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

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University of California, Irvine
DOE project award #DE-EE0009249
August 31st, 2021
Advance, demonstrate and optimize a thermally and chemically integrated Solid Oxide Electrolysis Cell (SOEC) system, as co-producer of H₂ and O₂, 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 H₂ produced

Specific CO₂ emissions rate < 90 kg CO₂/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

Total Project Budget: $5,664,862.00 – Total DOE Share: $4,043,993.00 – Total Cost Share: $1,620,869.00
**Direct Industrial CO2 emissions**

- **Iron and Steel**: 28%
- **Cement**: 27%
- **Other Industry**: 26%
- **Chemicals and Petrochemicals**: 13%
- **Pulp and Paper**: 3%
- **Aluminium**: 3%

**Steel industry:**

- World total 1869 Mton\textsubscript{steel}
- 6-6.5% of total anthropogenic CO\textsubscript{2} emissions

**Blast Furnace + Basic Oxygen Furnace (BF+BOF)**

- **Energy intensity**: GJ/ton\textsubscript{crude steel}
  - BF+BOF: 19-20
  - HDR: <8
  - Hybrid HDR: <9

- **Specific emissions**: ton\textsubscript{CO2}/ton\textsubscript{crude steel}
  - BF+BOF: 1.8-1.9
  - HDR: <0.09
  - Hybrid HDR: <0.09

- **Specific cost**: $/ton\textsubscript{eq pig-iron yr}
  - BF+BOF: 210
  - HDR: 200*
  - Hybrid HDR: 200*

- **Electric load**: GJ\textsubscript{el}/ton\textsubscript{crude steel}
  - BF+BOF: -
  - HDR: <7
  - Hybrid HDR: <7

*At 2 Mton/yr scale

**Hydrogen Direct Reduction (HDR)**

- **Hydrogen Eff.**: kWh/kg
  - Ref SOEC: 40
  - HDR: 35
  - Hybrid HDR: -

- **Syngas Eff.**: kWh/kg
  - Ref SOEC: 45
  - HDR: -
  - Hybrid HDR: 40

- **Oxygen Eff.**: kWh/kg
  - Ref SOEC: 6.5
  - HDR: <5
  - Hybrid HDR: <5
WP1: System integration and thermodynamic analysis
- Plant conceptualization and thermodynamic analysis
- DRI kinetics at high H₂ 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

August 31st, 2021
Solid Oxide Electrolysis Cells (SOEC) integrated with Direct Reduced Iron (DRI) plants for producing green steel
Voltage = 1.206 V
Current Density = 829 A/m²
Operating Power = 495 MW
Steam Utilization = 0.8936
Pressure = 7 bar
Efficiency = 95%

Hydrogen Direct Reduction (HDR) concept

Hydrogen map

Steam map

Air
Fuel

Steam and co-electrolysis

ANODE (+)

Sweep gas (air)

Flue gases to anode

Electrolyte

$\text{H}_2\text{O} + 2e^- \rightarrow \text{H}_2 + \text{O}^2-$

CATHODE (-)

$\text{CO}_2 + 2e^- \rightarrow \text{CO} + \text{O}^2-$

H₂ + CO with unreacted flue gases

Air
Fuel

SOEC+DRI layout

Electrolysis section

Preheating section

Reducing section

22
SOEC (Fe₂O₃ + Fe₃O₄ + Gangue)

Shaft furnace

Burner (O₂/NG)

Filter

Heat recovery & condenser

Storage/Use

Cooling & Fe₃C

DRI

EAF/Other use

Steel

Filter

Shaft furnace

Purge

NG

Cooling & Fe₃C

SOEC

DRI

EAF/Other use

Purge

NG

Cooling & Fe₃C

SOEC

DRI

EAF/Other use

Purge

NG

Cooling & Fe₃C

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Cooling & Fe₃C

SOEC

DRI

EAF/Other use
Carbon Free Hydrogen from Nuclear Power

9/2/2021
Leading the Clean Energy Transition
A bold vision for a carbon-free future

2019 Results: 44% Lower Carbon Emissions
2030 Goal: 80% Lower Carbon Emissions
2050 Vision: 100% Carbon-Free Electricity

Company-wide emissions reductions from the electricity serving our customers, compared to 2005
NUCLEAR CONSORTIUM: WORKING FOR THE FUTURE OF NUCLEAR

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Install Low Temperature Electrolysis (LTE) Skid [<em>Energy Harbor</em>]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technical and Economic Assessments (due mid-2021) [<em>Xcel Energy &amp; APS</em>]</td>
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<table>
<thead>
<tr>
<th>Phase 2</th>
<th>Installation of High Temperature Steam Electrolysis (HTSE) Skid [<em>Xcel Energy</em>]</th>
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<tbody>
<tr>
<td></td>
<td>Complete design work for Reversible HTSE skid [<em>APS</em>]</td>
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</tbody>
</table>

| Phase 3 – Future | Expansions on Phase 2 work, hydrogen storage, use demonstration, other. [*TBD*] |
Producing Hydrogen From Carbon-free Nuclear Energy
Pilot Project Schedule

- Project must be completed within 2 years of funding receipt
- All dates pending receipt of funding
Hydrogen & Integrated Electrolyzer Systems Panel

Noah D. Meeks, Ph.D., P.E.
R&D

For: Hydrogen Shot Summit
September 1, 2021
Roadmap for Emerging Hydrogen Applications

Increase utilization of existing infrastructure
- “Indirect Electrification” and value stacking
- Hydrogen competes against petrol

Scale decarbonized energy for transportation and industrial sectors
- Expand to chemical and thermal potential

Deep decarbonization of electricity operations and delivered gas
- Bulk energy storage
- Central station H₂-based power
Transportation and resilient / peak shaving power are early mover markets

Transportation: logistics, employees, customers, off-road  Future: shipping, aviation

Power

Electrolysis

Hydrogen

Fuel Cells

Resilient and High-value Power

PowerSecure Demo
- Demonstrate equipment performance
- Understand storage and scaling
- Develop strategic partnership with Plug Power

OPCO Distribution Center
- Integrate vehicle energy loads
- Develop strategic partnership with auto OEM
- Showcase customer opportunity for OPCO

Customer Sites
- Demonstrate value for customer
- Provide win-win-win-win for customer, Company, partners, and environment
Hydrogen Production - Electrolysis

- Hydrogen production via electrolysis is currently <5% current US hydrogen market (not using clean electricity)
- Overall cost of hydrogen primarily a function of power price & capacity factor
- Technological cost drivers are efficiency, capital cost, and lifetime

### Non-technology issues:
- Regulatory treatment of electrolysis uncertain
- “Indirect electrification” viewed as competing with “electrification” efforts
- Geographic deployment of fuel cell electric vehicles uncertain

<table>
<thead>
<tr>
<th>Target H₂ Cost ($/kg)</th>
<th>Target System Capex ($/kW)</th>
<th>Target System Efficiency (kWh/kg)</th>
<th>Average Power Price ($/kWh)</th>
<th>Capacity Factor</th>
<th>Lifetime (years)</th>
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<tbody>
<tr>
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</tbody>
</table>

Note: $1/kg is target for power generation → The capacity factor looks like energy storage.
Hydrogen-based power generation is likely part of energy storage.

Pre-combustion carbon capture

Energy Storage

Water

Natural Gas

Reforming Unit

CO₂ (CCS)

Fuel Cell or Gas Turbine

Power

NG may be blended

Hydrogen Pipeline / Storage

H₂ Markets

Electrolysis

H₂ Markets

Power

Hydrogen Pipeline / Storage

Fuel Cell or Gas Turbine
Cost reductions in energy storage are possible with technology.

**Unitized FC/EC Concept**
- Lower CAPEX
- Simplified operation
- Less flexibility

**Conventional concept with separate electrolysis and fuel cell systems**
- Degrees of freedom around multiple units
- Higher CAPEX
- More flexibility

**Integrated storage Concept**
- Lower CAPEX
- Improved efficiency with heat integration

**Electrolysis stacks**
- SOFC/EC stacks
- Fuel cell stacks (or H₂GT)

**Hydrogen Storage**
- Liquid chemical hydride or metal hydride
Hydrogen Shot Summit
Hybrid and Integrated Electrolyzer Systems Panel

Michael G. Green
September 1, 2021
Our Clean Energy Pathway

CLEAN ENERGY PATHWAY

2005: 24%
2019: 50%
2030: 65% (Estimated)
2050: 100% (Aspirational Goal)

Clean energy commitments
Consortium: The Future of Nuclear

Phased Approach - DOE Funded Scope

Phase 1
Install Low Temperature Electrolysis (LTE) Skid [Energy Harbor]
Technical and Economic Assessments (due mid-2021) [Xcel Energy & APS]

Phase 2
Installation of High Temperature Steam Electrolysis (HTSE) Skid [Xcel Energy]
Complete design work for Reversible HTSE [APS]

Phase 3 – Future
Scale up LTE demonstration for hydrogen/natural gas co-firing and synthetic hydrocarbon production. [APS]
Project Summary and Status

• ~20 MW low temperature electrolysis with on-site compression and storage

• Objectives
  – Co-fire up to 30% hydrogen / 70% natural gas blend in natural gas fired power plant
  – Synthetic hydrocarbon production

• Status
  – Submitted funding application in April 2021
  – Anticipate work to begin first quarter 2022
Electrolysis – How does it plug in on the grid?

Brittany Westlake, Ph.D.
Sr. Technical Leader, Low-Carbon Resources Initiative
EPRI
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Hydrogen Shot Summit
September 1, 2021
Decarbonization Pathways Enabled by Innovation

Decarbonization

Accelerate economy-wide, low-carbon solutions
- Electric sector decarbonization
- Transmission and grid flexibility: storage, demand, EVs
- Efficient electrification

Achieve a net-zero clean energy system
- Ubiquitous clean electricity: renewables, advanced nuclear, CCUS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas

~15-30 years

Past

Energy Efficiency

Cleaner Electricity

Today

Efficient Electrification

2030+

Low-Carbon Resources

2050
The **Low-Carbon Resources Initiative** (LCRI) is a five-year R&D commitment focused on the advancement of low-carbon technologies for large-scale deployment across the energy economy. This initiative is jointly led by EPRI and GTI.

**FOCUS**

- Multiple options and solutions to establish viable low-carbon pathways
- Technologies for hard-to-decarbonize areas of the energy economy
- Affordable, reliable, and resilient integrated energy systems for the future

**RESEARCH AREAS**

- **Hydrogen**
- **Ammonia**
- **Synthetic/Derivative Fuels**
- **Biofuels**

**Production Pathways**

**Integrated Energy Systems**

**Storage & Delivery**

**End Use Applications**

**VALUE**

- Independent, objective research leveraged by global engagement and collaboration
- Comprehensive value chain approach across adjacent sectors
- High-impact results that accelerate technology time to market

www.LowCarbonLCRI.com
Economy-Wide Low-Carbon Energy Pathways

Primary Energy
- Renewables
- Nuclear
- Natural Gas
- Petroleum & Coal
- Bioenergy & Waste

Conversion
- Hydrogen Production
- Electricity Generation
- Electricity

Storage and Delivery
- Electricity Storage
- Gas Storage
- Captured CO2
- On-Road
- Non-Road
- Liquid Fuels
- Distributed Resources
- Co-Gen/CHP
- Buildings
- Industry
- Transportation

Energy End-Use
- Buildings
- Industry
- Transportation
- Non-Road
- Liquid Fuels
- Direct Air Capture
- Conventional Synthetic Biofuel
- Natural Climate Solutions

Electricity Inputs
- Electricity
- Hydrogen
- Ammonia Synthesis
- RNG
- SNG
- CO2
- CO2
- Captured CO2
- Conventional Synthetic Biofuel
- Natural Climate Solutions
- Liquid Fuels
- Re-Fueling Infrastructure
- On-Road
- Non-Road
- Transportation
Integration of Alternative Energy Carriers

H₂ Production

- Nuclear
- Electrolysis
- Clean Generation
- Natural Gas CCS

H₂ Delivery

- Utilize Existing or Develop New Pipelines

H₂ End-Use

- Boiler
- Heavy Duty Transportation
- Electric Generation
- Advanced Fuel Cell
- Large Industry
- Chemical Process