
- Develop and submit additional articles for publication
- Present webinars and conference presentations to further disseminate results

Summary

- System conceptualization and modelling
  - Off-design analysis has been performed down to 60% of DRI furnace nominal point for both steam and co-electrolysis scenarios
  - Annual optimization analyses have been carried out to minimize the Total Annual Cost of the integrated system (including storage)
  - TAC < $350/ton have been demonstrated in all scenarios
- SOEC prototype construction
  - Pressure vessel has been design and sent out for fabrication
  - Major equipment has been purchased and control are being developed
- Scale-up design
  - An SOEC+DRI system design for a 2 Mt/y plant has been finalized
  - A complete layout (piping, mechanical, electrical) has been completed
  - CAPEX have been calculated and estimated at MM$ 2,441.00

