Oct. 25, 2022

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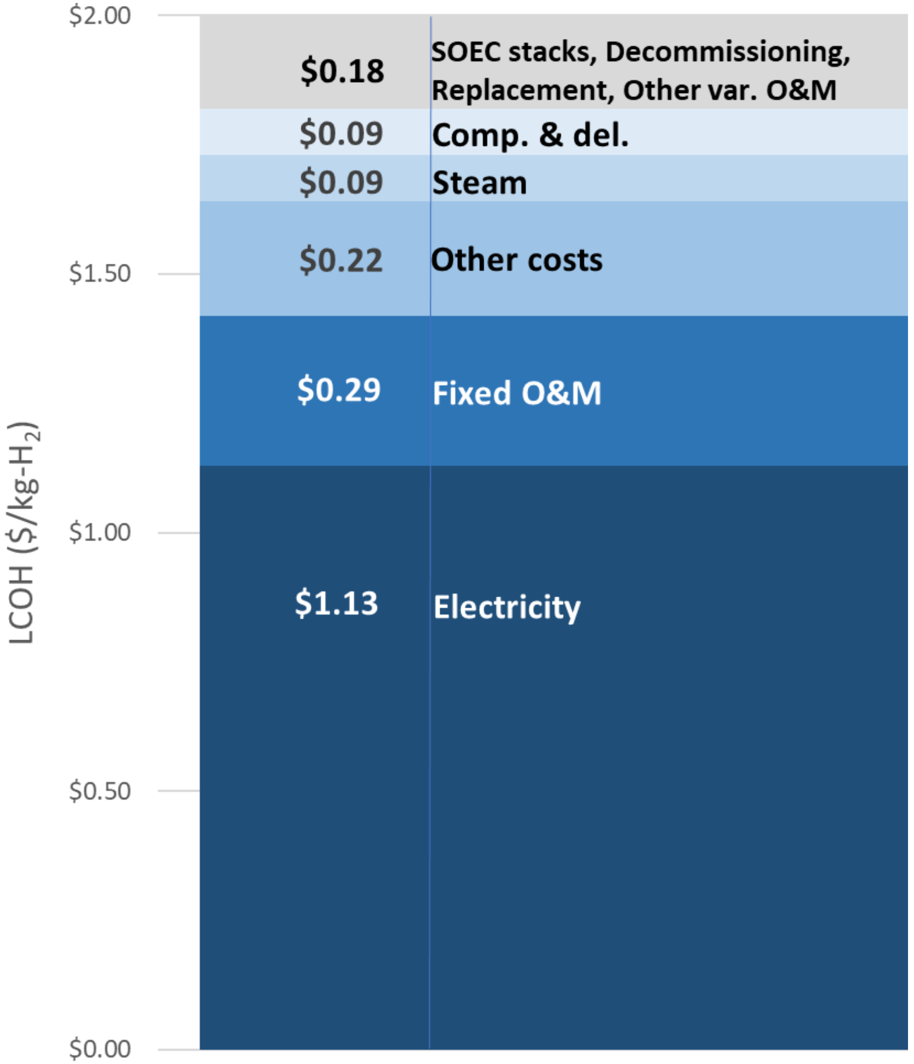
Performance Validation of a Thermally Integrated 50 kW High Temperature Electrolyzer System (INL/Con-21-69783)

DE-FOA-0002300: Grant 13163665
2021 SOFC Virtual Project Review Meeting

This presentation does not contain any proprietary, confidential or otherwise restricted information

Project Goals

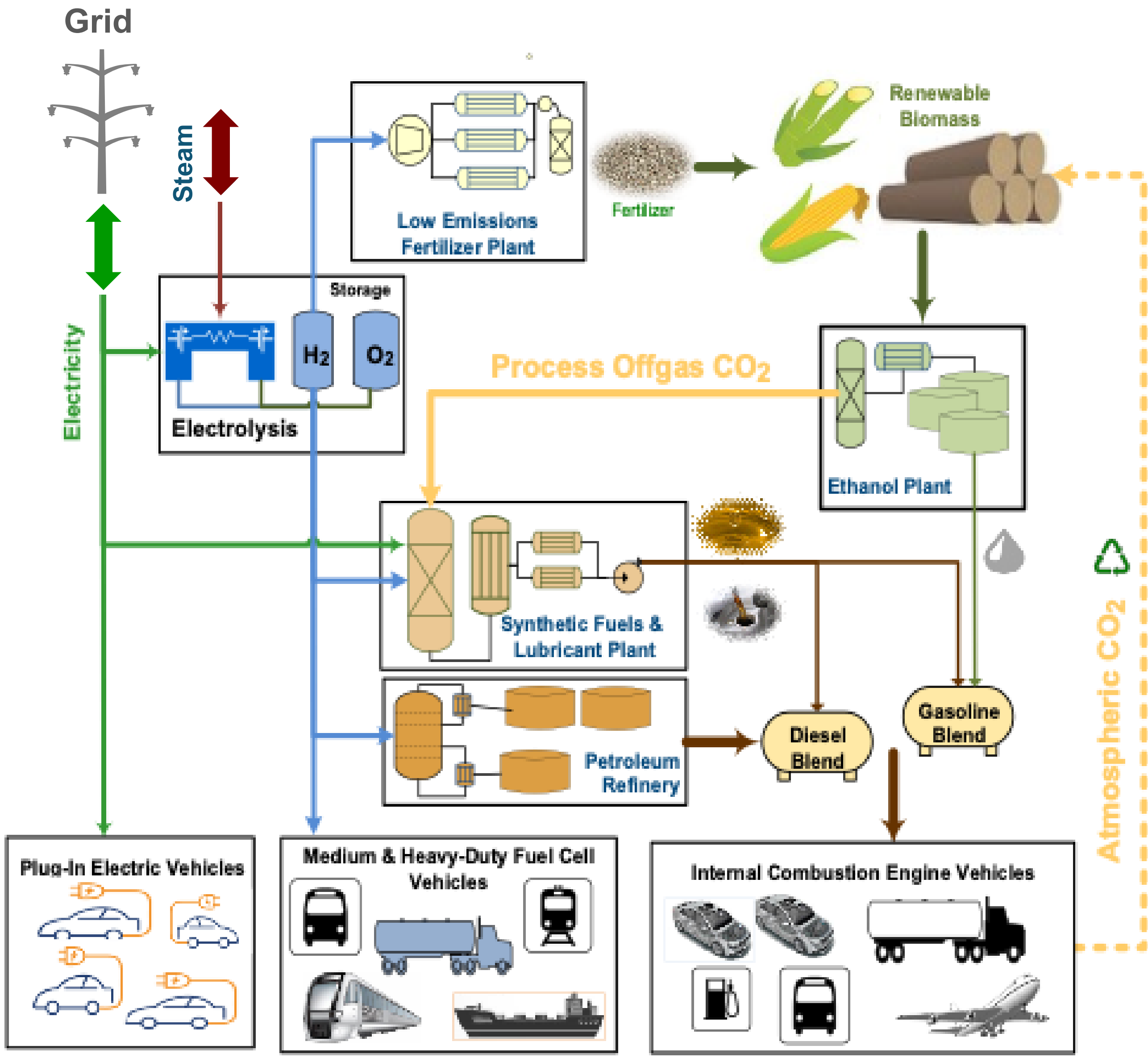
- Accumulate ~3,000 hrs operating a reversible solid oxide electrolysis (rSOC) system
  - A SOC system at INL will be modified for reversible operations:
    - 30-kW electrolysis mode/10-kW fuel cell mode
  - SOC stacks will incorporate improved catalyst in fuel electrode
  - Operation of rSOC system will be coupled to a steam generator programmed to mimic an 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: 06/30/2023

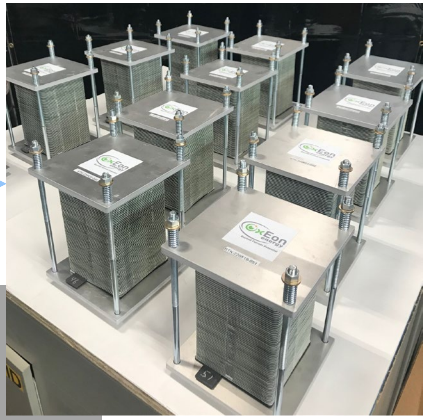
Relevance

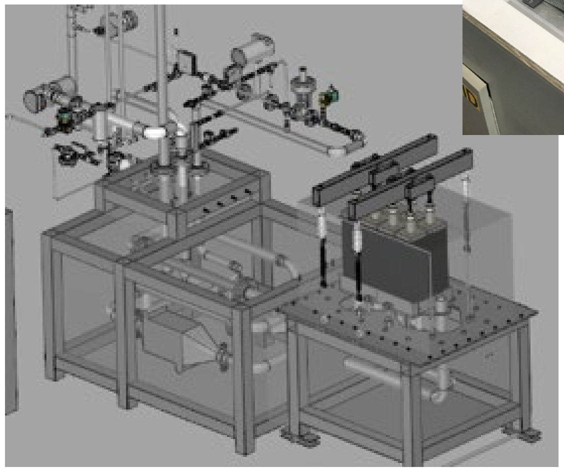
- **DE-FOA-0002300 AIO 2:**
  - Improving the cost, performance and reliability of reversible rSOC systems for clean hydrogen and clean power production
  - rSOC systems have opportunities to enter the marketplace but need proven system cost, performance, and reliability
  - rSOC systems can use the 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

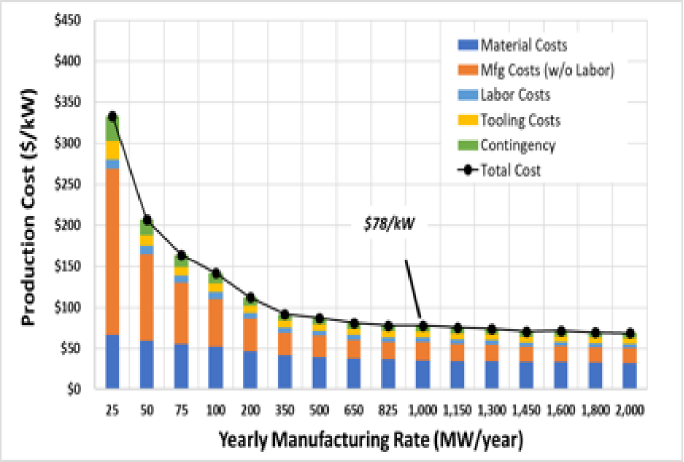


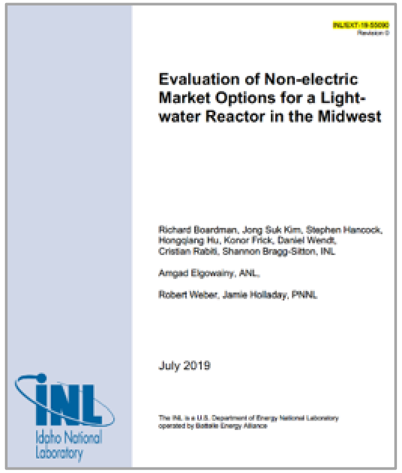
Approach

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








INL/EXT-19-55090
Revision 0

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

INL
Idaho National Laboratory

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

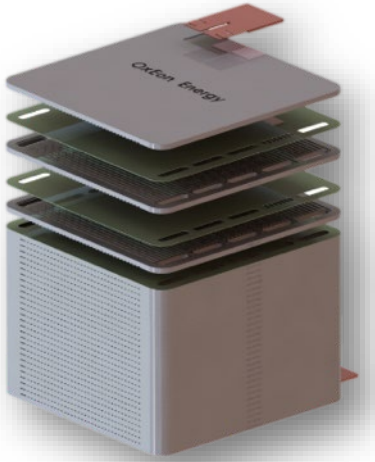
Challenges and Barriers

- Multiple SOC systems are being tested in a shared facility
  - Bloom >100 kW system: completed 2,000 hours in Sept. 2022
  - 30 kW rSOC system: plan to start testing in Dec. 2022
  - HFTO 50 kW open-architecture SOEC system: plan to start testing in Feb. 2023
  - FuelCell Energy 250 kW SOEC system: plan to start testing summer 2023
- Manufacturing delays
  - 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

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

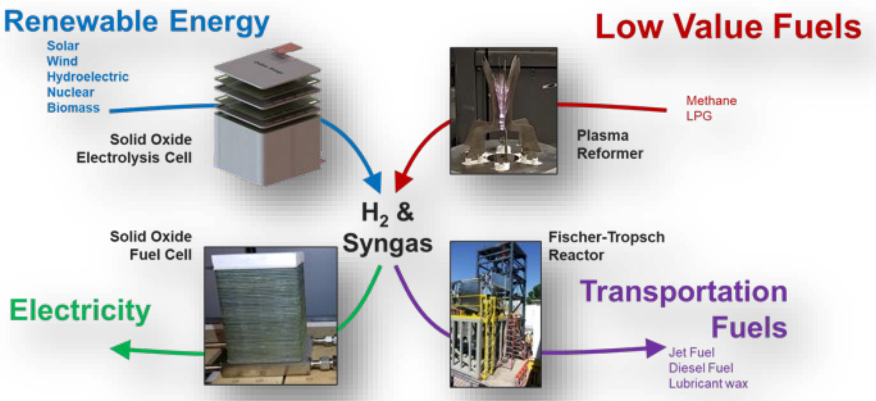


Solid Oxide Fuel Cell and Electrolysis Stacks

- 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

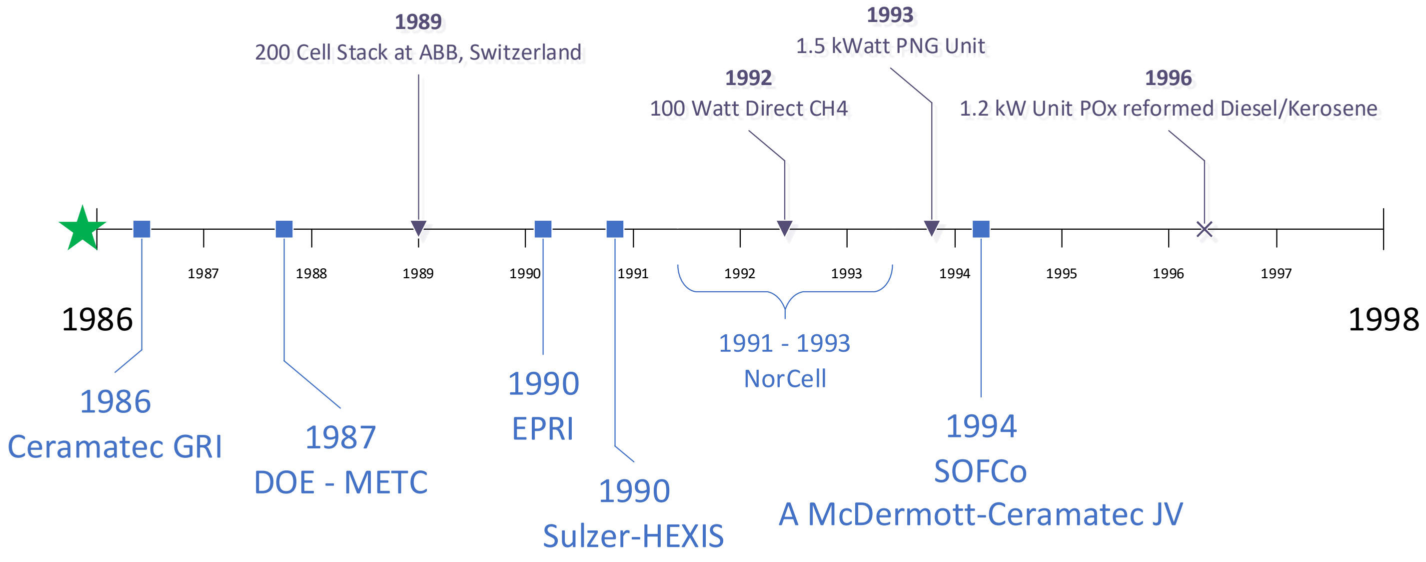
- Plasma Reformer – H_2 and Syngas for flare curtailment
- Fischer-Tropsch Reactors – Modular design for transportation fuel production from H_2 and Syngas

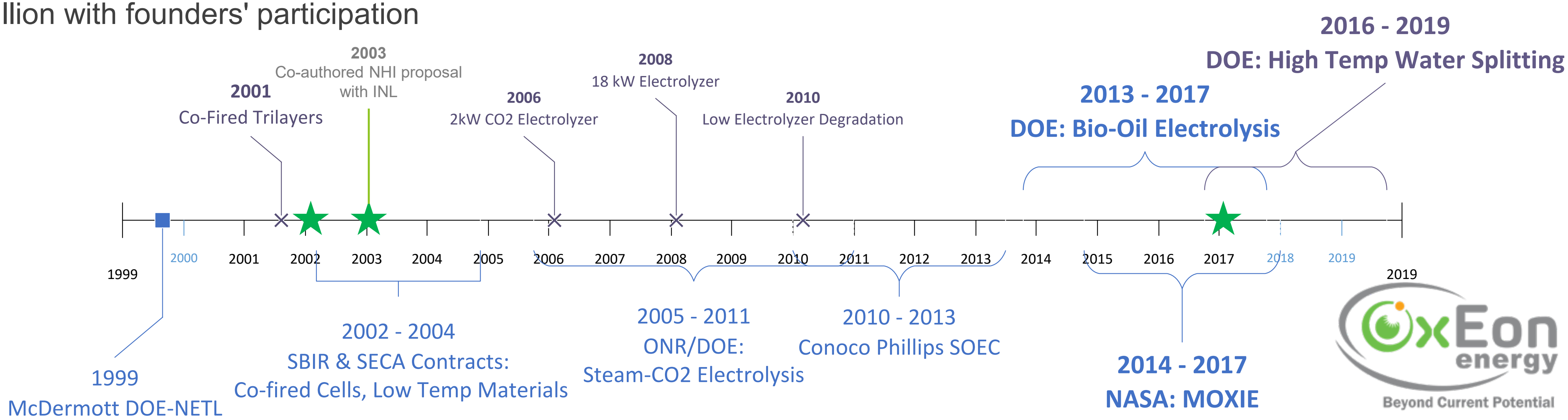


OxEon's Solid Oxide Heritage

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





OxEon energy
Beyond Current Potential

OxEon energy
Beyond Current Potential

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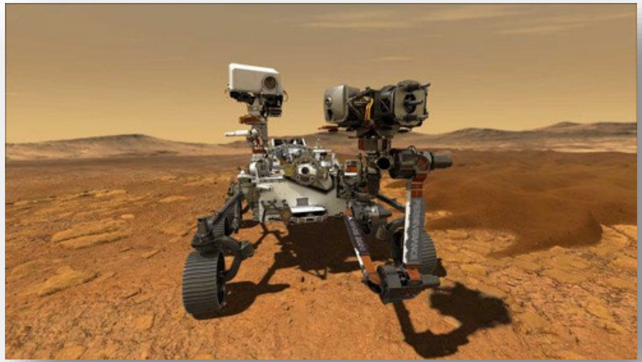
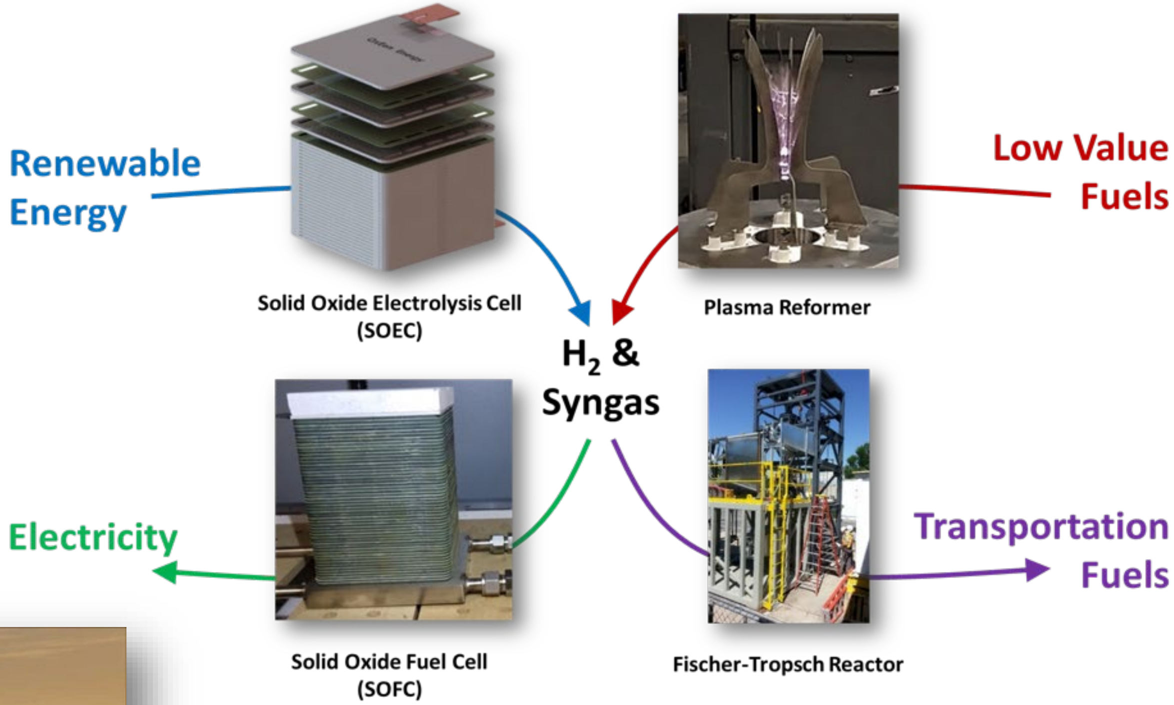
Stack Manufacturing at OxEon

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

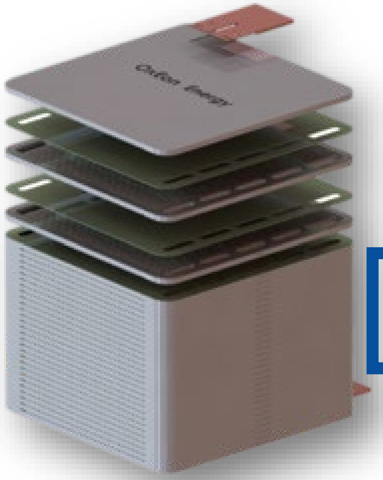
OxEon scaled the MOXIE Mars stack for terrestrial applications.





Further Use of OxEon SOC stacks: Bio-CO_2 to E-Fuels (DOE-BETO award: DE-EE0008917)

OxEon energy
Beyond Current Potential



Existing EPT Waste Food Digester

CO_2

Separated biogas

CH_4

OxEon Solid Oxide Co-Electrolysis

O_2 Enriched Sweep air

OxEon ATR Plasma Reformer

Syngas

Syngas

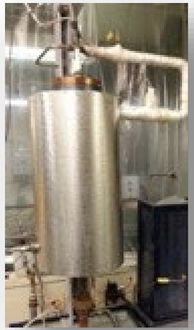
H_2O

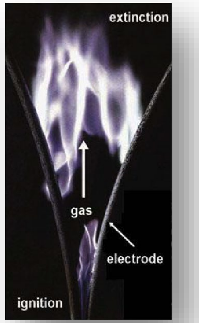
Steam from FT Cooling

OxEon Modular FT Reactor

Synthetic Liquid Bio-Fuels

Produced Water

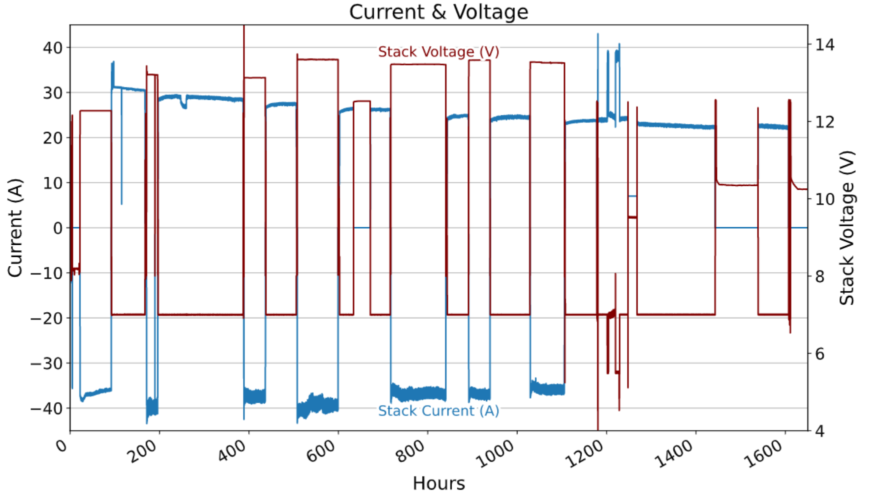




Catalyst Development & Stack Manufacturing (M0-12)

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

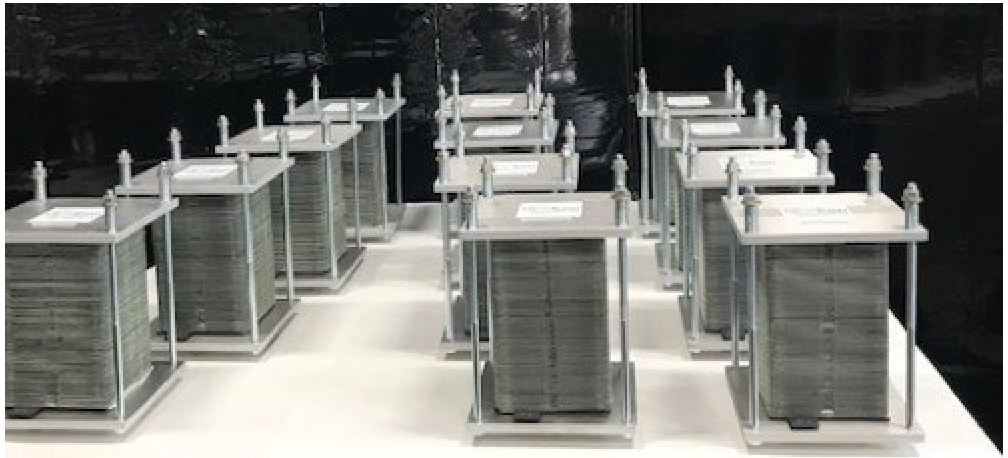
10-cell stack, 115 cm^2 active area



Electrolyte, electrode, catalyst, cell and stack production

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

Interconnect coating process in parallel with cell fabrication.

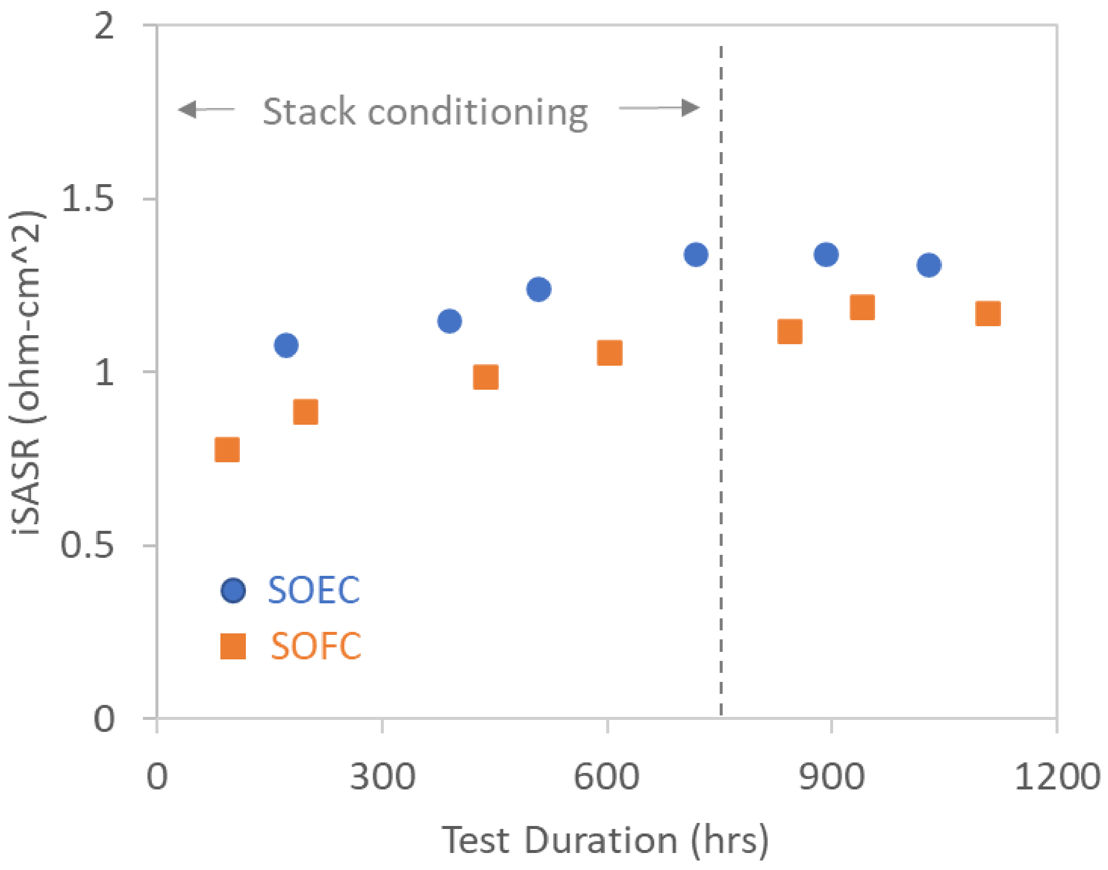


Catalyst Development & Stack Manufacturing (M0-12)

OxEon energy
Beyond Current Potential

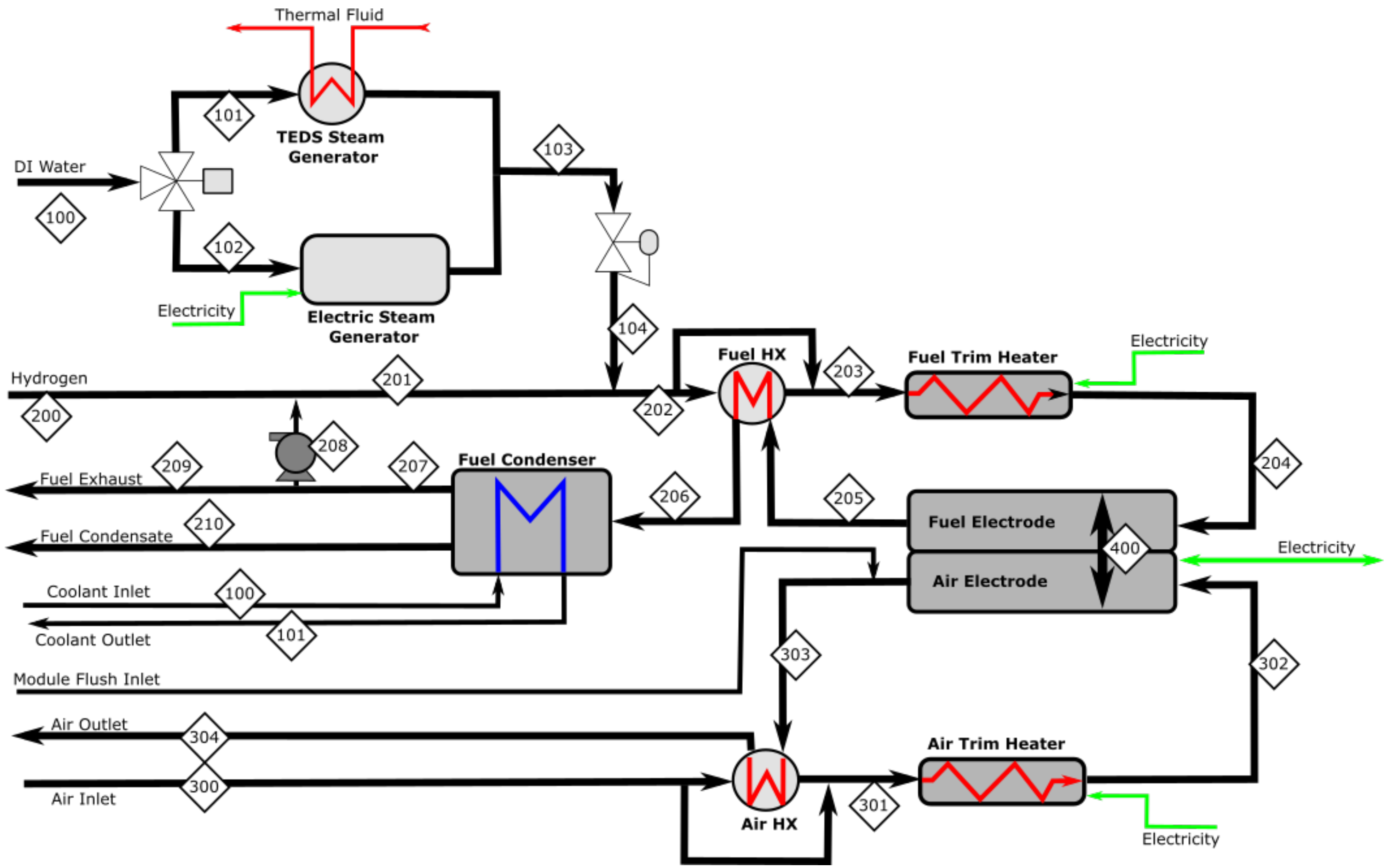
- Catalyst development
  - Ni-Ce-based catalyst on fuel electrode developed to produce Ni pockets on electrode surface (INL project).
  - Proprietary catalyst on air electrode (privately funded).

- 10 Cell Stack (STK-57)
  - Materials set incorporates
    - Barrier layer developments (NETL-funded)
    - Air electrode modification (privately funded)
  - Stable performance in SOEC and SOFC operations
  - ~800 hour conditioning period



System Design and Integration

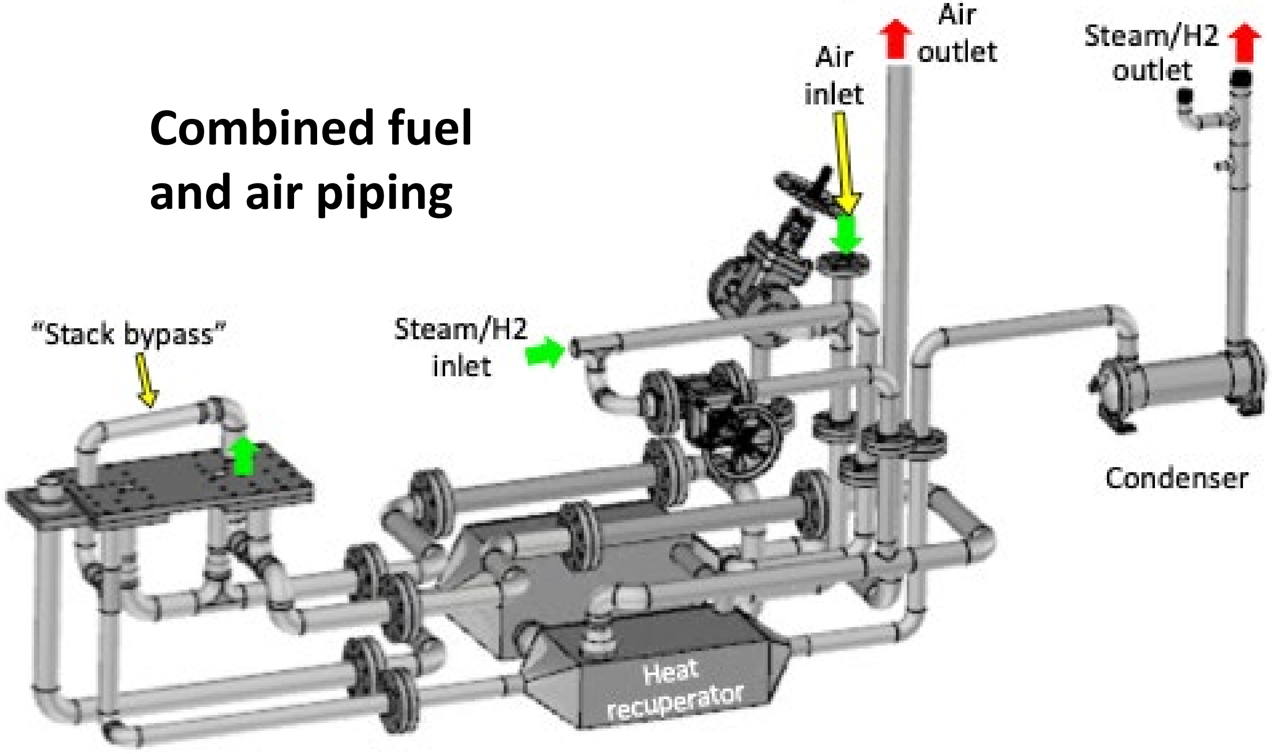
- Standard SOEC/SOFC design
  - High temperature heat exchangers (HXers) on fuel and air streams
  - HXer bypasses for incoming fuel and air streams in FC model
  - Trim heaters for EC mode
  - Fuel Condenser to separate water from product H2
  - H2 recycle loop with blower
- Steam from electric boiler or nonfired boiler



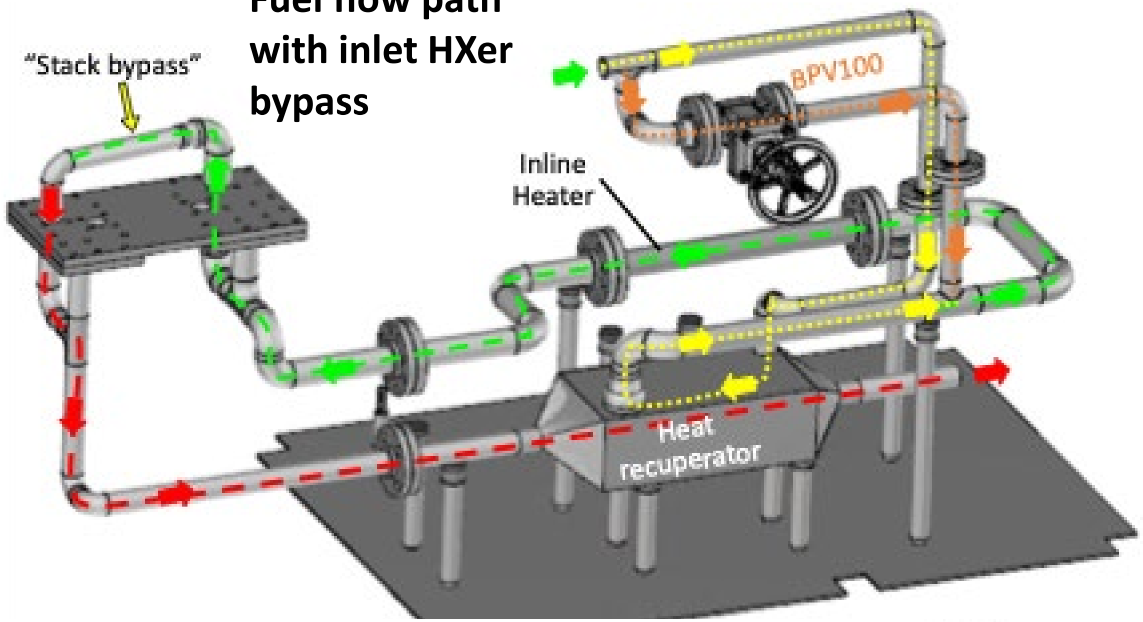
System Design & Integration

- High temperature piping design
  - Separate stack & HXer modules
  - Piping components supported on springs to allow thermal expansion; no bellows flanges

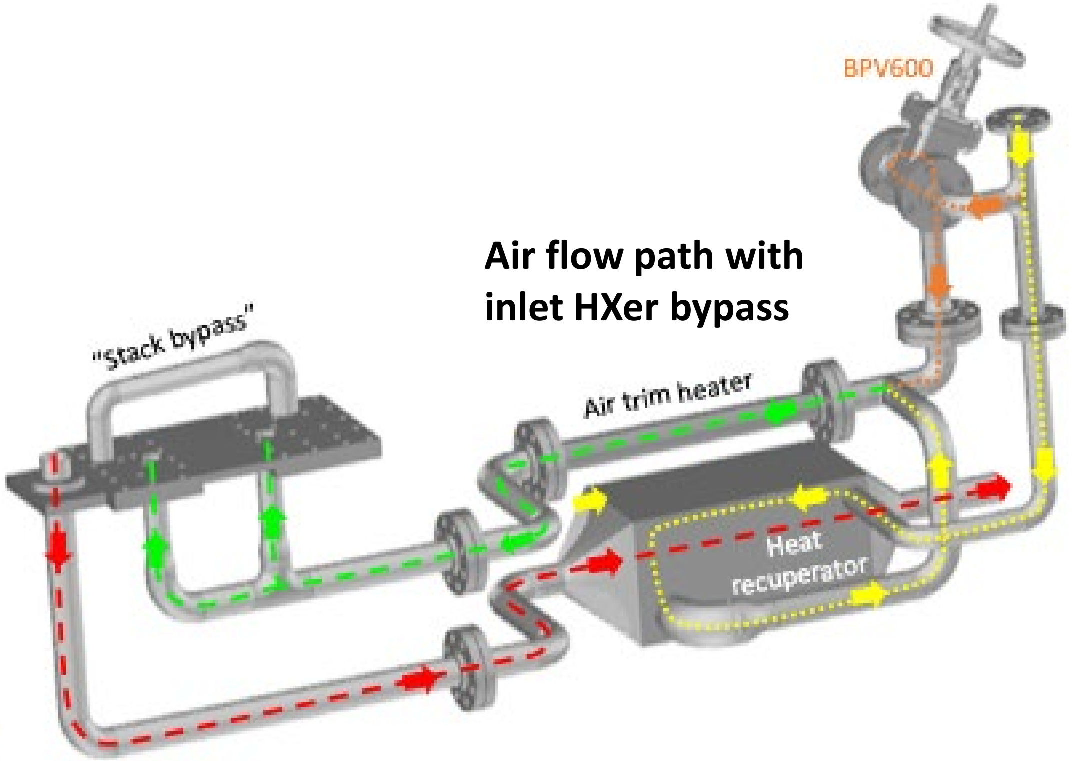
Combined fuel and air piping



Fuel flow path with inlet HXer bypass



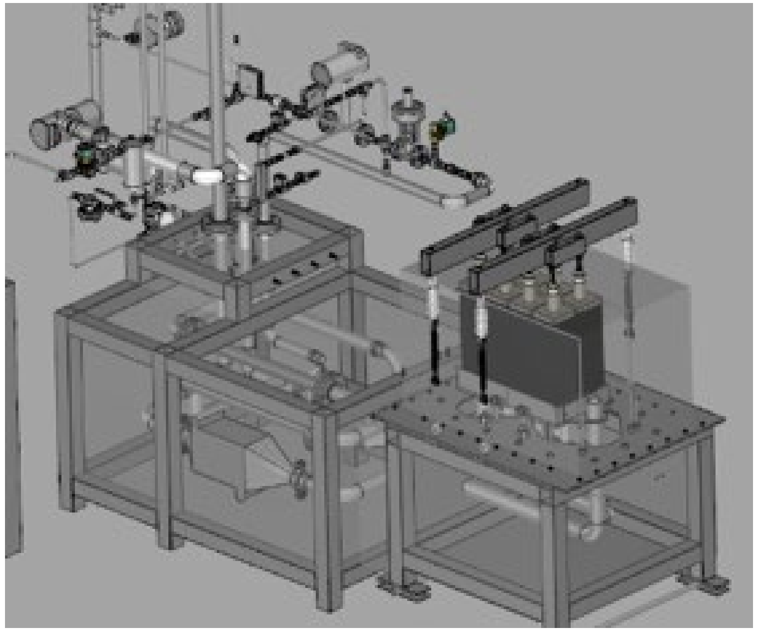
Air flow path with inlet HXer bypass



System Design & Integration

- Welding on 30 kW rSOC system piping expected complete by ~Nov. 8, 2022
- Piping photos are of similar 50 kW system
  - Does not have HXer bypass for FC mode

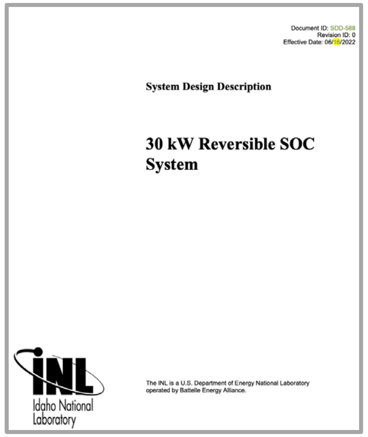
30 kW rSOC system assembly (no piping yet)



50 kW SOEC system assembly (with HT piping)

System Design & Integration

- 30 kW rSOC system located in custom 20 ft container with doors on three walls
- System Design Description document will be publicly available (~Jan. 2023)
- 12 OxEon SOEC stacks arranged in quad configurations on manifold



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Effective Date: 06/16/2022

System Design Description

30 kW Reversible SOC System

Idaho National Laboratory

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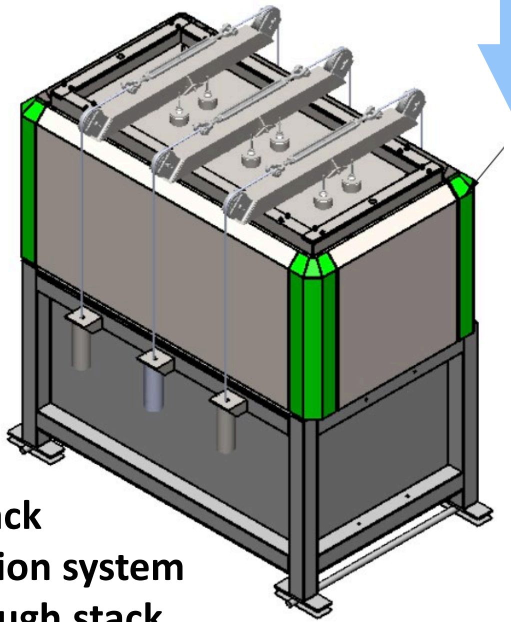
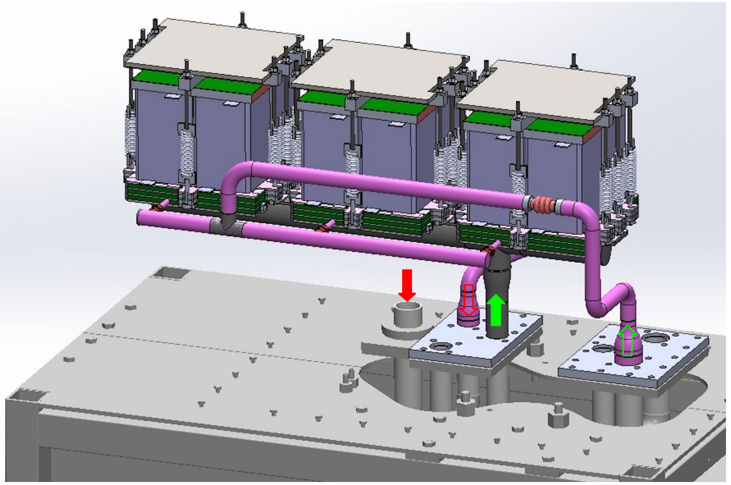
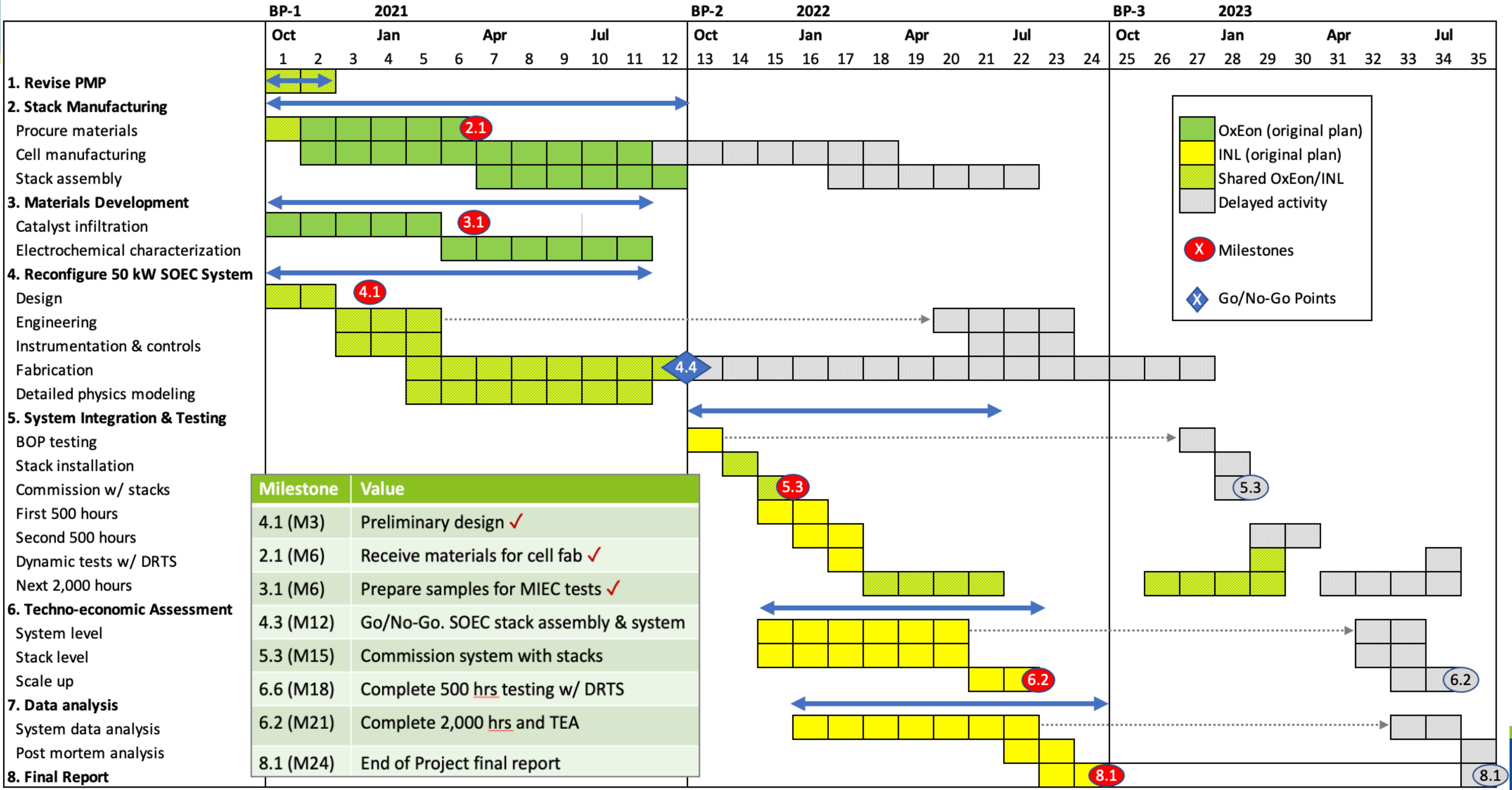


OxEon stack compression system (acts through stack module lid)



OxEon SOEC stacks on manifold

Revised Project Schedule

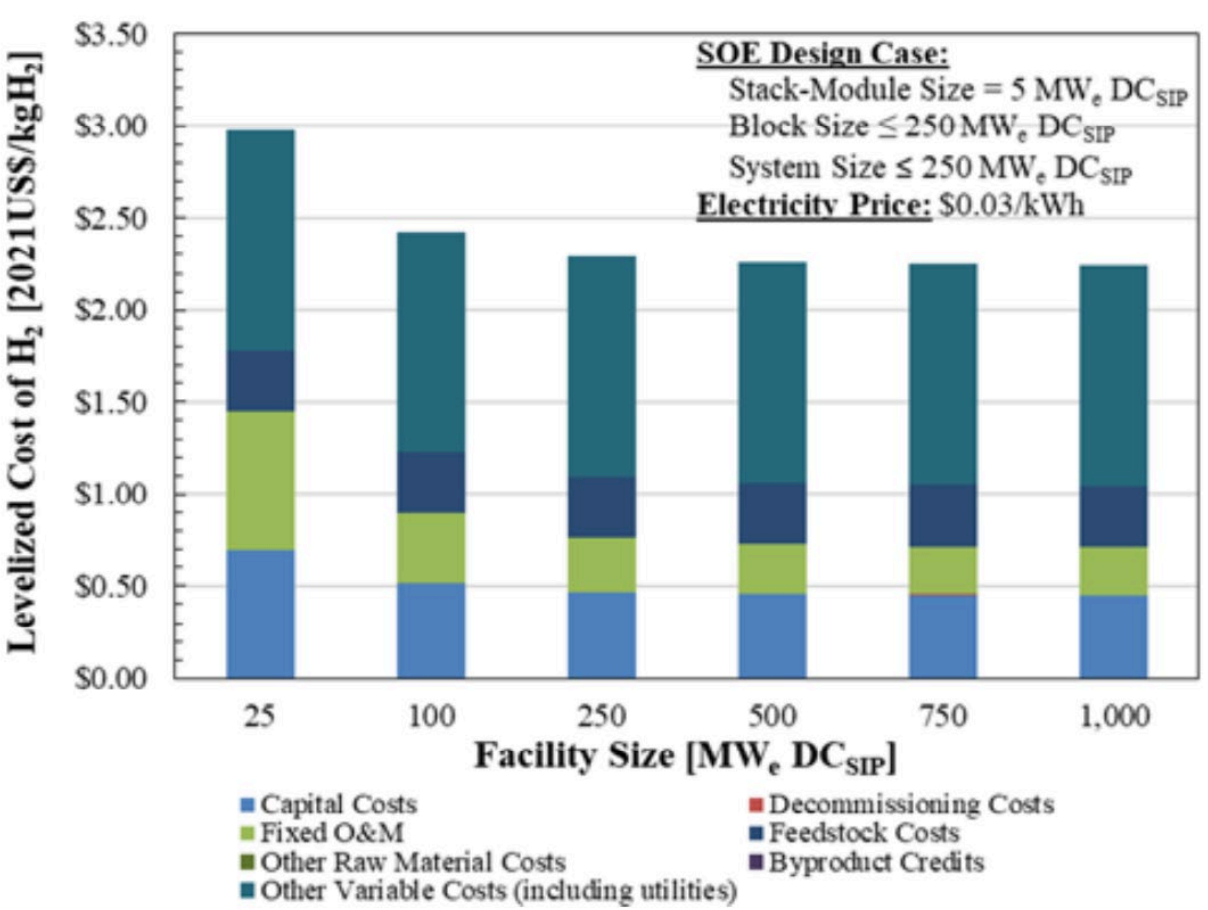


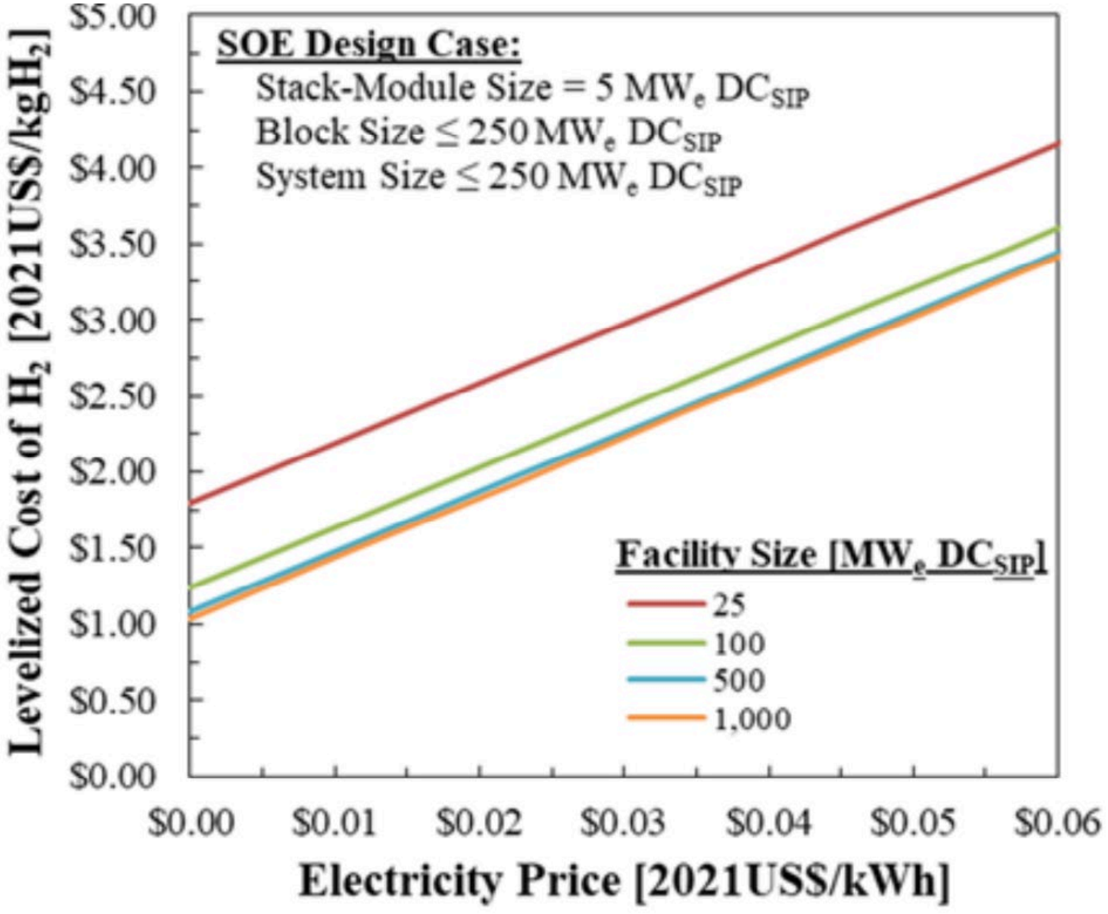
Milestone	Value
4.1 (M3)	Preliminary design ✓
2.1 (M6)	Receive materials for cell fab ✓
3.1 (M6)	Prepare samples for MIEC tests ✓
4.3 (M12)	Go/No-Go. SOEC stack assembly & system
5.3 (M15)	Commission system with stacks
6.6 (M18)	Complete 500 hrs testing w/ DRTS
6.2 (M21)	Complete 2,000 hrs and TEA
8.1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

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

TEA will show potential to produce H_2 at $2/kg on a cost of electricity of $30/MWhr

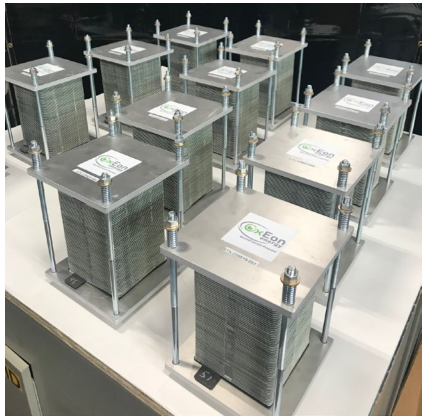
- Will follow methodology used for previous reports





Source of Figures: J.H. Prosser, et al., 2022. Submitted for peer review (joint manuscript between Strategic Analysis & INL)

Summary



- Task 2 – Stack manufacturing
  - Manufacturing by OxEon is complete
- Task 3 – e^2 Catalyst development
  - Catalyst development complete
- Task 4 – Reconfigure 50-kW SOEC system
  - Engineering complete
  - Last major item to be received is the high temperature piping system – expected ~ Nov. 8, 2002
- Task 5 – System integration and testing
  - System integration – expected ~ Dec. 15, 2022
  - System will be instrumented to measure thermodynamic performance
  - System will be operated for 3,000 hrs (Jan. – Jul. 2023)
- Task 6 – Technoeconomic & thermodynamic analysis (TEA)
  - Thermodynamic analysis will demonstrate potential to achieve > 85% system efficiency in SOEC mode
  - TEA will show potential to produce H_2 at \$2/kg on a cost of electricity of \$30/MWhr.

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