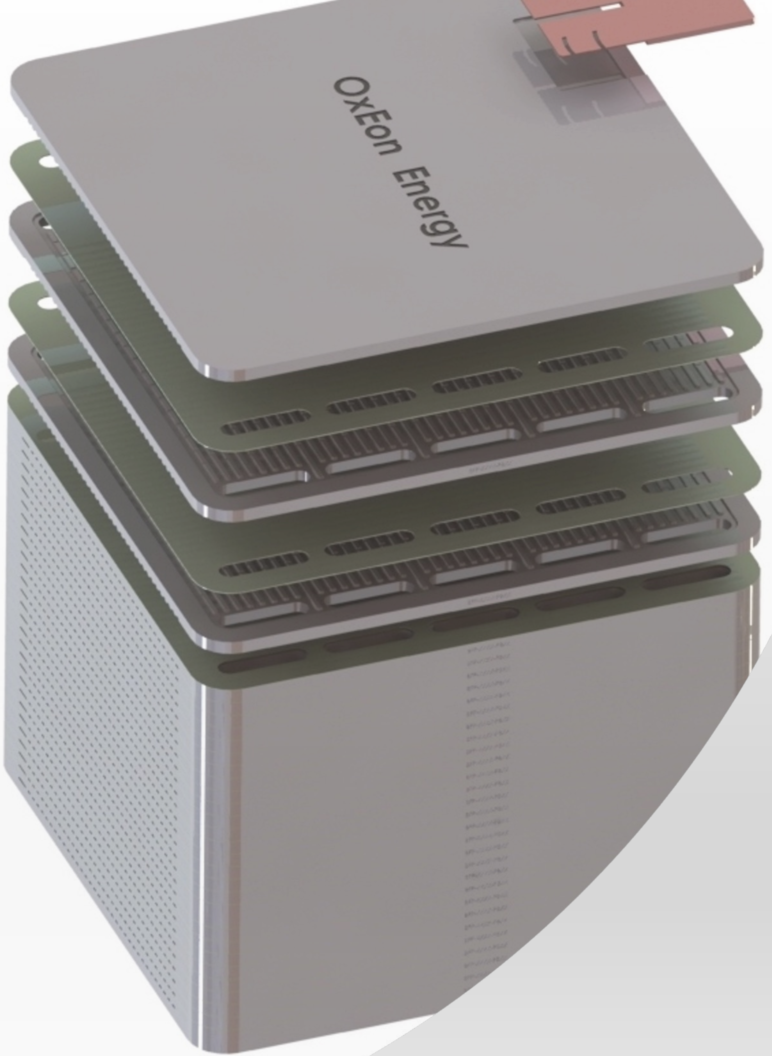


Beyond Current Potential

Rocket Propellant Production on Mars

Solid Oxide Electrolysis Coupled Synfuel Development for Aerospace Applications

Space Resources Roundtable

June 2022

N. Davis, J. Elwell, J. Hartvigsen, S. Elangovan

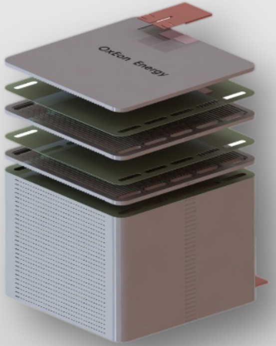
OxEon Energy, LLC
Utah, USA

OxEon Energy, LLC

OxEon energy
Beyond Current Potential

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

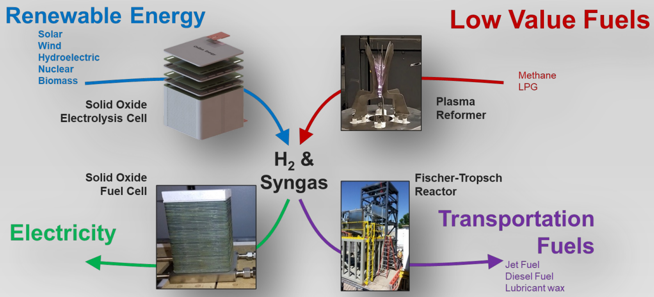


Solid Oxide Fuel Cell and Electrolysis Stacks

- 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



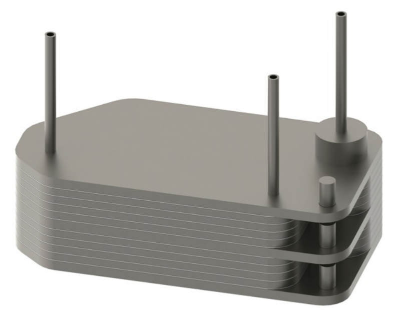
Solid Oxide Fueled Space Exploration

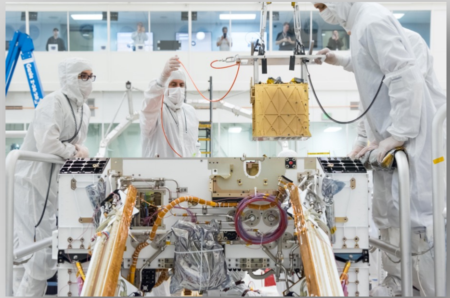
NASA funded flight program

- Only flight qualified SOEC in history
- Only TRL9 SOEC device in history
- First production of oxygen from the Mars Atmosphere

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





Active OxEon Projects with NASA for Next Generation

- **Mars:** Oxygen and Methane Production from co-electrolysis
- **Lunar:** Liquid Propellants for LH_2/LO_x-Fueled Cislunar Transport
- **SBIR**: Cathode Development for Redox Tolerance

MOXIE: Flight Qualification

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Baseline Performance

- 21 consecutive stacks built with *aerospace quality standards and traceability* having a maximum baseline performance of 1.6 ohm-cm^2 dry CO_2 and 99.9%+ O_2 purity

Cycling Performance

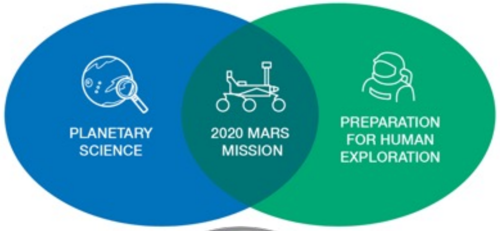
- 3 stacks with 21 cycles of identical test procedure having varying cycle-to-cycle flow rates and final cycle averages of 10.1 g O_2/hr production and 99.8% purity – Targets exceeded
- 1 stack to cycle 61 with >99.6% purity at a controlled production rate of 6 g/hr at 55g/hr feed

Structural Stability Testing

- **No leak or significant performance change after 10kN crush testing**
- Stacks tested to 25kN force with no crossover or external leakage
- *Load to failure required 62.2kN (>30 margin of safety from design)*

Shock/Vibe Testing

- Stacks vibrated at JPL and post vibe tested at OxEon
- **No leak or significant performance change post vibe!**
- **No leak after shock testing, no significant performance change!**



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Cryo-Cycling

- Vibe stack cryo-cycled to -40°C (40 cycles), -55°C (3 cycles), -65°C
- **Stack performance and purity unchanged in operational cycling post test**

MOXIE on Mars

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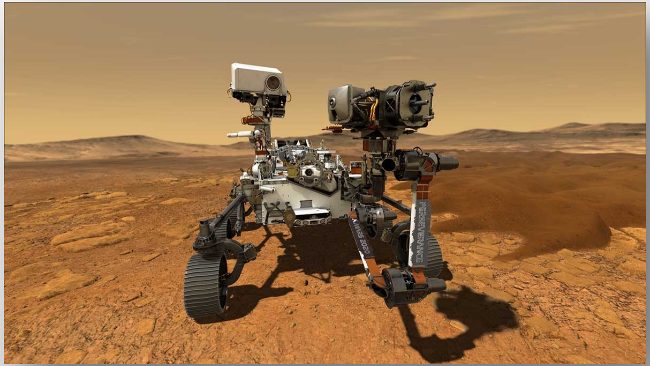
Beyond Current Potential

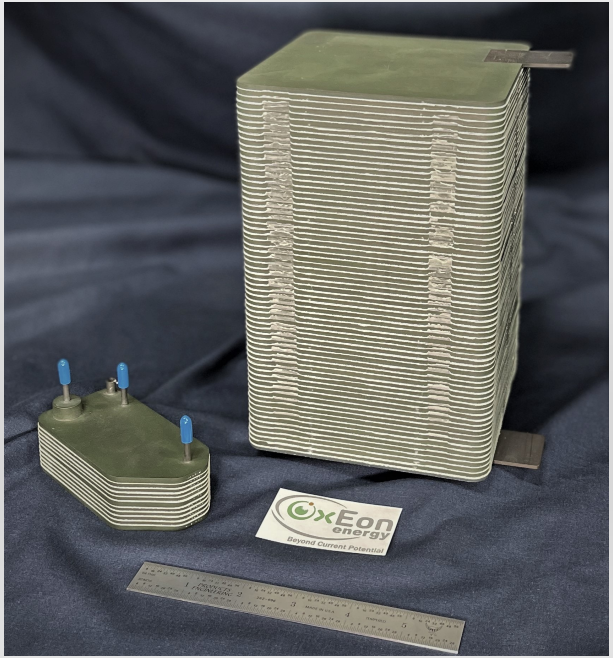
- First 100 Sols
  - Sol 5 "Aliveness Test" Mon Feb 22
  - Sol 13 First run with Run Control Table (RCT)
  - Sol 14 "Health Check" of heaters and compressor
  - Sol 59-60 April 20, First Oxygen
    - Produced 5.4 g O_2 pre-dawn, peak rate of 6 g/h (2 A current)
  - Sol 81 May 12, 2nd Oxygen
    - Nighttime (early AM) operation
    - Produced 7 g O_2, 8 g/h peak
  - Sol 100 May 31 3rd Oxygen
    - Mid-day operation with lower atmospheric density
      - Extended 8 g/h operation
- Accumulated 9 Oxygen producing cycles
  - Day and night oxygen producing runs spanning the climactic extremes of the Mars year
- See Mike Hecht's talk for further details



Images courtesy of NASA

SOXE Scale-up Design Basis

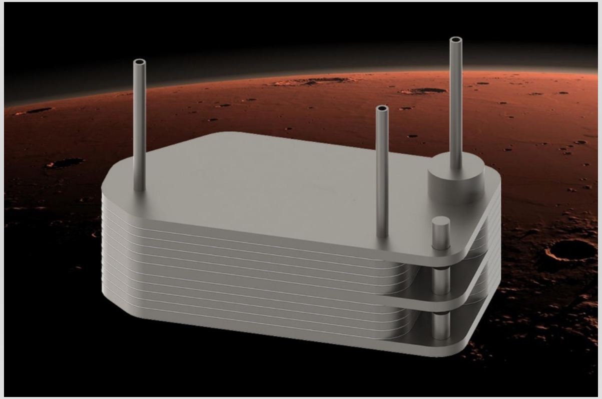
- Stack Design Basis for NextSTEP-2 ISRU Project
  - Manned Mars mission target rate of >2 kg/h O_2 from dry CO_2
    - **8-stack** module projected output: **2.48 kg/h O_2 from dry CO_2**
    - Also targeting 167 g/h CH_4
  - Crew life support atmosphere revitalization
    - Recovery of oxygen from metabolic respiration products
    - Single stack oxygen recovery for up to ~19 person crew
- Materials set same as selected for MOXIE
  - Hermetic seals, thermal cycle stable
  - Interconnect design of 110 cm^2 active area
    - Configuration that closely parallels a flight like design
    - 5x MOXIE cell area
  - 52 cell stack projected to meet target capacity
    - 20A with **dry CO_2** producing **310 g/h O_2**
    - 44A with 3 **H_2O+CO_2** producing **683 g/h O_2**



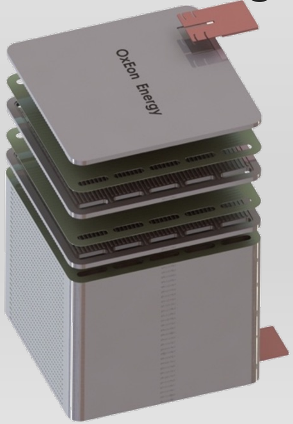
Program Technology Advancements

- Scale-up of MOXIE to mission scale ISRU design
  - Cell area increased by a factor of 5
    - MOXIE cell active area = 22.7cm^2, newest ISRU design active area = 110cm^2
  - Initial fabrication and testing currently occurring with 10-cell stacks
  - Mission scale 65-cell stacks each 33x MOXIE capacity (~2.5kW$_e$)
    - Multi-feed capable: O_2 from dry CO_2 or CO_2-H2O mix, also yielding CO-H_2 (to CH_4)

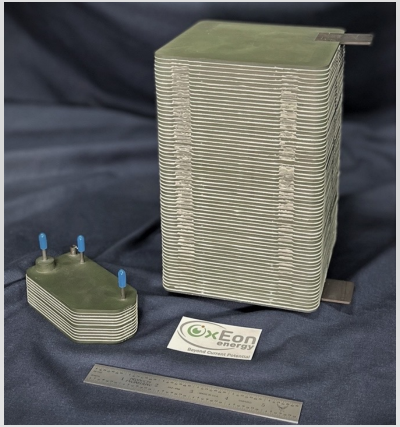
MOXIE stack design



OxEon mission-scale ISRU stack design



MOXIE with OxEon mission-scale stack



Oxygen on Mars: Now What?

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NextSTEP Program: NASA Funded Contract for SOEC Stack Scale Up and coupling for Oxygen and Methane production

Objectives & Approach

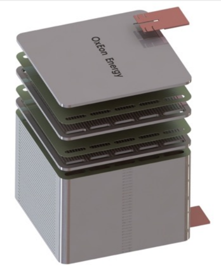
Objectives:

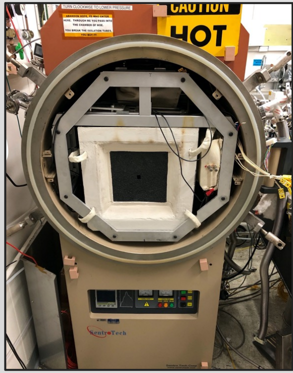
- Produce a large format solid oxide electrolysis stack (SOXE) that produces high purity oxygen, H_2, & CO
- Produce a methanation reactor
- Use the H_2, CO from CO_2/Steam electrolysis to produce CH_4 rates required in Mars mission plans

Approach:

- Phase 1: Individual component fabrication and testing; integration design; test components in relevant environment. Complete
- Phase 2: Finalize integrated design; build an integrated system; test system in relevant environment. Underway

Mars resource
CO_2 & H_2O
↓
SOXE
↓
O_2 | CO & H_2
↓
Methanation
↓
Propellant O_2 | CH_4
Byproduct H_2O





JPL Mars Chamber

SOXE & Methanation Product GC

Table 1 SOXE Co-Electrolysis dry basis product compositions measured by GC.

JPL Sample #	Sample ID	Day	H_2	CO	CO_2	CH_4
C1	16-Sep	Thurs	49.1	18.4	32.5	<0.1
C2	9/16 8:50 pm	Thurs	41.0	21.6	37.3	<0.1
C3	9/16 8:55 pm	Thurs	51.6	17.8	30.6	<0.1
C1'	9/17 5:50 pm	Fri	51.0	17.6	31.4	<0.1
C2'	9/17 5:55 pm	Fri	48.1	17.2	34.8	<0.1
C1"	9/18 5:45 pm	Sat	48.0	19.3	32.7	<0.1
C2"	9/18 5:45 pm	Sat	51.4	18.2	30.4	<0.1

Table 2 Methanation Reactor dry basis product compositions measured by GC.

JPL Sample #	Sample ID	Day	H_2	CO	CO_2	CH_4
M1	16-Sep	Thurs	<1.0	<0.1	64.95	35.05
M2	9/16 9:20 pm	Thurs	<1.0	<0.1	64.99	35.01
M3	9/16 9:25 pm	Thurs	<1.0	<0.1	66.08	33.92
M1'	9/17 6:35pm	Fri	<1.0	<0.1	64.57	35.43
M2'	9/17 6:40 pm	Fri	<1.0	<0.1	64.98	35.02
M1"	9/18 6:30 pm	Sat	<1.0	<0.1	64.88	35.12
M2"	9/18 6:30 pm	Sat	<1.0	<0.1	64.71	35.29
M0"	9/18 7:00 pm	Sat	<1.0	<0.1	64.73	35.27

- Integrated Breadboard
  - 10-cell non-ISRU SOXE
  - Open anode channels
  - Methanation system
  - In JPL Mars chamber
- Flow rate basis
  - 40% utilization
  - 20A
- Achieved 20A
- For margin 18-19 A
- 65-Cell ISRU system This month at OxEon, August at JPL

Phase 2 – Scale-up Underway

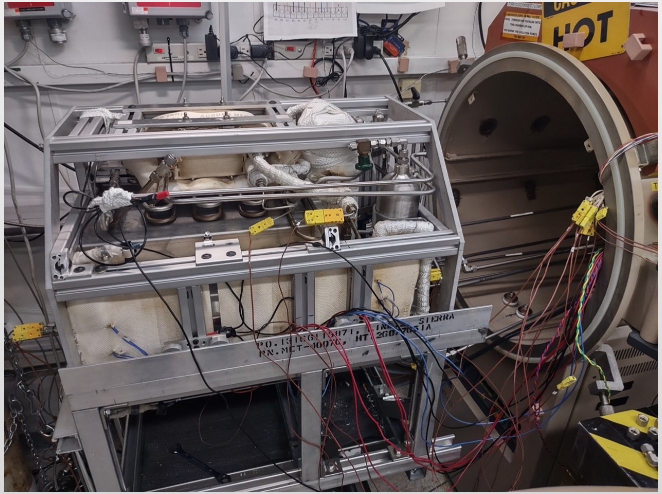


Photo: Installation of the Phase I system into the Mars test chamber at NASA's Jet Propulsion Laboratory

- Completed 65-cell sealed ISRU-design stack build
- Individual extended test of mission scale SOEC and methanation reactor
- 1000 hour coupled system test targeting 167 g/hr Methane production from a SOEC fed methanation reactor
- 100 hour coupled system test at Mars Ambient – Tested in JPL's Mars Test Chamber

ISRU Lunar Application

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Beyond Current Potential

Tipping Point Program: NASA Funded Contract for Cryogenic Propellant Production and Management (CPM)

Objectives & Approach

Objectives:

1. Develop lunar ice processing system for H_2 & O_2 production
   - The Moon's south pole is a permanently shadowed region (PSR) that contains water ice
2. Test integrated breadboard system in cryo-vac chamber
3. Develop and exercise system optimization model
4. Develop techno-economic model for system

Approach:

- Individual component fabrication and testing; component integration design; test components in relevant environment
- Integrate SOEC system with BOP; test system in relevant environment

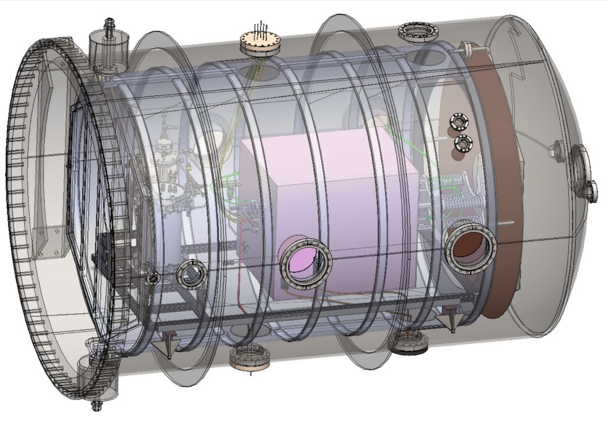
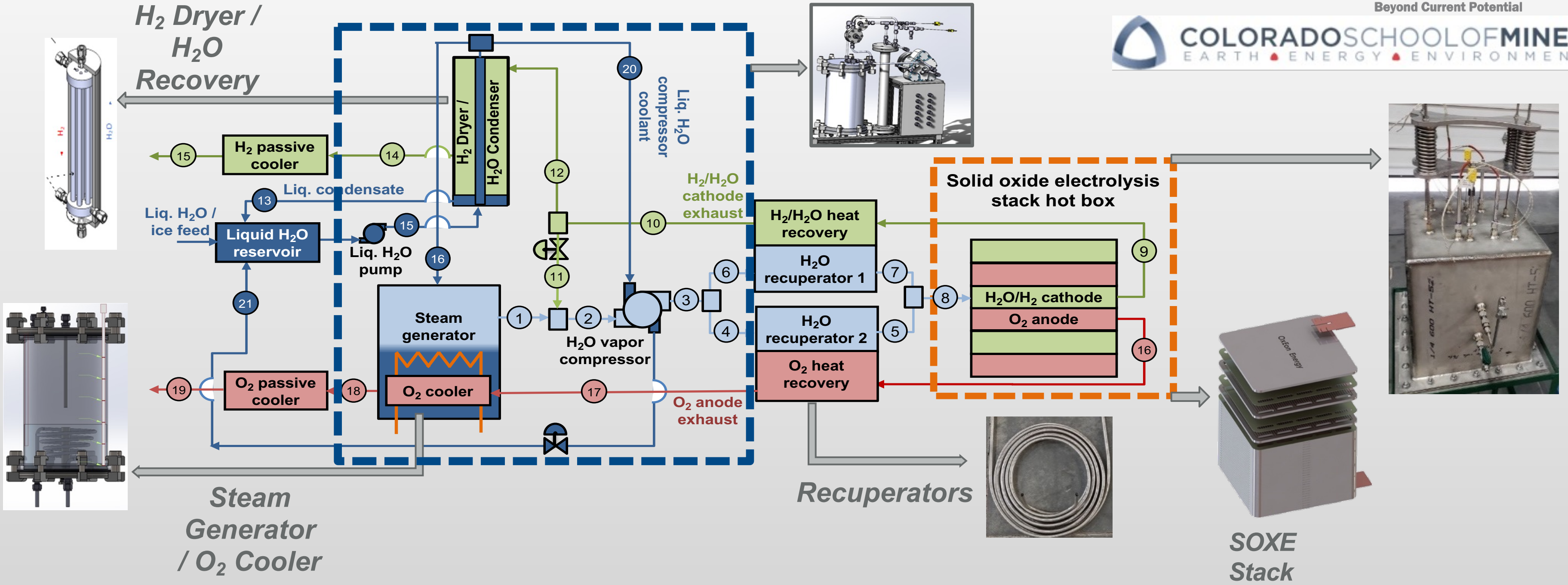


Diagram of system installed in test chamber

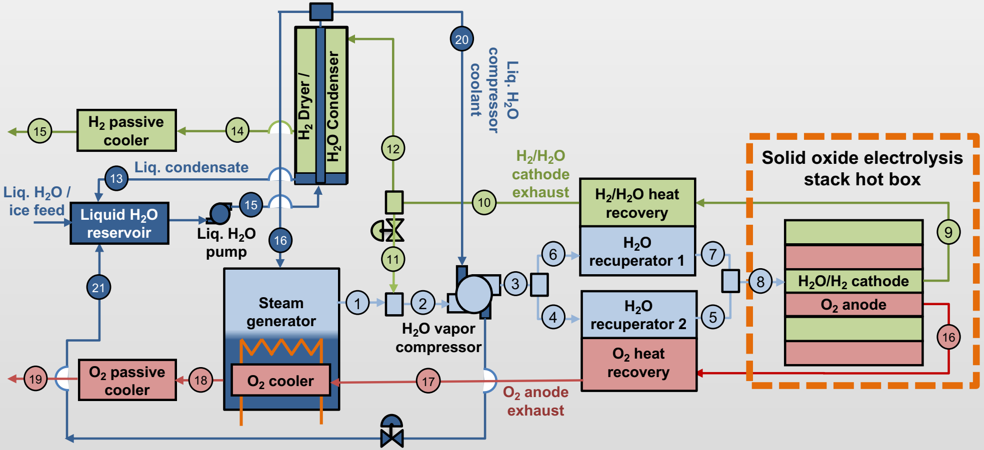
Optimizing SOXE System with BOP



- Colorado School of Mines led a modeling effort to optimize stack mechanical components, cells, and thermal integration, for operation at elevated temperatures in cryo-vac conditions typical of PSRs;
- Model used to design the integrated lab-scale demo stack and BOP

Lunar System Optimization

- Constrained optimization using MATLAB ‘fmincon’ for SOXE system configuration used to minimize ‘objective’ functions:
  - **specific work w_{sp}** – system kWh_e per kg H_2
  - **specific mass m_{sp}** – system dry kg (includes passive coolers) per kg H_2 produced per yr
  - **specific cost C_{sp} = \$70000m_{sp} + \$0.36w_{sp}**



- System architecture takes in cold, liquid H_2O and includes the following BOP:
  - ➢ controlled vaporization of liquid H_2O with electric heating,
  - ➢ compression of steam to stack,
  - ➢ anode and cathode exhaust heat recuperation,
  - ➢ passive H_2 drying with H_2O condensate recovery,
  - ➢ passive radiative coolers of O_2 and H_2 outlet flows.

Program Technology Advancements

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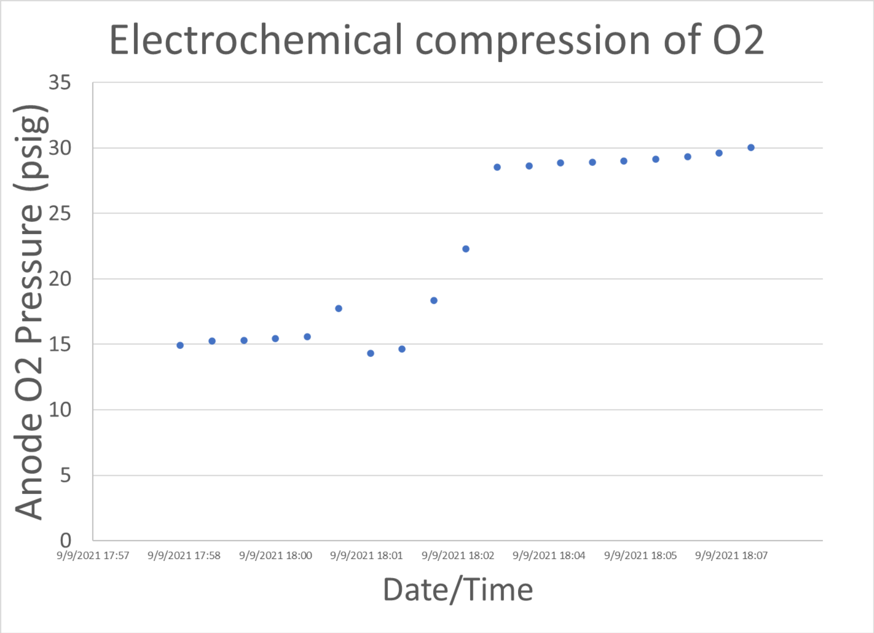
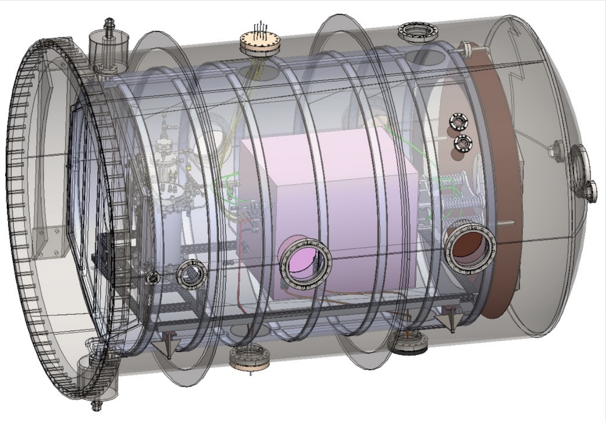
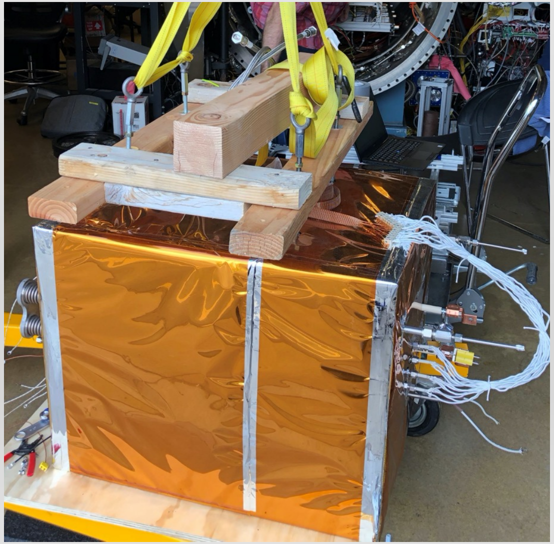
- Electrochemical compression of O_2 demonstrated with a 10-cell short stack
  - Testing demonstrates program key performance parameter: threshold value 1 bar, project goal 2 bar



OxEon SOXE Subsystem

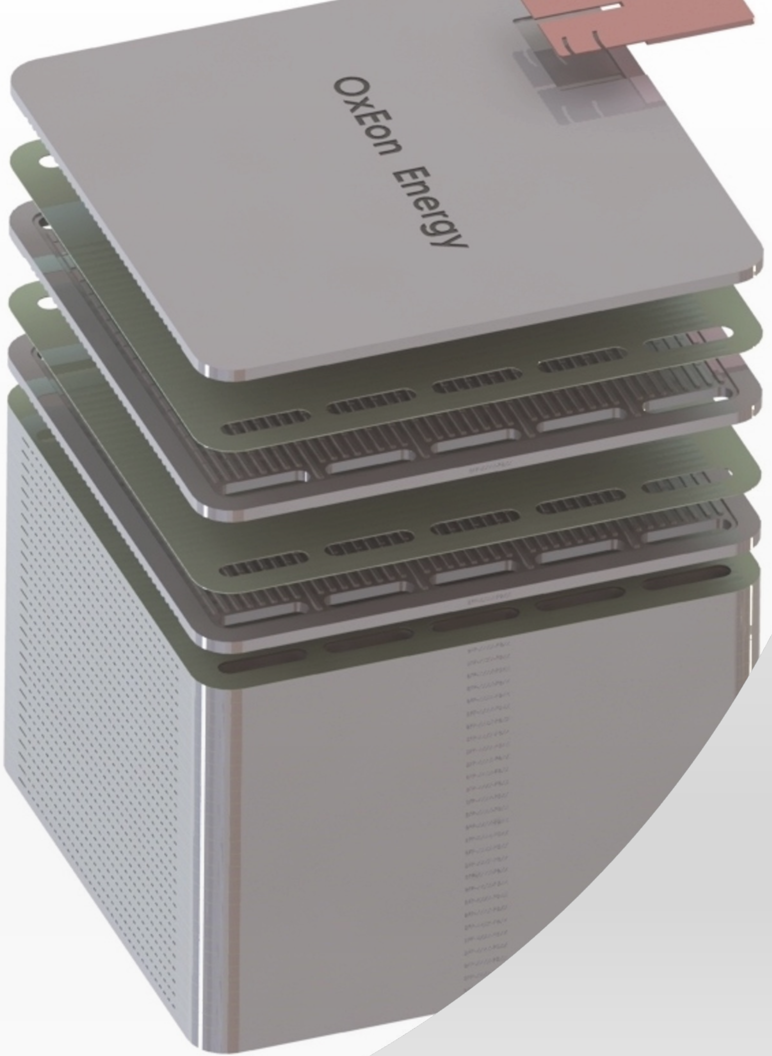
- OxEon subsystem scope includes a hotbox housing for the SOXE stack with thermally integrated heat recuperation of product streams for feed preheat
    - Hotbox designed to be a pressure barrier since program started when heritage open anode channel interconnects were still in use
    - New ISRU design is being used in stack, so pressure liner is redundant
    - Future systems will not require hotbox system to hold pressure, will result in mass decrease





Capabilities Enabled by Solid Oxide ISRU

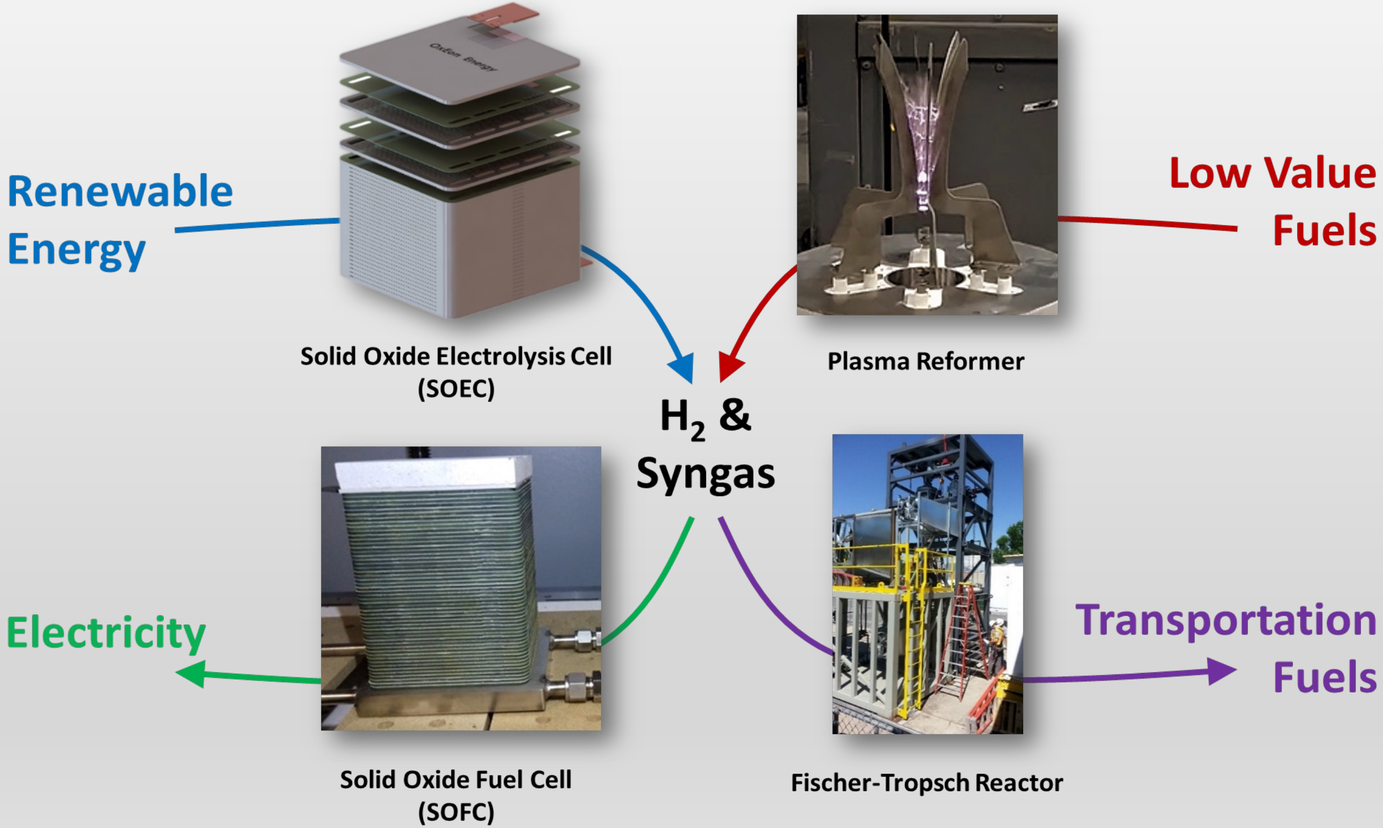
- Atmospheric ISRU
  - Flight qualified solid oxide CO_2 electrolysis stack (SOXE) for Mars 2020 mission
  - Scale-up plans for full scale Mars ISRU
    - 27 tons at 2.1kg/hr O_2 for ascent vehicle propellant in ~18 months from landing to next launch window
- Power generation from stored O_2 and CO or H_2 & CO
  - Mobile power
  - Backup power
- Life Support - Atmosphere Revitalization
  - Recovery of oxygen from both water vapor and CO_2
  - Potential to recover more oxygen from respiration products than consumed in respiration
    - Oxygen recovery from metabolized carbohydrate respiration products
  - Possibility of production of useful products from associated C & H
    - Methane propellant, paraffin wax (thermal & radiation shield), liquid hydrocarbon



Beyond Current Potential

Extending MOXIE Learning to Terrestrial Applications

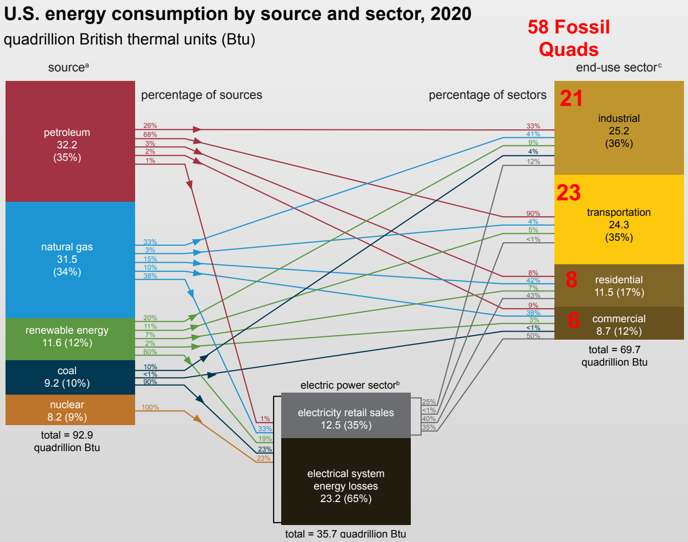
Energy Cross-Sector Coupling



OxEon Technology Space

De-Fossilization By End-Use Sector

- Fossil Quads By End-Use Sector
  - 21 Industrial
  - 23 Transportation
  - 8 Residential
  - 6 Commercial
- Electric contribution
  - 21 Electric in
  - 6 Electric out



1 Dollar 1 Kilogram 1 Decade

- Electrofuels & Chemicals
  - (Too) Energy Intensive?
  - Displacing 52 Fossil Quads is intense!
  - 1,740 GW electrolysis at η=100%
  - 3.8x 458 GW annual average grid load
- Requires Lots of Hydrogen
  - 1,740 GW produces 51k metric tons/h
- Energy Density Comparisons
  - 2.8 MJ/L Lithium-ion battery
  - 5.3 MJ/L GH_2 at 69 MPa
  - 10 MJ/L LH_2 at 20 K
  - 9 MJ/L C(S)NG at 25 MPa
  - 11.5 MJ/L anhydrous NH_3 at 0.8MPa
  - 15.6 MJ/L methanol liquid
  - 39 MJ/L synthetic bio-diesel liquid
    - Value dense
    - Storable
    - Transportable
  - Fossil fuel replacements
    - Drop-in fit for purpose

OxEon energy
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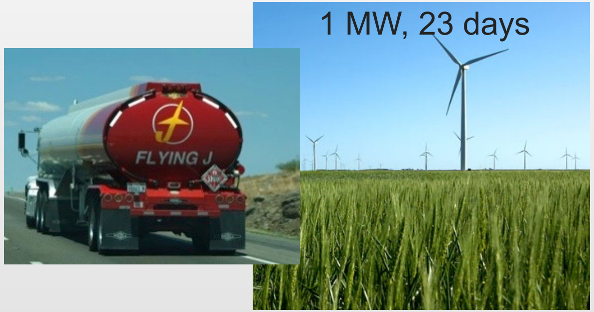
Synthetic Fuels As a Store of Renewable Energy

Beyond Current Potential

- Hydrogen storage in synthetic fuels
- Comparative Energy Density
  - JP-8 33-36 MJ/liter (43 MJ/kg, 0.76 to 0.84 kg/liter)
  - Diesel 36 MJ/liter (46 MJ/kg, 0.86 kg/liter)
  - Hydrogen 4.4 MJ/liter (work of compression is 10-12% of LHV)
    - at 690 bar (10,000 psi) Z=1.43

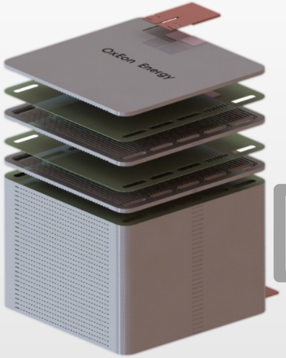


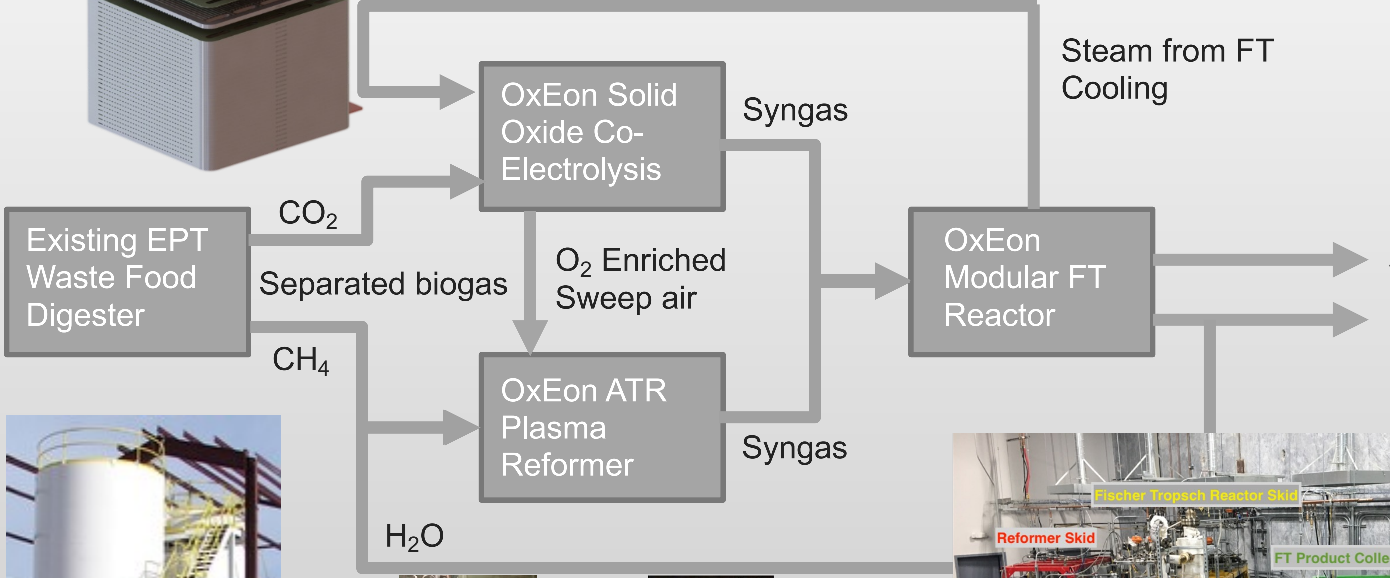
23 MW-days on one 40m^3 tank truck

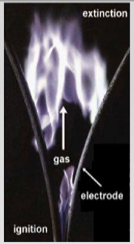
- Storable, pumpable, for on-demand energy
- Established markets for liquid fuels
  - Highly developed infrastructure
  - Vehicle fleet will take decades to retire
  - US demand, 7.3 billion bbl/yr, > $400 billion/yr

2 min “Recharge”
at 0.5 kg/s & 46 MJ/kg
= 23 MW recharge rate

Bio-CO_2 to E-Fuels







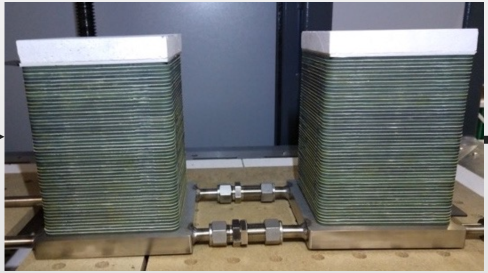
OxEon Power To Fuels Facility

Beyond Current Potential

100% Efficiency in SOEC Stack

Steam + CO_2

Renewable & Nuclear Electric Power



Solid Oxide Electrolysis Stacks

Syngas

$CO+2H_2$

Compression & Storage

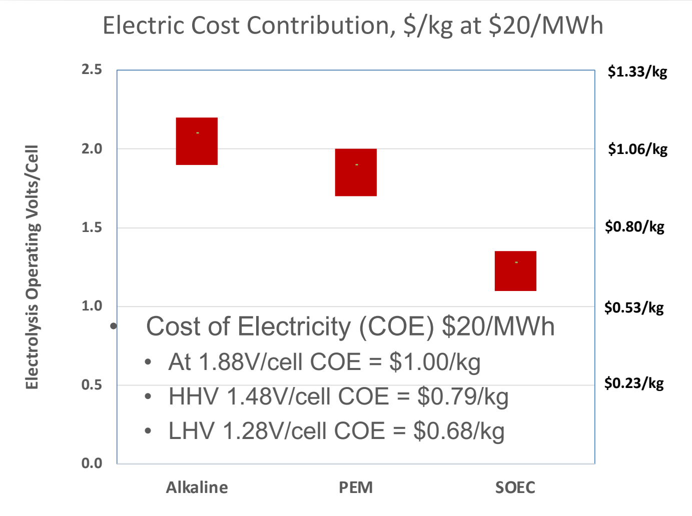
Exothermic ~80% Efficiency

Fischer Tropsch Synthesis Pre-Pilot Plant

FT Liquid & Wax Products

- Cetane 60.2 by ASTM D613
- FT 46.5 MJ/kg vs. diesel 46 MJ/kg & B100 FAME 40 MJ/kg

Why Solid Oxide Electrolysis



- Solid Oxide nominal operating point 1.28V
  - LHV Thermal Neutral Voltage (100% stack efficiency)
- Synthesis process integration to raise steam
  - Low temperature heat (~200°C) saves 0.2V or $0.10/kg
  - 50% more hydrogen per MWh at 1.28V vs 1.91V

- Electrochemistry Deployment Options?
  - Onboard, on demand
    - Fuel cells & batteries
    - Low capital utilization factor
    - New distribution & fueling infrastructure

  Or

  - Stationary, storable & dispatchable
    - Electrolysis: H_2 and CO_2 to synfuels
    - High capital utilization factor
    - Use of existing infrastructure & fleet
    - Industrial, Residential & Commercial
      - SNG, Hythane, Hydrogen

Solid Oxide Electrolysis Cell (SOEC)

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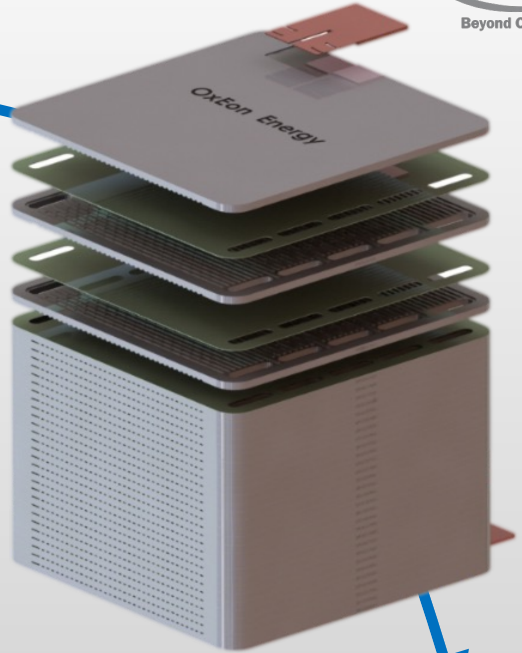
Renewable Energy



SOEC's generate pure H_2 (or H_2 + CO) & O_2

$$H_2O\ (steam) + electric\ power \rightarrow 2\ H_2 + O_2$$

$$H_2O\ (steam) + CO_2 + electric \rightarrow (H_2 + CO) + O_2$$

The products can be used as-is or converted to synthetic fuels.

One-step production and compression add further flexibility in end use.

H_2

Syngas (CO + H_2)

Advantages

- **1/3 less energy consumption** than water electrolysis
- All **solid-state device** eliminates liquid electrolyte management required in other technologies
- Extreme **cold tolerance**
- Products don't require additional purification

Fischer-Tropsch Process

Syngas ($CO + H_2$)

The Fischer-Tropsch process produces liquid hydrocarbon fuels from syngas

$$(2n+1)\ H_2 + n\ CO \rightarrow C_n H_{(2n+2)} + n\ H_2O$$

$$H_2 + CO \rightarrow \text{liquid hydrocarbon fuels}$$

Catalysts (Fe, Co) and process conditions facilitate the reaction and determine the hydrocarbon product.

Advantages

- Biogas conversion produces **non-fossil transportation fuels**
- **Modular design** reduces capital costs to start up and expand system
- FT is an established technology that produces syncrude, which can be converted to standard fuels with minimal upgrading.

Transportation Fuels

Jet Fuel
Diesel Fuel
Lubricant wax

Thank You

Additional Info:
Nathan@OxEonEnergy.com

Contributing Partners

The Human Exploration and Operations Mission Directorate contributes funding for SOXE ISRU through its Advanced Exploration Mission Systems Division. Design validation was supported by stress and flow simulations performed at NASA Glenn Research Center. Relevant environment testing is being conducted at the Jet Propulsion Laboratory. Technical and programmatic guidance by the COR is provided through NASA Johnson Space Center.