Performance Validation of a Thermally Integrated 50 kW High Temperature Electrolyzer System

DE-FOA-0002300: Grant 13163665

2021 SOFC Virtual Project Review Meeting

Nov. 16-18, 2021

Integrated Energy Systems

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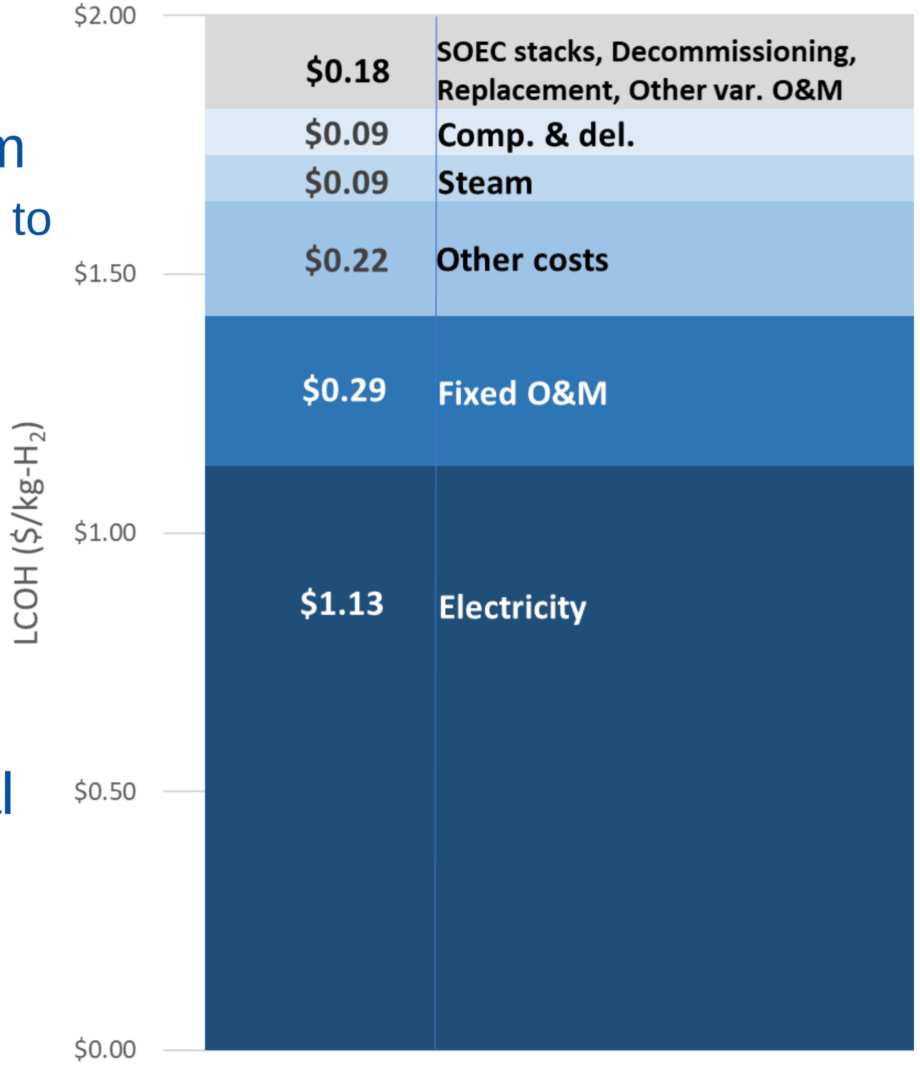
Project Goals

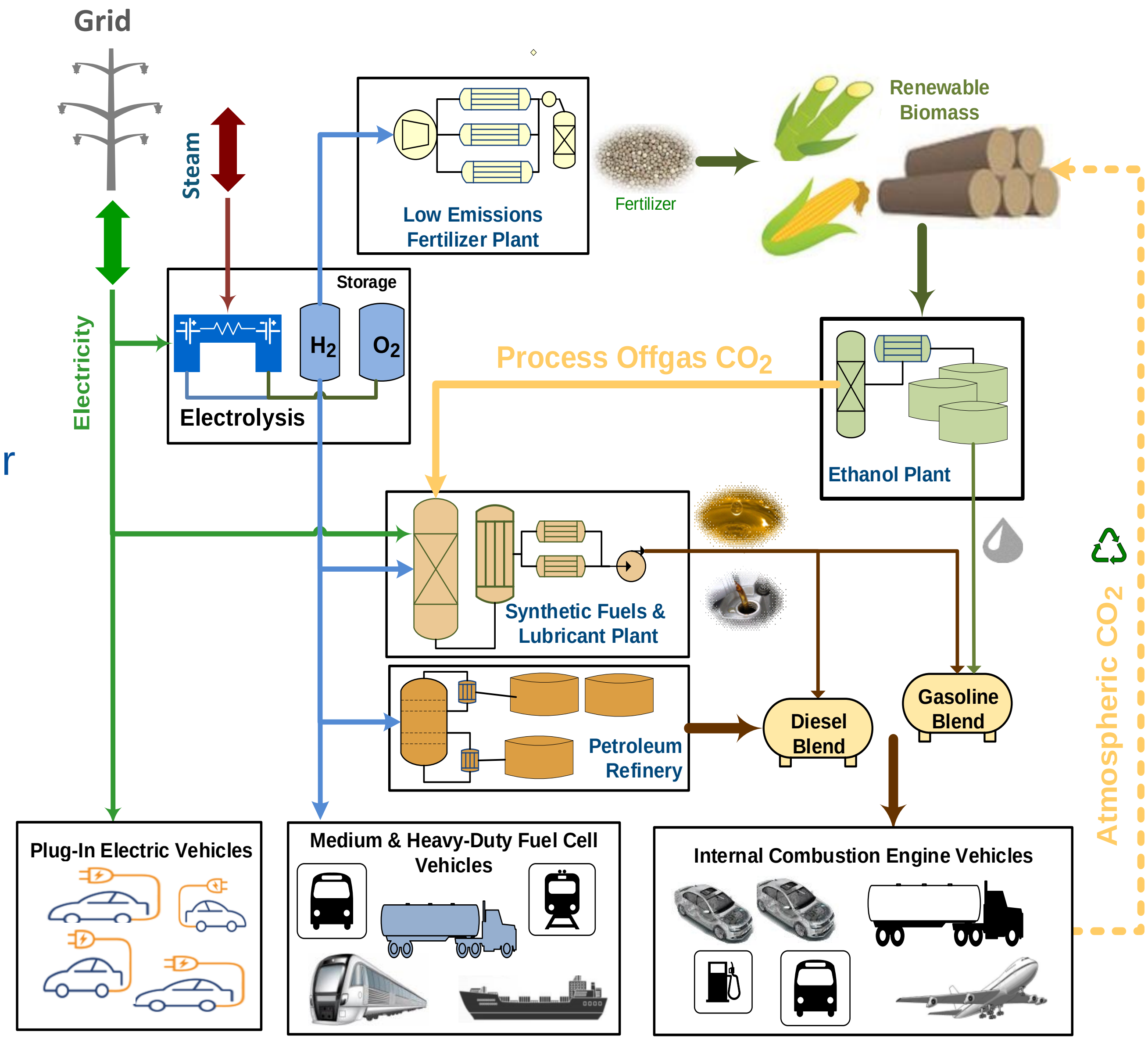
- Accumulate ~3,000 hrs operating a reversible SOC system
  - An SOEC system currently being fabricated at INL will be modified to create a reversible solid oxide (rSOC) system with 30-kW electrolysis mode/10-kW fuel cell mode operation
  - SOC stacks will incorporate improved catalyst in fuel electrode
  - Operation of rSOC system will be coupled to a Thermal Energy Distribution System (TEDS) that will be configured to mimic industrial source of low-grade heat
- Thermodynamic analysis will demonstrate potential to achieve > 85% system efficiency in electrolysis mode
- Technoeconomic analysis (TEA) will demonstrate potential to produce hydrogen at a cost of $2/kg on a cost of electricity of $30/MWhr.

  - Project Start Date: 10/01/2020
  - Project End Date: 9/30/2022



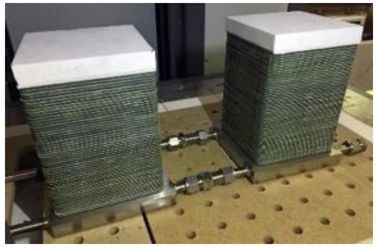
Relevance

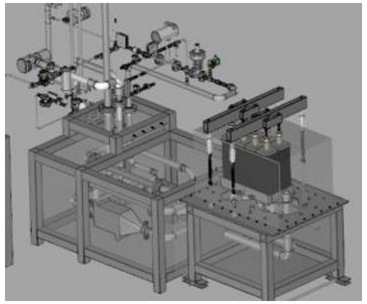
- **DE-FOA-0002300 AIO 2:**
  - Improving the cost, performance and reliability of reversible solid oxide electrolysis/fuel cell (rSOC) systems for clean hydrogen and clean power production
  - rSOC systems have many opportunities to enter the marketplace but need proven system cost, performance, and reliability
  - rSOC systems can use the same system components (stacks, heat exchangers, piping, power converters, etc.) to reduce capital cost and maximize equipment capacity factor (% of time at maximum power)
  - May be deployed at small scale to meet needs of diverse users for clean energy utilization, storage, and supply (supports environmental justice)
    - Full design of BOP system will be open-access

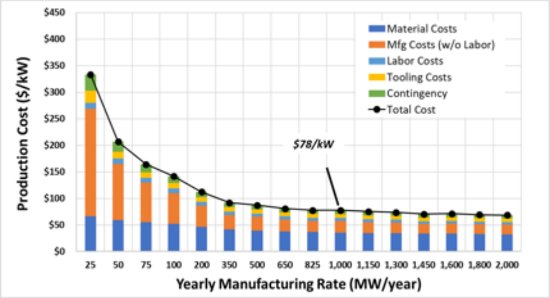


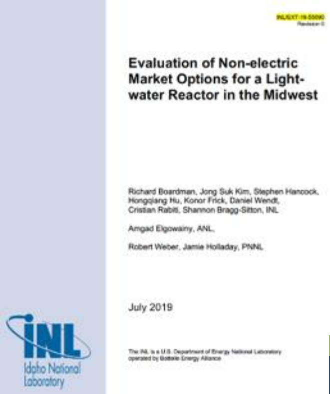
Approach (New Project)

- Task 1: Revise Project Management Plan
- Task 2: Stack manufacturing (OxEon)
- Task 3: e^2 Catalyst Development (MIT)
- Task 4: Reconfigure 50 kW SOEC system
- Task 5: System integration and testing
- Task 6: Technoeconomic Analysis
- Task 7: Data analysis
- Task 8: Final Report









Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest

Richard Boardman, Jong Suk Kim, Stephen Hancock, Hongqiang Hu, Konor Frick, Daniel Wendt, Cristian Rabiti, Shannon Bragg-Sitton, INL

Amgad Elgowainy, ANL,

Robert Weber, Jamie Holladay, PNNL

July 2019

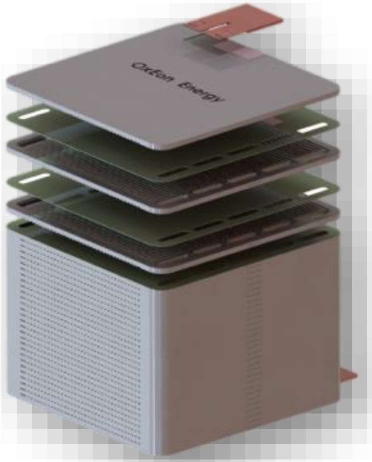
The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Idaho National Laboratory

OxEon Energy, LLC

Utah R&D/Mfg Facility – Founded in 2017 after successful 30-year collaboration with founders of previous affiliation

- New 24,000 ft^2 (2230 m^2) office, laboratory, and manufacturing facility
- NASA, DOE, DOD and Commercial funding
- Tape casting, cell and stack production, and testing
- End-to-end power to synfuels pilot plant in operation

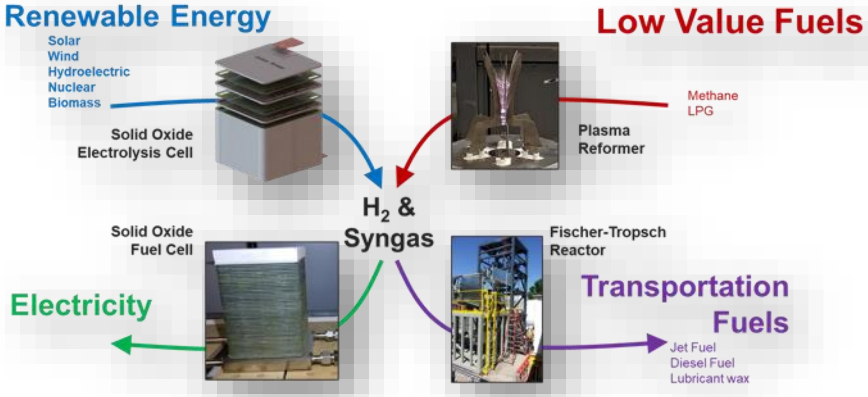


Solid Oxide Fuel Cell and Electrolysis Stacks

- Longest running solid oxide fuel cell & electrolysis group in world
- Only flight qualified, TRL 9 SOEC unit in history
- 30kW/10kW reversible system test program in process

Fuel Reformation and Generation

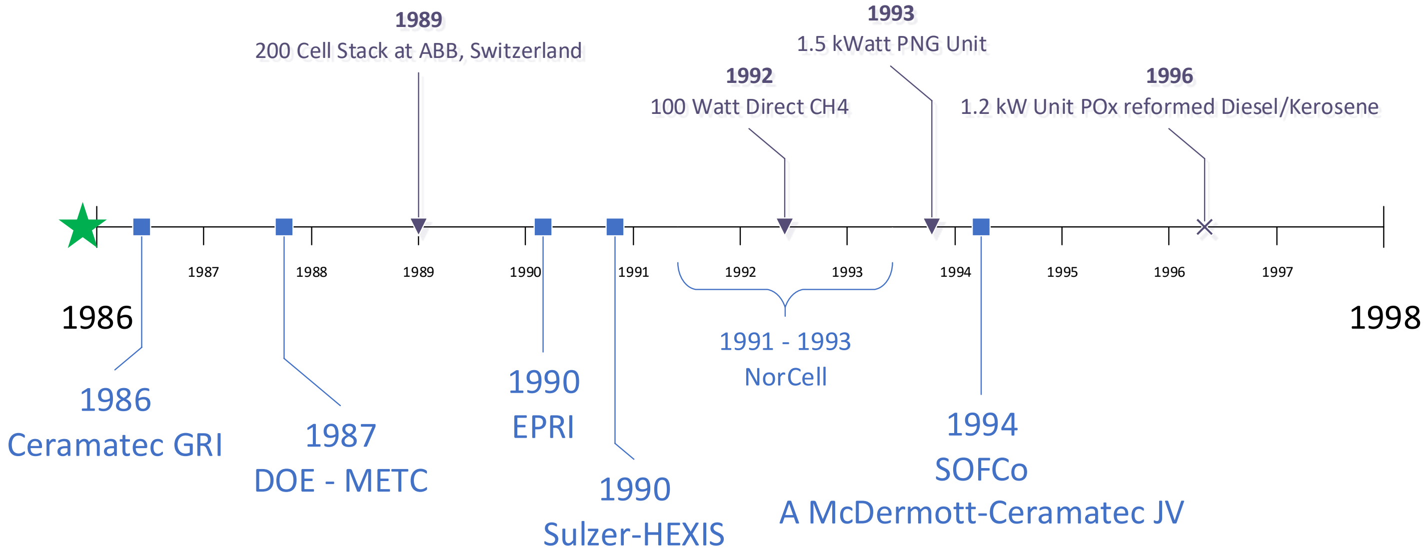
- Plasma Reformer – H_2 and Syngas for flare curtailment
- Fischer-Tropsch Reactors – Modular design for transportation fuel production from H_2 and Syngas

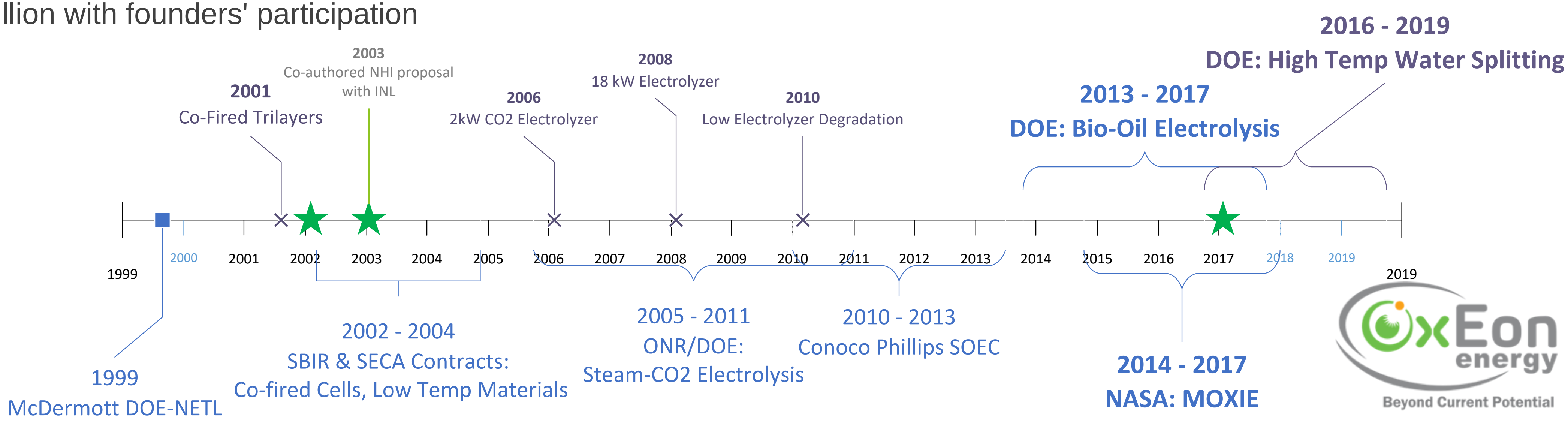


OxEon's Solid Oxide Heritage

Key Milestones

- ★ 1986 - SOFC R&D began
- ★ 2002 - Solid Oxide Electrolysis R&D began
- ★ 2003 – OxEon founders and INL co-authored initial nuclear hydrogen proposal that started our nearly 30-year collaboration
- ★ 2017 - OxEon Energy formed to develop commercial products and build on ISRU developments
- Cumulative Solid Oxide R&D investments >$150 Million with founders' participation





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Beyond Current Potential

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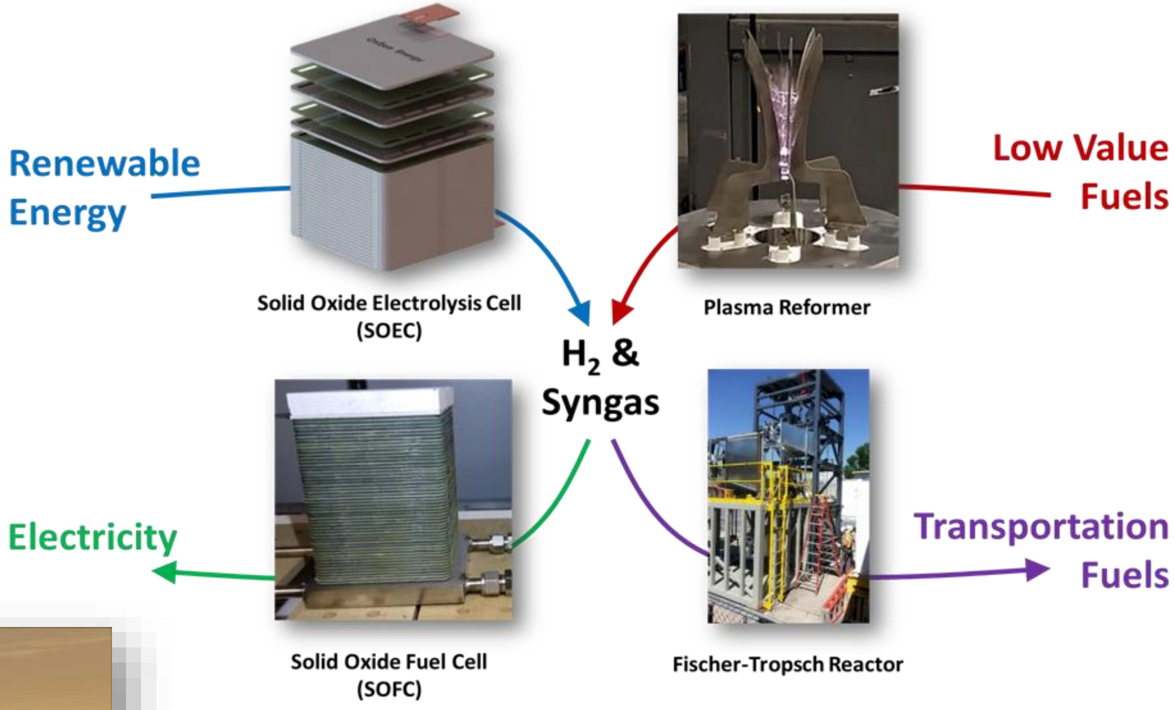
Stack manufacturing (M0-12)

OxEon stacks for this project are suitable for electrolysis and fuel cell operations as well as other applications

OxEon scaled the MOXIE Mars stack for terrestrial applications.



Further Use of OxEon SOC stacks: Bio-CO_2 to E-Fuels

OxEon Solid Oxide Co-Electrolysis

Syngas

Steam from FT Cooling

Existing EPT Waste Food Digester

CO_2

Separated biogas

CH_4

O_2 Enriched Sweep air

OxEon Modular FT Reactor

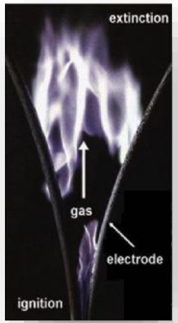
Synthetic Liquid Bio-Fuels

Produced Water

OxEon ATR Plasma Reformer

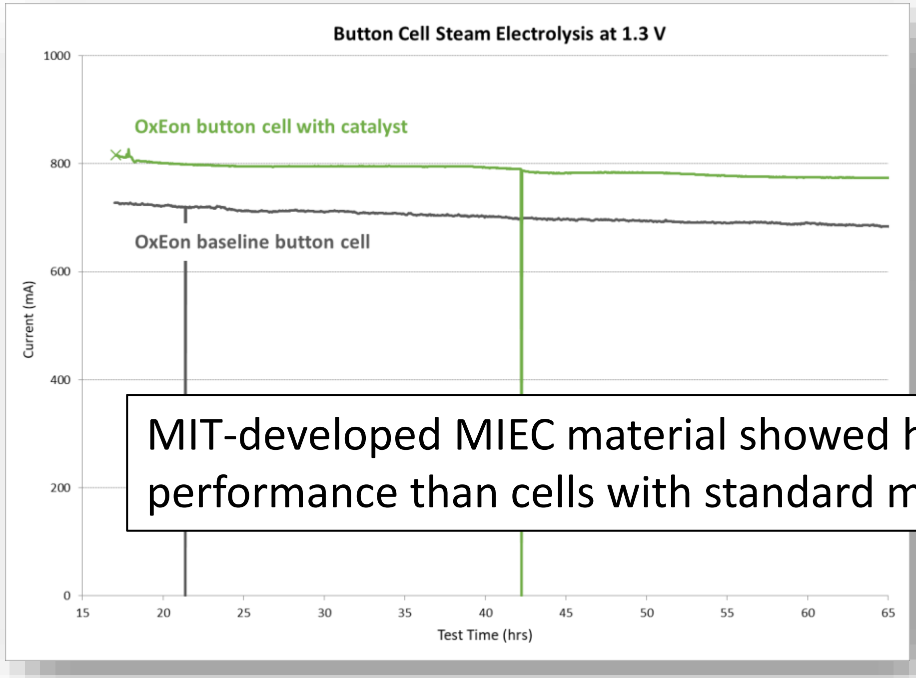
Syngas

H_2O



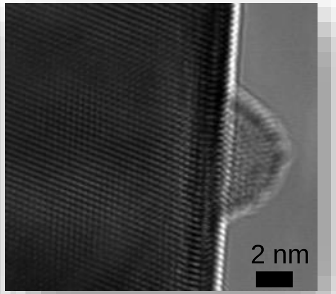
Catalyst Development & Stack Manufacturing (M0-12)

Prof. Bilge Yildiz's group at MIT is addressing catalyst performance and stability.



MIT-developed MIEC material showed higher initial performance than cells with standard materials set

Electrolyte, electrode, catalyst, cell and stack production



Interconnect coating process in parallel with cell fabrication.

Electrode / Coating Material	# Powder Batches			% Complete	
Ceria underlayer	Total Needed	Complete	QA Ink In	Powder	QA Ink
Air electrode	6 (3 & 3)*		3	83%	100%
Air-side current collector	3		2	67%	67%
Fuel electrode	7	2	5	100%	71%
Interconnect barrier powder	9	4	5	100%	56%
Ceria underlayer	12	5	N/A	42%	N/A

*3 lots for underlayer, 3 lots to mix with air electrode

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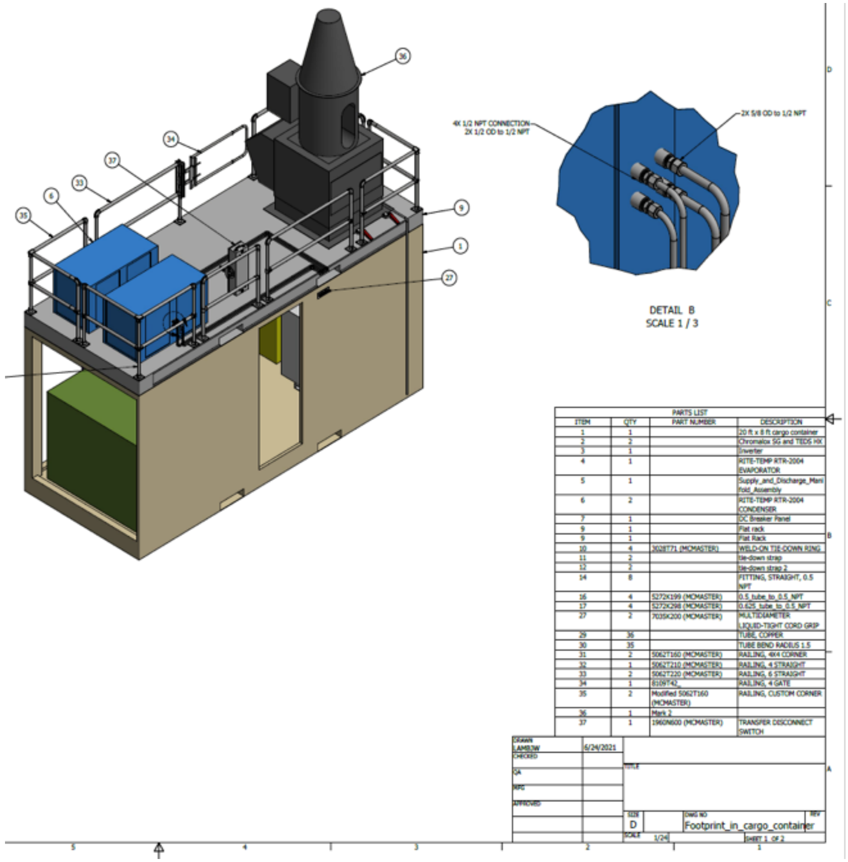
System Design and Integration (M0-12)

System integration plans have been modified to accommodate concurrent operation of other demonstrations:

- 100-kW Bloom Energy SOEC system (installed Sept. 2021)
  - Planned operation thru Sept. 2022 (~5,000 hrs)
- 250-kW FuelCell Energy SOEC system (expected installation May 2022; funded thru FOA-0001817)
  - Planned operation thru Sept. 2023 (>5,000 hrs)
- 50-kW SOEC system funded by HFTO
  - Planned operation thru 2023 with stacks from multiple vendors
- 30-kW electrolysis mode/10-kW fuel cell mode operation
  - This project. Basic build of system is funded by HFTO, and this project funds customized parts for reversible operation, such as heat exchangers, bypass lines, stack connections.



All demo systems will share a common support facility for power and steam supply as well as product gas processing

System Fabrication & Integration (M0-12)

- Fabrication of 50-kW system almost complete
- Fabrication of 30-kW rSOC system will start in Nov. 2021
- Basic support facility, including power supplies and steam generation, and low levels of hydrogen drying, dilution and exhaust are nearly complete
- FlexEnergy has redesigned the heat exchangers to reduce cost for high throughput manufacturing. Four different units have been tested to verify suitability for scaled-up manufacturing
- New heat exchangers are sized for 100-kW SOEC/15-kW SOFC

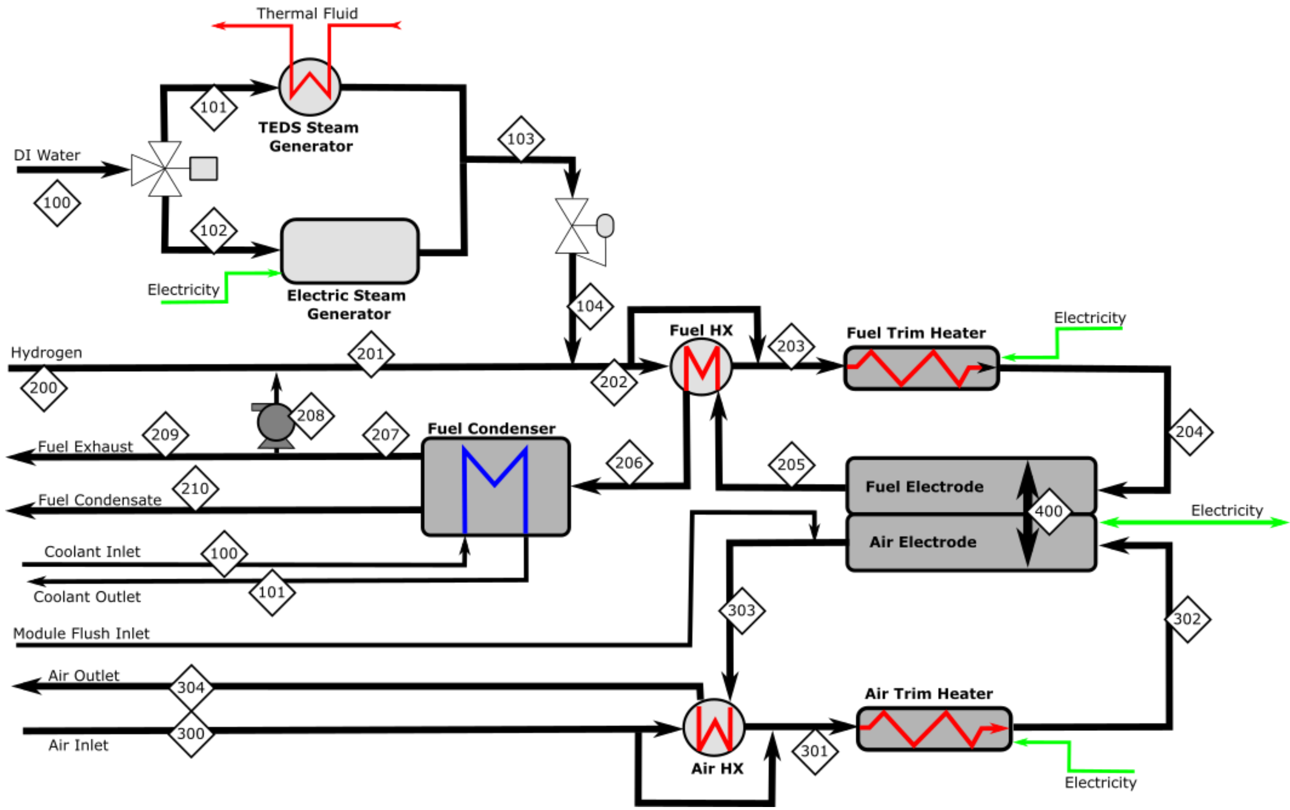
SOC support facility installed in a cargo container, including CE+T Americal Power Converters (150 kW) and Chromalox CSSB-100 steam generator

Heat exchanger fabricated by FlexEnergy for the 50-kW SOEC system

Approach – Task 6: Technoeconomic Analysis (M15-20)

Thermodynamic analysis will demonstrate potential to achieve > 85% system efficiency in electrolysis mode

- Existing 50-kW SOEC system design achieves theoretical 90% DC electrical efficiency
- Potential to achieve >85% system efficiency will require
  - Very high AC-DC converter efficiency (96%)
  - Re-use of unconsumed steam
  - High- and low-temperature heat recuperation (not fully shown in figure)
  - Very low thermal losses (usually associated with large commercial systems)



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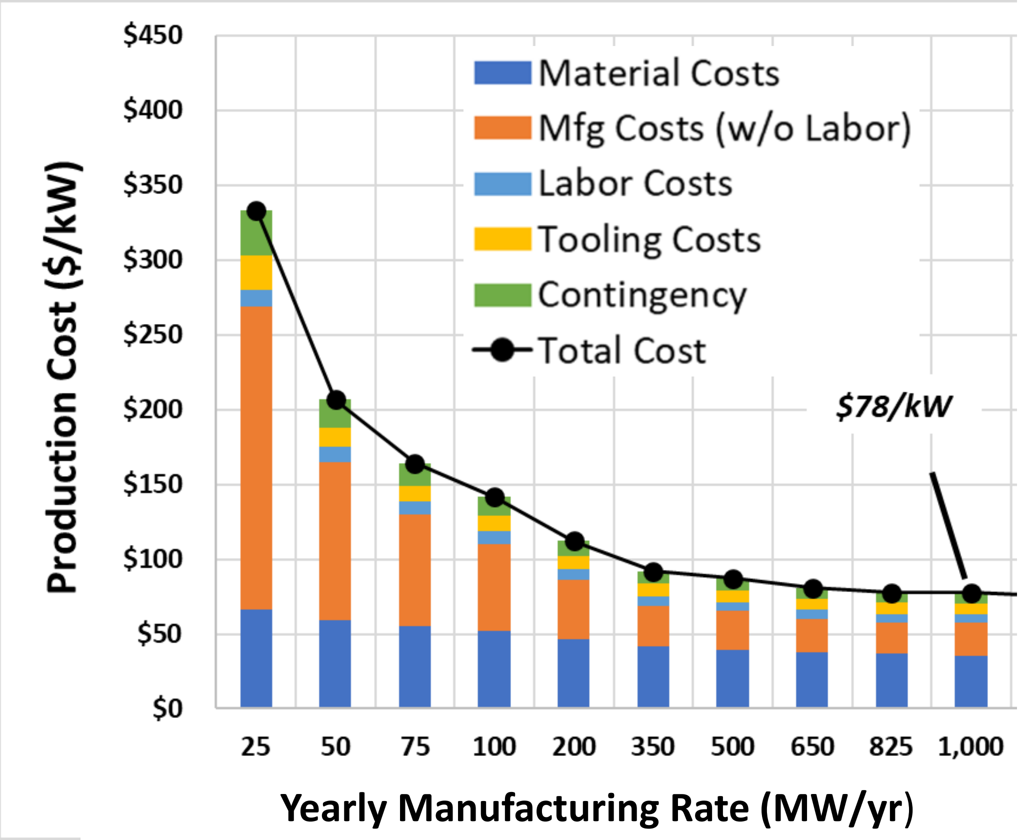
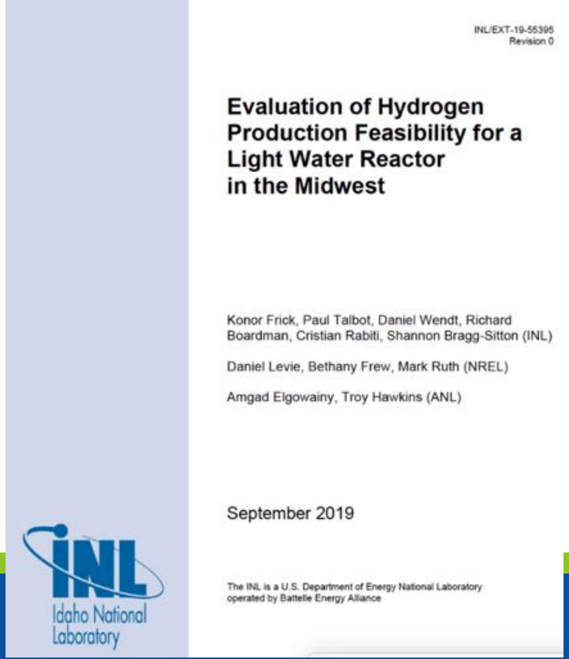
Approach – Task 6: Technoeconomic Analysis (M15-20)

Technoeconomic analysis (TEA) will demonstrate potential to produce hydrogen at a cost of $2/kg on a cost of electricity of $30/MWhr

- Will follow methodology developed for previous INL and Strategic Analysis reports
- Target areas for improvement will be O&M costs, SOC stack costs, other costs, and steam costs



Total manufacturing cost of SOC stacks using electrode-supported cells. Source: Strategic Analysis Report to INL: Solid Oxide Electrolysis Stack Manufacturing Cost Analysis (Interim Report) April 2021.



INL/EXT-19-55395
Revision 0

Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest

Konor Frick, Paul Talbot, Daniel Wendt, Richard Boardman, Cristian Rabiti, Shannon Bragg-Sitton (INL)

Daniel Levie, Bethany Frew, Mark Ruth (NREL)

Amgad Elgowainy, Troy Hawkins (ANL)

September 2019

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Remaining Challenges and Barriers

- Challenge: Multiple SOC systems are being tested in a shared facility
  - Bloom >100 kW system: plan to start testing in Nov. 2021 (press release in May)
  - HFTO 50 kW open-architecture SOEC system (1st unit): start testing in Jan. 2022
  - 30 kW rSOC system (2nd unit, this project): plan to start testing in Mar. 2022
  - FuelCell Energy 250 kW SOEC system: plan to start testing by June 2022
- Challenge: Manufacturing delays
  - Fabricators have had weld qualification challenges (now performing 100% x-ray radiography on welds with design temperature >500 °C)
  - COVID-19 issues have slowed procurement
    - For example, >10 month delay obtaining heat exchangers

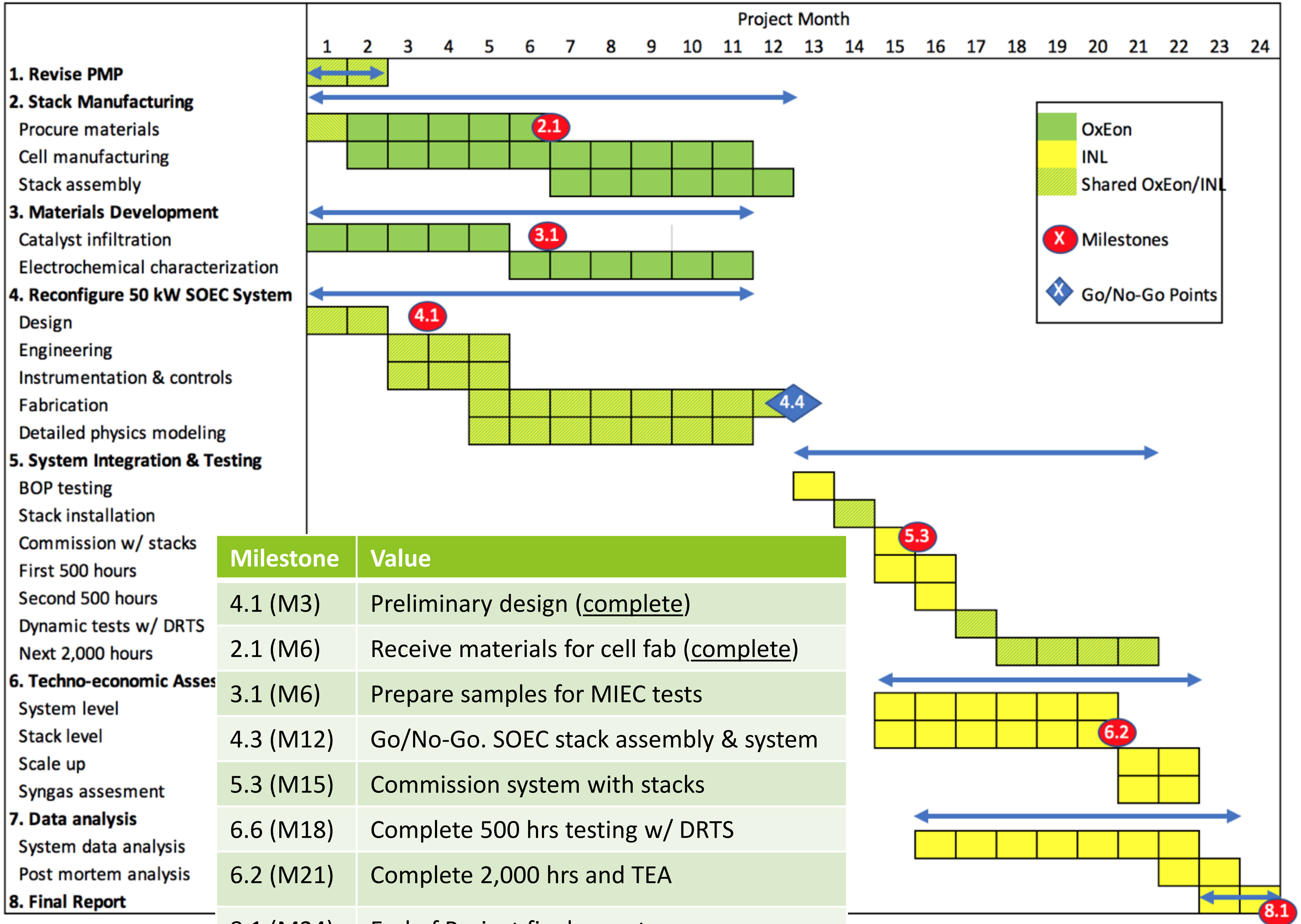
Proposed Future Work

Tasks 1-3 delayed ~3 months due to contracting and delays with 1st 50 kW SOEC system

- Anticipate being back on schedule by Month 15

Go/No-Go Decision (M12)

- Need stacks & BOP ready for installation; project has 4 month cushion to still meet end-of-project date
- Will be able to take advantage of learnings from developing and testing prior 50 kW SOEC system



Milestone	Value
4.1 (M3)	Preliminary design (complete)
2.1 (M6)	Receive materials for cell fab (complete)
3.1 (M6)	Prepare samples for MIEC tests
4.3 (M12)	Go/No-Go. SOEC stack assembly & system
5.3 (M15)	Commission system with stacks
6.6 (M18)	Complete 500 hrs testing w/ DRTS
6.2 (M21)	Complete 2,000 hrs and TEA
8.1 (M24)	End of Project final report

Summary

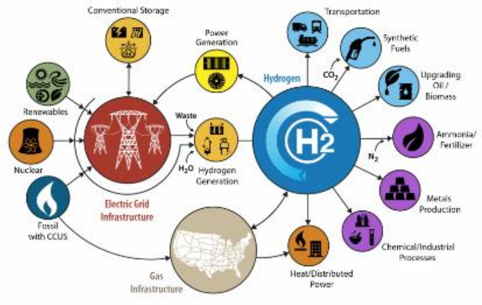
- Task 2 – Stack manufacturing
  - OxEon is manufacturing 30-kW rSOC stacks (previously manufactured >15-kW SOC stacks for INL)
- Task 3 – e^2 Catalyst development
  - New catalyst nanoparticle exsolution will substantially lower the polarization resistance and improve stability
- Task 4 – Reconfigure 50-kW SOEC system
  - First 50-kW SOEC system will be commissioned by Jan. 2022
  - Design for second system has been modified; will be commissioned for rSOC by Mar. 2022
- Task 5 – System integration and testing
  - System will be integrated with low-grade heat source and operated for >3,000 hrs
  - System will be instrumented to measure thermodynamic performance
- Task 6 – Technoeconomic & thermodynamic analysis
  - Thermodynamic analysis will demonstrate potential to achieve > 85% system efficiency in SOEC mode
  - Technoeconomic analysis (TEA) will demonstrate potential to produce hydrogen at a cost of $2/kg on a cost of electricity of $30/MWhr.

Proposed future work is subject to change based on funding levels

Technical Backup Slides and Additional Information

OxEon’s Collaboration with INL

2021
Supporting H2@Scale & Hydrogen Shot Vision



2003
OxEon & INL co-authored initial nuclear-H_2 proposal that started our collaboration

2020
10kW SOEC Module (4x 65-cell stacks) delivered to INL for testing in 2021

2002 2007 2012 2017 2022

Integrated Laboratory Scale (ILS) Test
720 cells, three 4-stack modules, 60-cell stacks
Produced 5.7 Nm3/h H2, 17.5kW

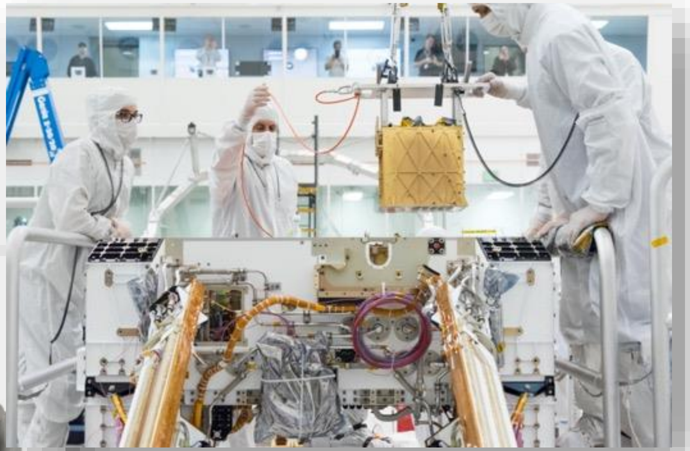
5kW SOEC Module tested at INL
Achieved 5kW target Vop < Vtn

30kW reversible SOEC/SOFC system in production
780 cells, 3x 4-stack modules, 65-cell stacks

Solid Oxide Propelled Space Exploration

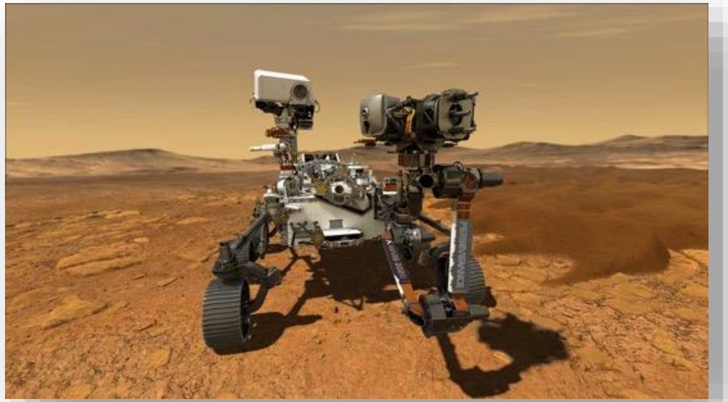
NASA funded flight program

- Only flight qualified SOEC in history
- Only TRL9 SOEC device in history
- First production of oxygen from the Mars atmosphere
- Six successful SOXE (SOEC) runs on Mars that matched expectations from model and testing on earth



MOXIE SOXE TEAM:

- **MIT:** Program prime and science team lead
- **JPL:** Systems integration
- **OxEon:** Stack development and production
  - **TRL3 to 6 in 18 months!!**
  - Hermetically sealed, ruggedized stack capable of withstanding launch, entry, descent and landing



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Active OxEon Projects with NASA for Next Generation

- **Mars**: Oxygen and Methane Production from co-electrolysis
- **Lunar**: Liquid Propellants for LH2/Lox-Fueled Cislunar Transport
- **SBIR**: Cathode Development for Redox Tolerance

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Beyond Current Potential

Current Solid Oxide Projects

- NASA
  - Mission scale stacks for CH_4 & O_2 propellant production on Mars
  - LOx & LH_2 propellant production from lunar polar crater ice
  - Redox-, thermal cycle-,and coking-tolerant electrode

- Commercial
  - Private microgrid reversible 20kW SOEC/10kW SOEC system

- DOD
  - Bi-propellant fueled SOFC system for Air Force Research Lab/ University of New Mexico

- DOE
  - NETL program – SOEC for low cost hydrogen production (with PNNL)
  - BETO Biogas to Liquids CO2 steam co-electrolysis
  - Preparing to test 10 kW HTSE at INL
  - **Building reversible 30 kW SOEC/10 kW SOEC for INL installation**

Stack manufacturing (OxEon) (M0-12)

Stacks for this project are suitable for electrolys and fuel cell operations as well as other applications

OxEon 30kW electrode and interconnect coating powder and ink production status.

Electrode / Coating Material	# Powder Batches			# Power Batches In		% Completion	
Ceria underlayer	Total Needed	In Progress	Complete	non-QA Ink(s)	QA Ink	Powder	QA Ink
Air electrode	6 (3 & 3)*	1			3	83%	100%
Air-side current collector	3	1			2	67%	67%
Fuel electrode	7		2		5	100%	71%
Interconnect barrier powder	9		4		5	100%	56%
Ceria underlayer	12	2	5	N/A	N/A	42%	N/A
*3 lots for underlayer, 3 lots to mix with air electrode							