CHANGING WHAT'S POSSIBLE

# Reversible Fuel Cells for Long Duration Storage

## Thomas Zawodzinski, University of TN-Knoxville

### Team Members: Peroxygen Systems Inc

## Project Vision

**Not your grandfather's Fuel Cell!**

Peroxide as a Product enables high efficiency, low cost

Virtually no self-discharge over long periods!

# ~~Reversible Fuel Cells~~

# Peroxide Enabled Long Duration Electrochemical Energy Storage (PELoDEES)

**Thomas Zawodzinski, University of Tennessee-Knoxville**

**Team Members: Peroxygen Systems Inc, Electrosynthesis Inc**

## Project Vision

**Not your grandfather's ~~Fuel Cell~~ EES System!**

Peroxide as a Product enables high efficiency, low cost

Virtually no self-discharge over long periods!

| | |
|---|---|
| Total project cost: | $1.5M |
| Length | 24 mo. |

# ARPA-e Project Overview

## Technology Summary

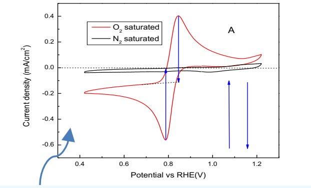
- Advanced reversible two-electron catalyst, implemented as a high surface electrode.
- Tailored OH$^-$ conducting membranes.
- Flow fields for mixed phase air electrodes.
- Demonstrated as peroxide generation cells and as Zn-peroxide batteries.

## Technology Impact

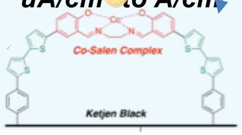
- Dramatic lowering of cost of peroxide, allowing on-site generation.
- High efficiency batteries with reversible air electrode.

## Proposed Targets

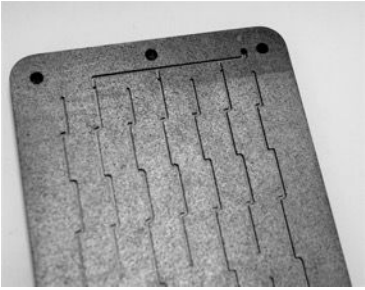
| Metric | State of Art | Proposed |
|---|---|---|
| Air electrode cycling, loss at 100 mA/cm$^2$ | >300 mA/cm$^2$ | <100 mA/cm$^2$ |
| Peroxide production | <100mA/cm$^2$ @1.2 V | 400mA/cm$^2$ @1.2 V |
| Battery single cell cycling efficiency | <50% RT | 80% RT |



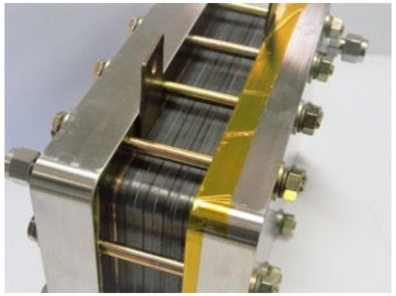
***Reversible ORR to be translated to high surface area electrodes uA/cm to A/cm$^2$***



***Highly conductive OH$^-$ conducting membranes tailored to use***



**Advanced flow field**



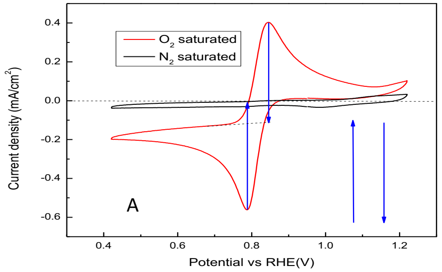
**Final Goal: Stack**

*Demonstrated High Efficiency Air Electrode for Multiple Applications*

# Innovative, reversible air electrode chemistry

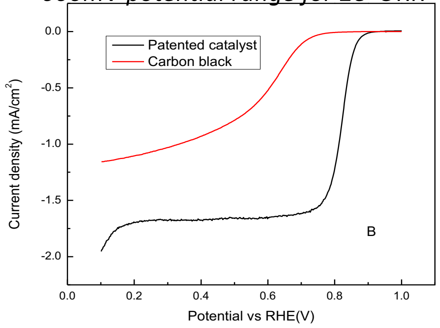
$$O_2 + H_2O + 2e^- \rightleftarrows HO_2^- + OH^-$$

*2e$^-$ Chemically and electrochemically reversible*



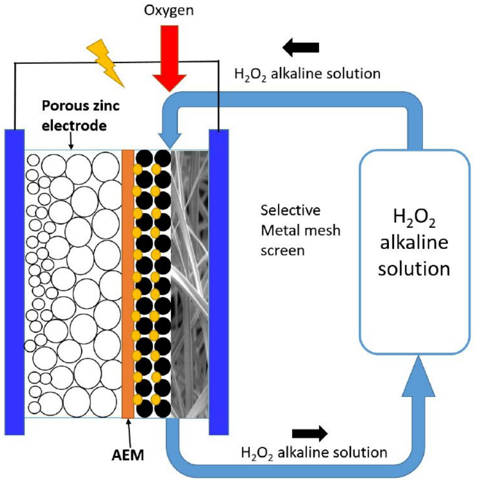
*Theoretically best possible 2e$^-$ ORR catalyst*

*600mV potential range for 2e$^-$ ORR*

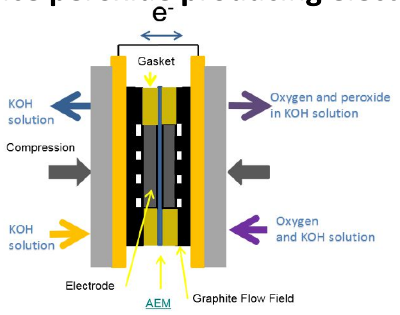


Provides the Basis
for Enhanced Performance
in Applications

Air electrodes for High Energy Density Batteries

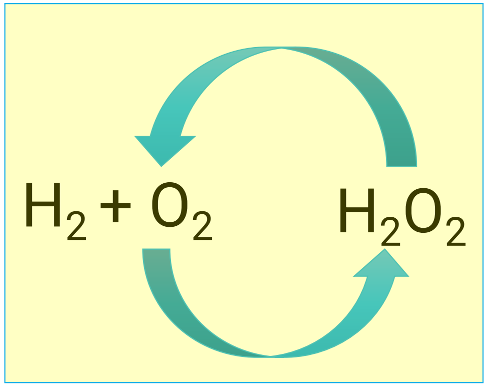


**High performance peroxide producing electrolyzer**

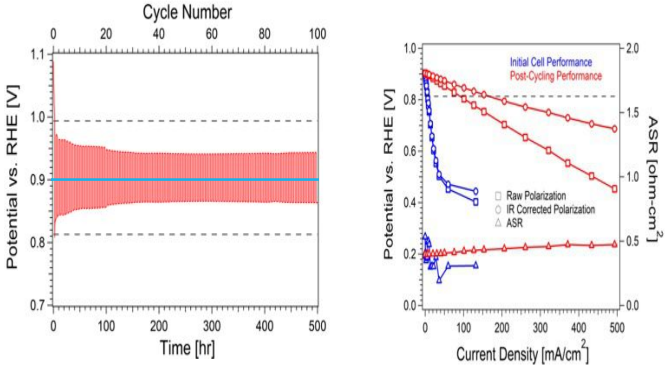


**Air electrode is a general and widely applicable component**

# PELoDEES: A Path to Efficient Cycling to Leverage $H_2$ Storage Innovations in Catalysts-Cell-Stack-System



**Reversible Fuel Cell (with a twist)**



Electrode performance

Hydrogen and Oxygen in charged state—cheap, easily available, near zero self-discharge!

BUT

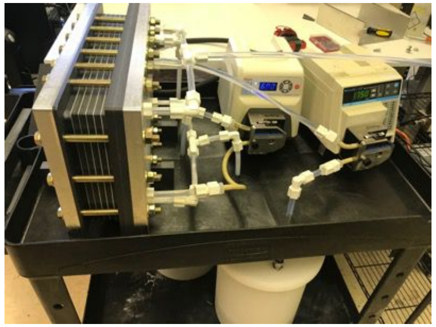
Conventional fuel cells are inefficient with expensive catalysts.

**ENTER PELoDEES**

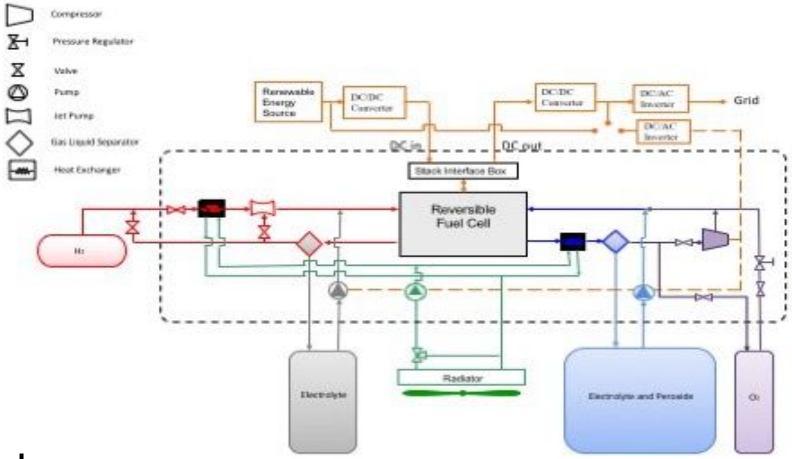
***We discovered cheap catalysts to produce peroxide with electrochemical reversibility***

***High efficiency***

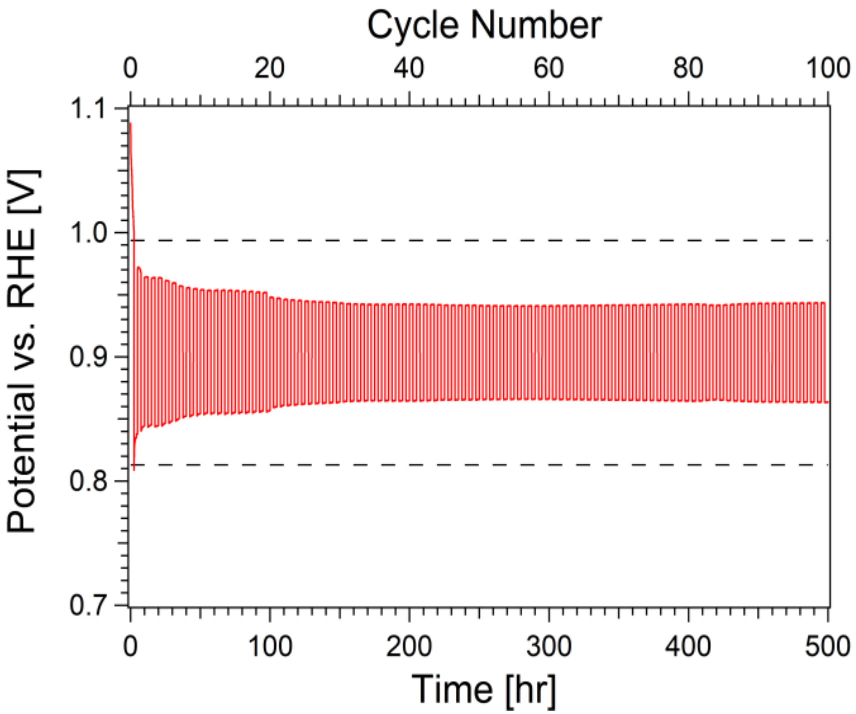
***Possible long-term storage with extremely low self-discharge: in charged state we store $H_2$ and $O_2$***

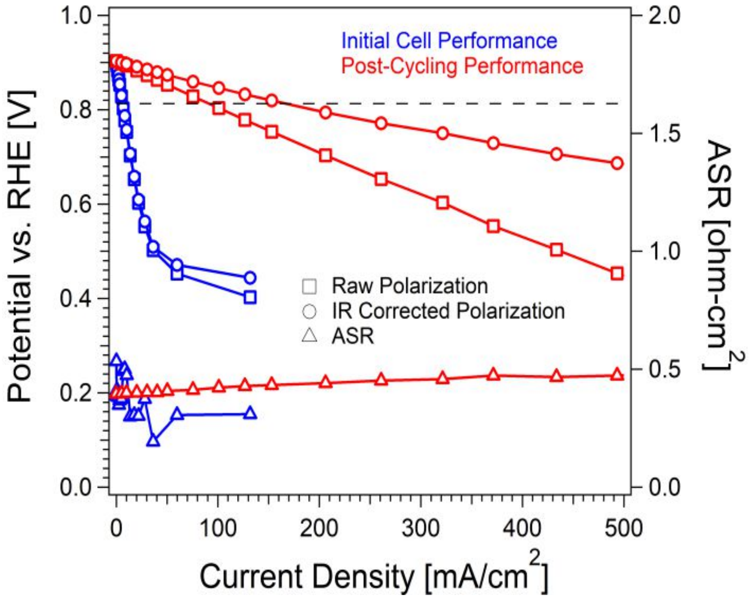


Stack at PSI
Now Phase2 Chemicals



# Symmetric Cell Cycling





Room Temp     Kodak CLAM

40mA/cm2 3hr Charge/ 3hr Discharge cycles

1mgSF15-70 Catalyst (or equiv) /cm2 with 28% and 16% AS4 in the electrode

100ml/min Air (0.57A/cm2) with 10ml/min 2.5M NaOH w/ 1M $H_2O_2$ (6.5A/cm2)

100µL/hr 30% H2O2 added (0.01A)

# The Team

- **Tom Zawodzinski, PI:** 30 years experience as a leader in electrochemical S&T—fuel cells, batteries, flow batteries, etc.
- **UTK team**—senior scientists: Shane Foister (chemical synthesis), Gabriel Goenaga (testing), Ramez Elgammal (material development)
- **PSI**: small (but growing) company commercializing peroxide catalyst technology
- **New partner (projected): Electrosynthesis Co.--**~40 years experience testing and scaling electrochemical technology.
- **Unique consulting and 'ecosystem' infrastructure**: Former GM fuel cell stack and system design for manufacturing doing design and TEA; small polymer company makes batches of starting materials; coating at scale at Kodak

Emma (Woodhouse)
Zawodzinski

# Project Objectives

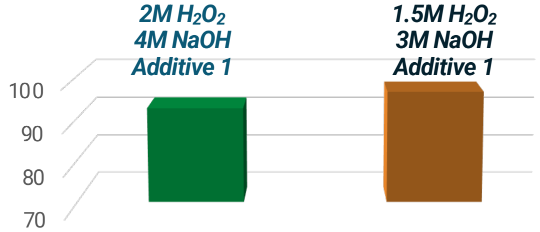
- Technical Risks
  - 1. Catalyst performance on hydrogen electrode.
  - 2. Managing two-phase flow in stacks.
  - 3. For ‘one-stack’ design, achieving proper balance of material properties under reverse polarity.
- Prototype Size: In this phase of the work, we aim for proof of concept on 100 $cm^2$ cells and possibly a short stack.
- Scaling: The larger cell design is essentially a modular array of the 100 $cm^2$ cells. We have previously developed stacks using this concept. System design is relatively straightforward.

# Results: Long term stability

## Peroxide stability

- Concern based on literature values of decay rate in alkaline solution
- More recent additive package shows stability of ~97% over 10 hours
- TEA shows minimal cost from ‘make-up’
- Stability in fully charged state is essentially unlimited (self-discharge minimal)
  - This enables long duration between cycles

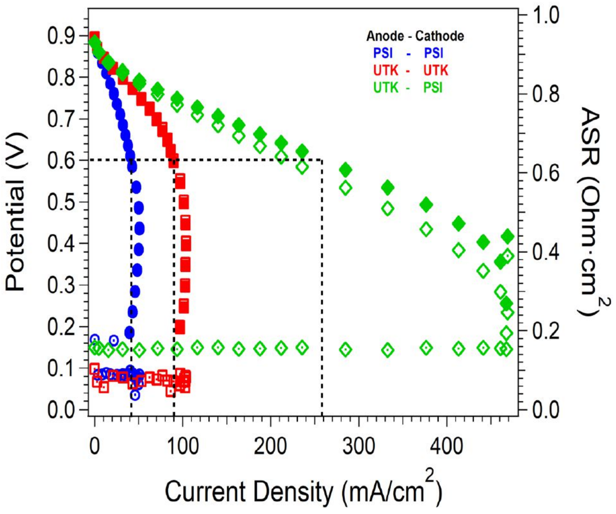
***Peroxide Stability, 30 °C, 10 hours***

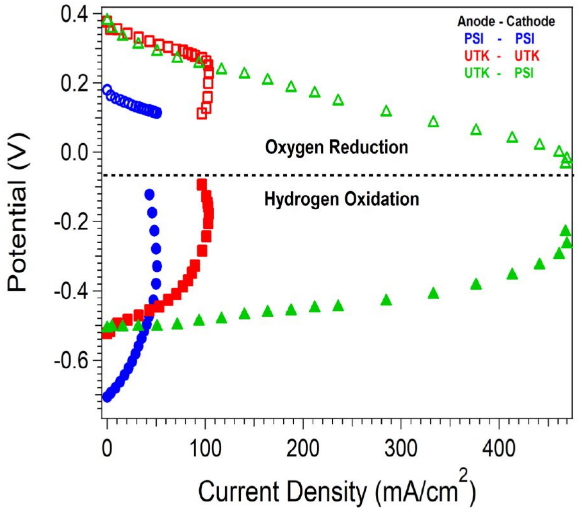


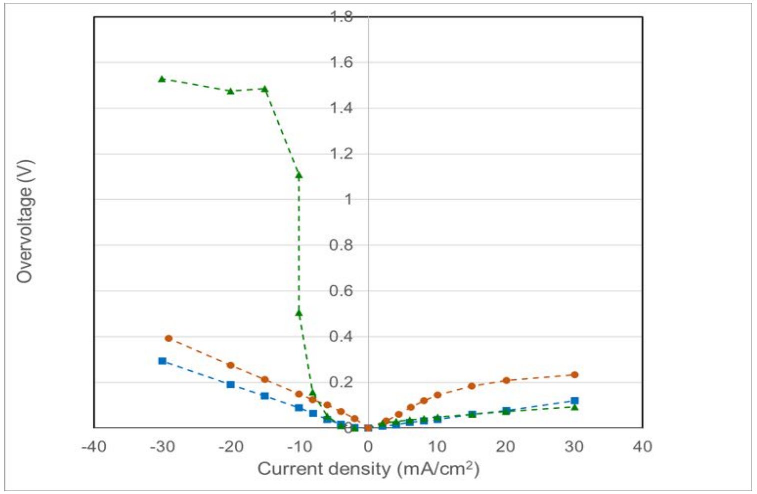
| | 2M $H_2O_2$, 4M NaOH, Additive 1 | 1.5M $H_2O_2$, 3M NaOH, Additive 1 |
|---|---|---|
| ***average*** | 92.9% | 96.8% |
| ***std. dev.*** | 0.3% | 0.4% |

# Results: Performance in 'single cell' systems

- Scaled-up to 100 cm$^2$ cells; results match those in 5 cm$^2$ cells
- Polarization curves (left) indicated that two different electrode constructs (labeled UTK and PSI) needed for positive and negative electrodes
- Hydrogen polarization curve indicate promising reversibility (hydrogen electrode shown) for single cell operation

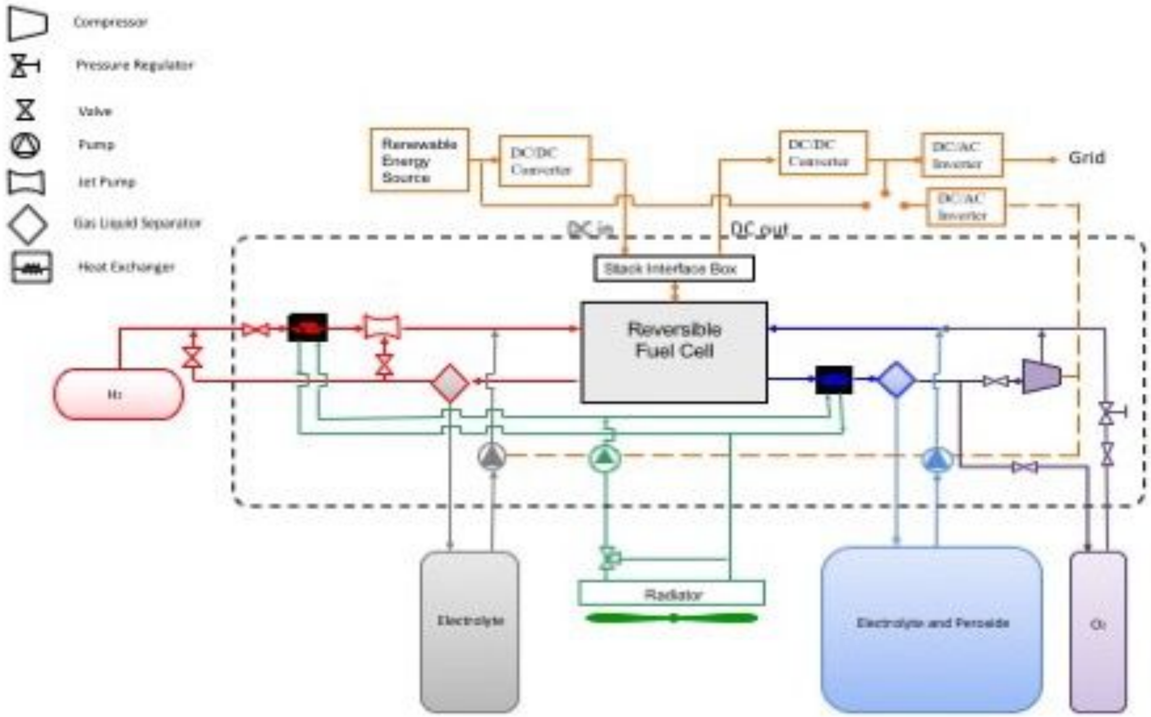






- Performance targets (cell current density) can be met or exceeded but some difficulty with catalyst reproducibility.
- Cycling is beginning at this time.

# Technoeconomic Analysis



High P Dual Stack + BOP

ow P Dual Stack + BOP

Low P Single Stack + BOP

# Concept Cell Designs

**Reactions**

*Discharge*

($H_2$ side): $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

($O_2$ side): $O_2 + 2H_2O + 2e^- \rightarrow H_2O_2 + 2OH^-$

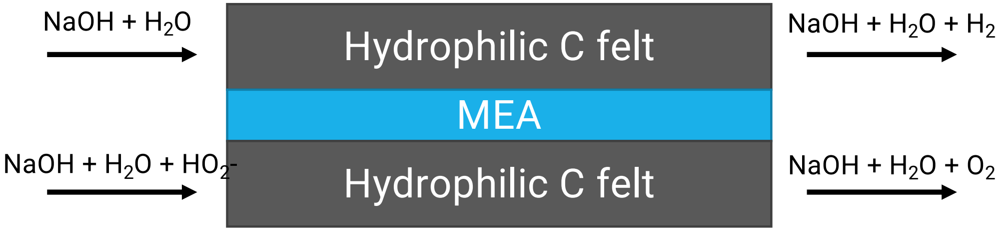
*Charge*

($H_2$ side): $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

($O_2$ side): $H_2O_2 + 2OH^- \rightarrow O_2 + 2H_2O + 2e^-$

## Separate Electrolyzer and Fuel Cell Stacks

### Charge



$NaOH + H_2O$ →

Hydrophilic C felt

MEA

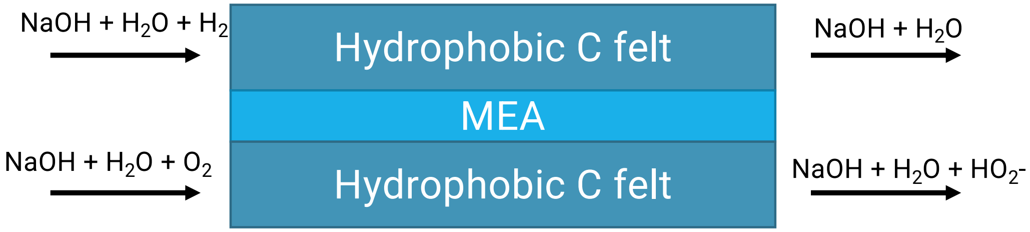
Hydrophilic C felt

$NaOH + H_2O + HO_2^-$ →

$NaOH + H_2O + H_2$ →

$NaOH + H_2O + O_2$ →

### Discharge



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Hydrophobic C felt

MEA

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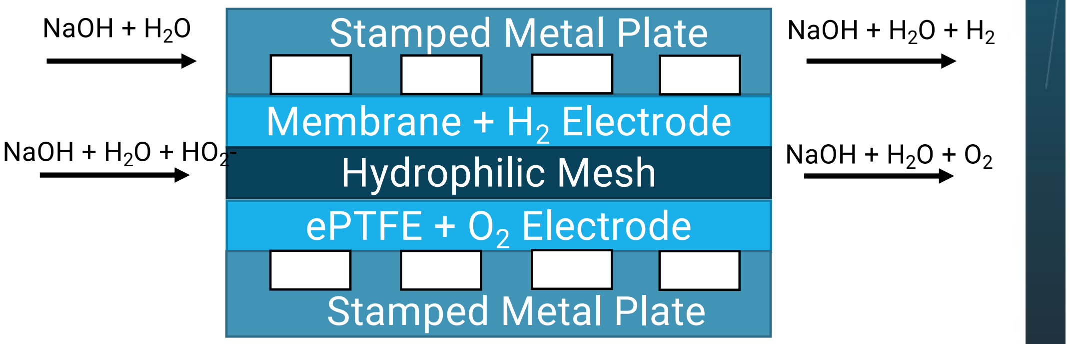
$NaOH + H_2O + O_2$ →

$NaOH + H_2O$ →

$NaOH + H_2O + HO_2^-$ →

## Single Stack with Oxygen Electrode Flow Architecture

### Charge



$NaOH + H_2O$ →

$NaOH + H_2O + HO_2^-$ →

Stamped Metal Plate

Membrane + $H_2$ Electrode

Hydrophilic Mesh

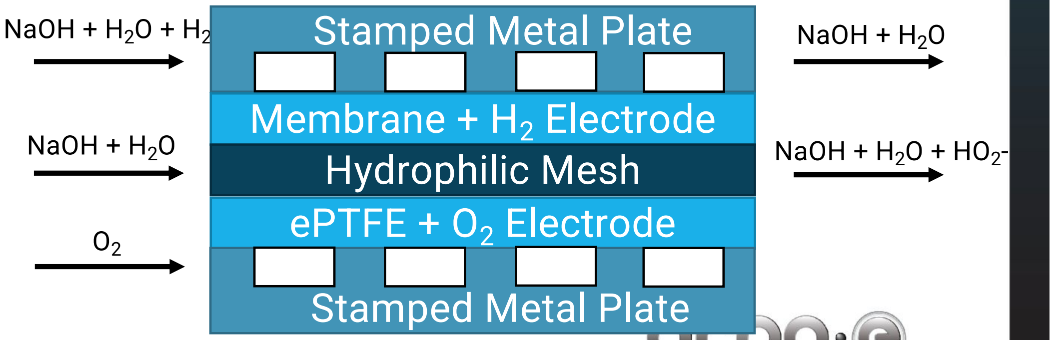
ePTFE + $O_2$ Electrode

Stamped Metal Plate

$NaOH + H_2O + H_2$ →

$NaOH + H_2O + O_2$ →

### Discharge



$NaOH + H_2O + H_2$ →

$NaOH + H_2O$ →

$O_2$ →

Stamped Metal Plate

Membrane + $H_2$ Electrode

Hydrophilic Mesh

ePTFE + $O_2$ Electrode

Stamped Metal Plate

$NaOH + H_2O$ →

$NaOH + H_2O + HO_2^-$ →

# Technoeconomic Analysis: Costs

For system components, the following cost inputs were used:

- compressor/pump efficiency = 60%
- compressor/pump costs = \$1000 + \$1000/kW compressor/pump power
- low-pressure tank (balloon) cost = \$4/m$^2$ tank material. Commodity prices for aluminum coated mylar range from 0.5 to 2 \$/m$^2$. The higher price allows for fabrication cost.
- solution tank cost = \$2/kg tank material with density of 8,000 kg/m$^3$ and thickness of 3 mm.
- O&M = 20% of Cp, capital cost for power-specific components.

*Additional Cost Input for Part 2*

- DC-DC boost = \$200/kW which was added to the power costs
- Miscellaneous = 10% of capital costs (both power and energy)
- Covers for storage balloons = \$20/m$^2$ footprint sized at 2x the gas storage balloons added to the energy costs
- Building Rent = \$60/m$^2$ footprint size at 100 m$^2$ plus 2 m$^2$ per stack which was added to the O&M costs
- Labor = \$100,000/yr which was added to the O&M costs

$$LCOS = \left[\left(\frac{1}{\eta_{RTE}} - 1\right) P_c \sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t} + \sum_{t=1}^{T} \frac{O\&M(t)}{(1+r)^t} + \left(\frac{C_E}{\eta_D} + \frac{C_P}{d}\right)\right] * \left[\sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t}\right]^{-1} \qquad [1]$$

# Technoeconomic Analysis

- Detailed and complete breakdown of stack parts, costs
- Performance based on our SOTA

| Total Stack size (m$^2$ active area) | 122 |
|---|---|
| H2/O2 tank (each) (m$^3$) | 554 |
| Solution tank (m$^3$) | 11.4 |
| | |
| discharge parasitic (% of stack power) | 0.6 |
| charge parasitic (% of stack power) | 0.02 |
| discharge efficiency (%) | 90 |
| round trip efficiency (%) | 81 |
| | |
| stack costs ($k) Internal Stack Cost | 60 |
| stack costs ($k) NREL Stack Cost | 34 |
| power costs ($k) (w/ NREL Stack Cost) | 37 |
| energy (tank) costs ($k) | 5 |
| | |
| LCOS ($/kWhr) Internal Stack Cost | 0.053 |
| LCOS ($/kWhr) NREL Stack Cost | 0.034 |

## Size Matters

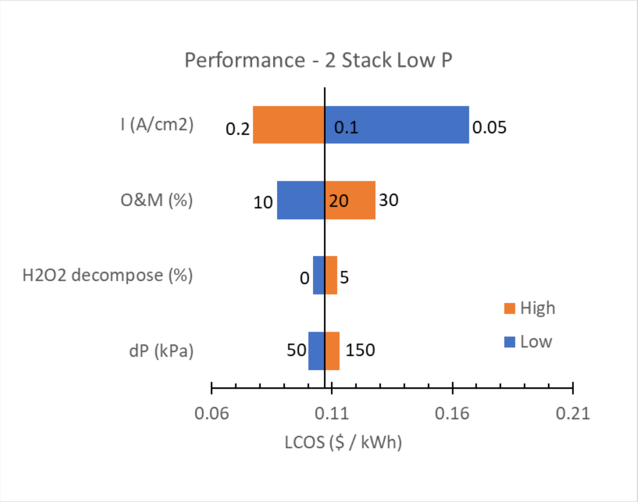
| | 0.1 A/cm$^2$ | 0.2 A/cm$^2$ |
|---|---|---|
| 100 kW | 0.304 | 0.289 |
| 1 MW | 0.084 | 0.069 |
| 10 MW | 0.062 | 0.046 |

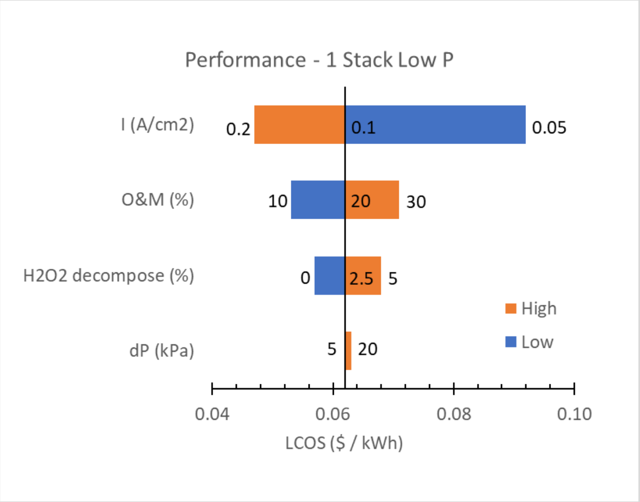
***LCOS ($/kWhr) using NREL stack costs***

A ~100x increase in size was needed to reduce the impact of labor costs to an acceptable LCOS value. Doubling of stack performance reduced the cost by 0.015 $/kWhr.

# Results:  Cost

- Cost estimates (all-in) show clear paths to meeting cost targets
  - Enabled by low cost materials, high efficiency
- Many configurations, ways of using system possible





- *Solar farm storage use case:*

10 MW system had an LCOS of **0.039 $/kWhr***. **Based on recent results, we have small gains on this figure.**

*Operating at 0.2 A/cm$^2$ (1.1 V charge, 0.71 V discharge) with 10 hr discharge, 9.75 hr charge and 4.25 hr idle with 2.5% peroxide decomposition and H$_2$ and O$_2$ makeup, without labor or DC-DC boost,

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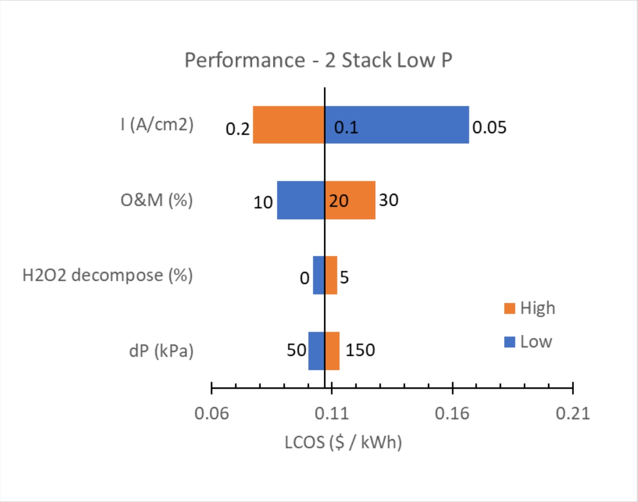

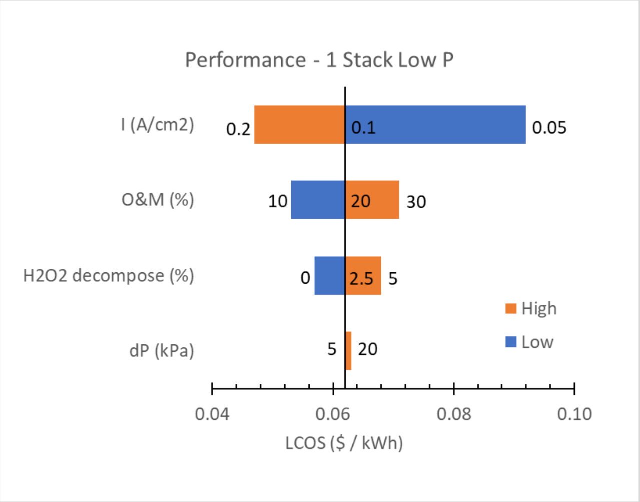

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# Challenges and Potential Partnerships

- Known issues that we attacked
  - Proving sufficient peroxide stability and cost of mitigation. *Solved*
  - Stack design issues. *We have functioning solutions.*
  - Getting to a system understanding, supply chain. *Baked into project.*

- Known unknowns: Coulombic efficiency issues (catalysts).

- Unknown unknowns: (Accelerating development and/or deployment) Cycling performance; Solving stack design challenges and getting to system implementation; Identification of long-duration use cases. Teaming with integrators.

- Partnerships: Eventually plan to form a joint-venture company for next stage of development beyond next BP.' **Options open.**

# Technology-to-Market

- **Our ultimate goal**

Provide inexpensive and flexible LDS based on hydrogen and oxygen, including a whole-system concept and paths to manufactured system.

- **Timeline**

We are still fairly early stage in development; hardware design is modular and all work is directly connected to system considerations.

- **Getting Beyond the Current Status**

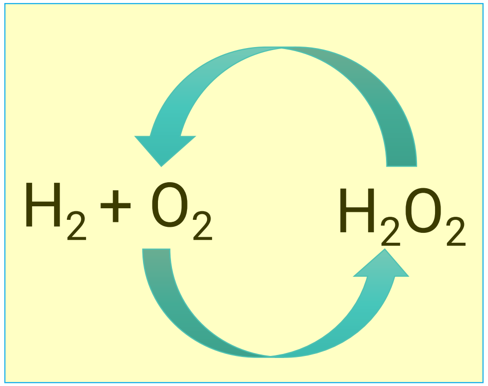
Some teaming with system developers/integrators. Improved catalyst synthesis. An end to COVID-based restrictions (to allow some planned material scale-up)!

Possible commercial applications and market entry options:

Applications: transportable LDS for disaster response and related. Possibilities for seasonal $H_2$ storage.

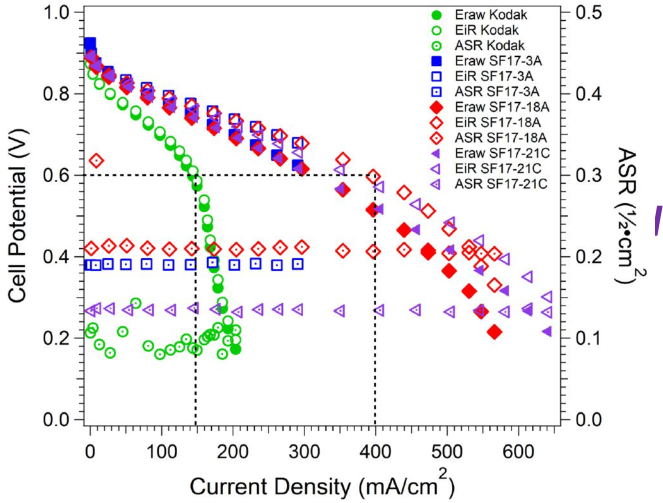
Market Entry Approach: Options open; PSI is key partner now but spin-off likely.

# Summary: PELoDEES
# Innovations in Catalysts-Cell-Stack-System



**Reversible Fuel Cell (with a twist)**

***Good performance***



***Inexpensive core technology***
***High efficiency***

***Possible long-term storage with extremely low self-discharge: in charged state we store $H_2$ and $O_2$***

Status

- Stack-sized cell modules built and tested; material, catalyst issues being addressed.
- Cycling of cells imminent.
- System design in hand. Next phase would include ‘brassboard’ system.

Possible commercial applications and early options: transportable LDS for disaster response and related. Possibilities for seasonal $H_2$ storage.

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Thanks to Scott, Max and Sean for helpful discussions throughout.