A Novel Stack Approach to Enable High Roundtrip Efficiencies in Unitized PEM Regenerative Fuel Cells

Dr. Katherine Ayers
Nel Hydrogen
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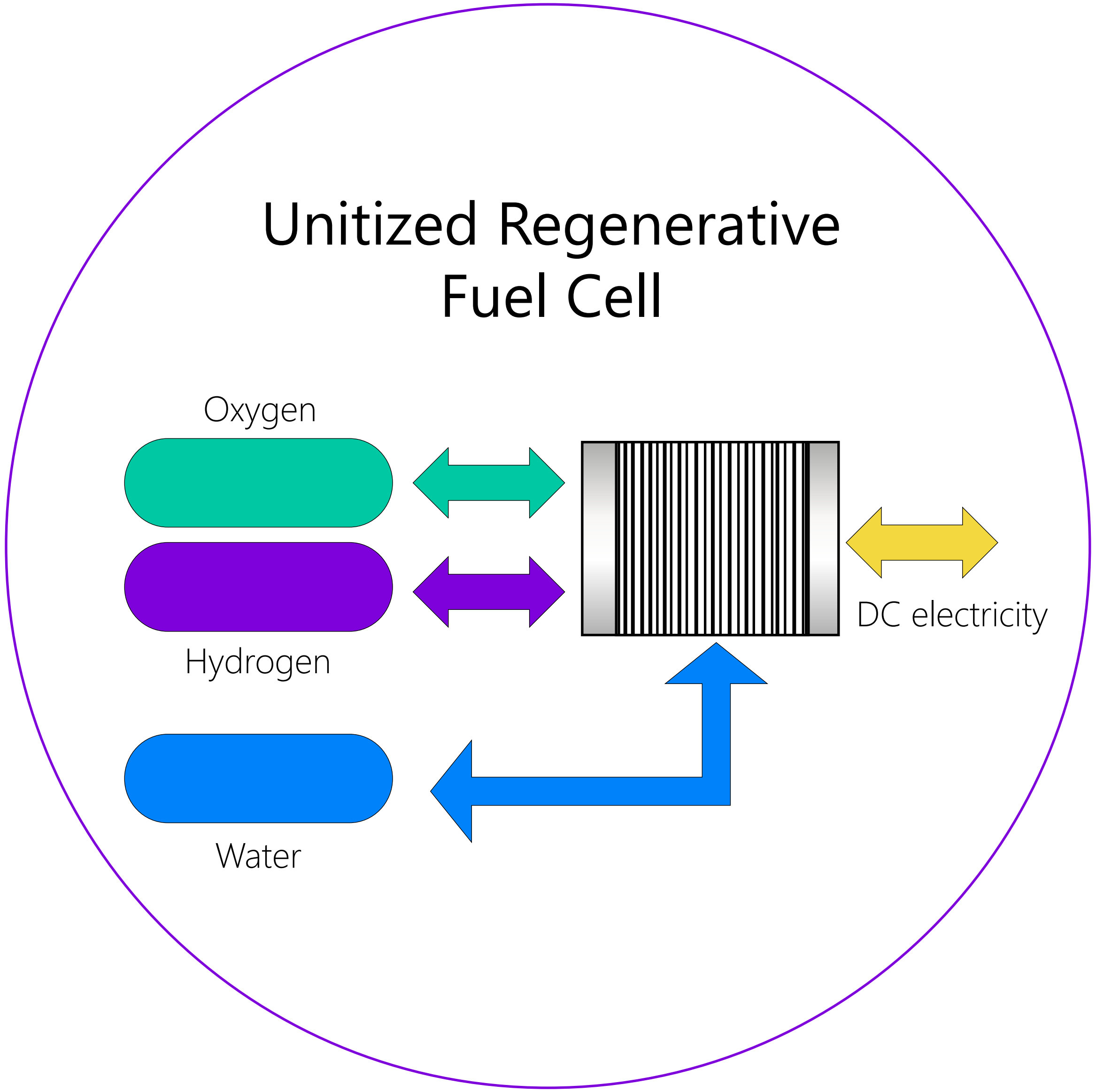
Project ID #FC331

Project goal

The overall project goal is to demonstrate a Unitized Reversible Fuel Cell (URFC) system based on Polymer Electrolyte Membrane (PEM) technology that can achieve 50% round trip efficiency and reliable performance under relevant duty cycles, with projected costs below $1,750/kW



Project Overview

- Time and budget
  - Project start date: April 1, 2020
  - Project end date: September 30, 2024
  - Total project budget: $2.5M
    - Total recipient share: $500K
    - Total federal share: $2M
    - Total DOE funds spent*: $1715K
- Partners
  - EPRI: Brittany Westlake
  - Southern Company: Noah Meeks
  - LBNL: Adam Weber
  - Gaia: Whitney Colella
- Barriers
  - Barriers addressed
  - No regenerative fuel cell specific barriers
  - Optimization between fuel cell and electrolyzer barriers:
    - Fuel cells
      - Durability
      - Cost
      - Performance
    - Hydrogen production
      - Capital cost
      - System efficiency
      - Electricity cost

*As of 12/31/2023

Relevance and impact

- Technology
  - An efficient RFC enables long term, utility scale storage to enable higher renewable energy penetration
  - Hydrogen has advantages over batteries for storage durations greater than 8 hours
  - Ideally a Unitized RFC (URFC) would eliminate a stack and balance of plant to simplify and reduce cost
- Outreach
  - Utility participation enables consideration of integration issues and optimization for best use cases
  - Public education of benefits of this technology to balance renewables on the utility grid

Key project tasks

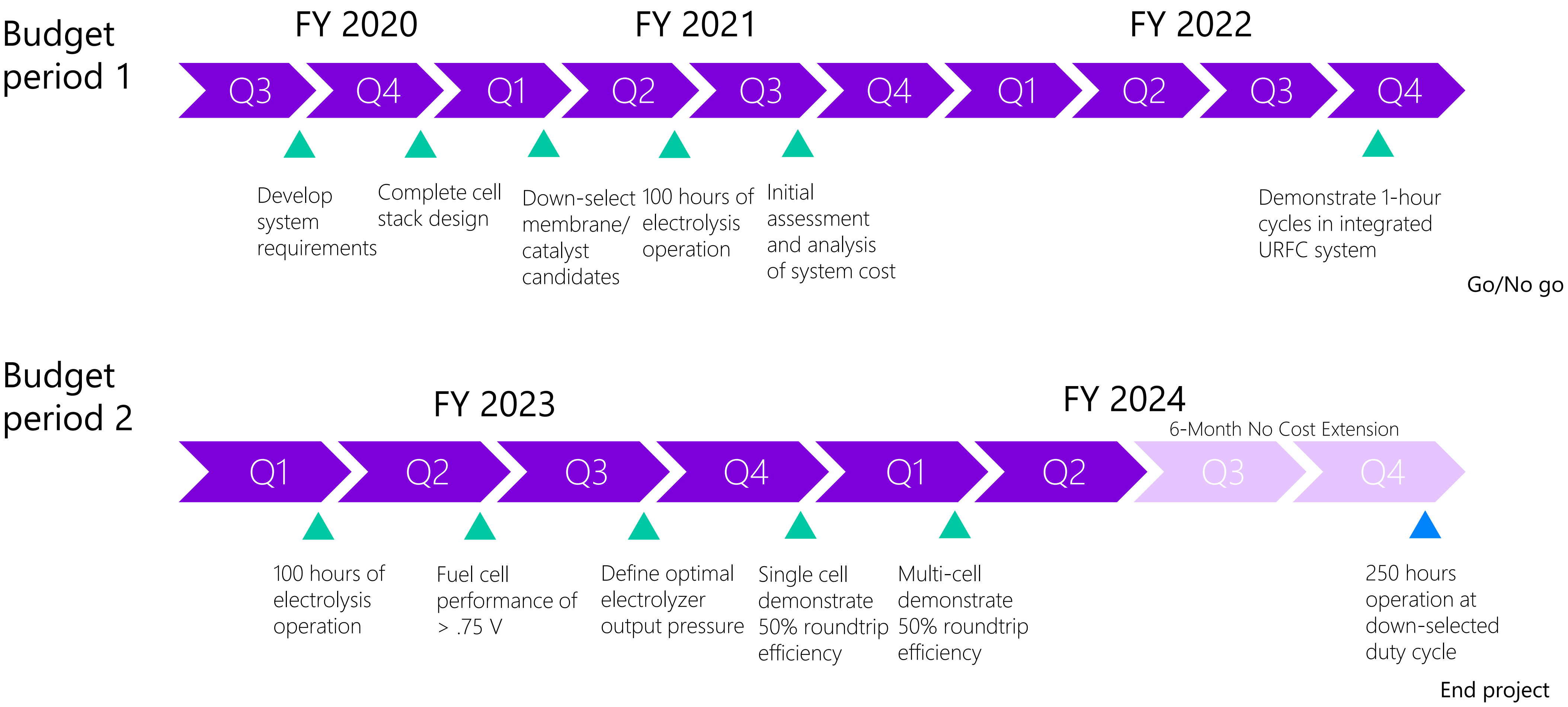
- Stack optimizations
  - Hardware design and material selection
  - Optimization of cell water management
- System modification
  - Build integrated test system to demonstrate URFC
- RFC system testing
  - Test and benchmark performance under application specific duty cycles
- System analysis
  - Techno-economic analysis to optimize CAPEX and OPEX costs
  - Modeling of use cases
  - Interconnection considerations
- Outreach/Project management

Multi-MW PEM installation

APPROACH

Key milestones

Completed milestone
Future milestone



APPROACH

Safety Planning and Culture

- Nel's #1 Must Win Battle is safety – metrics include lost time and total recordable incident rates, near miss capturing, monthly required safety training, and safety observation tours
- QR code established for reporting of observed hazards and actions taken/recommended
- Project milestones related to safety:
  - Complete pre-start safety review for URFC upgrade
    - Review completed 9/30/2021; actions closed 11/4/2021
    - P&ID, electrical schematic, and product requirements documents reviewed as part of effort
  - System errors and warnings software indicators verified and issues resolved.
- Annual reviews performed for all test stands including URFC test stand, standalone fuel cell test stand, and stand alone electrolyzer test stand (3-page checklist)
  - Includes electrical, mechanical, and chemical sections

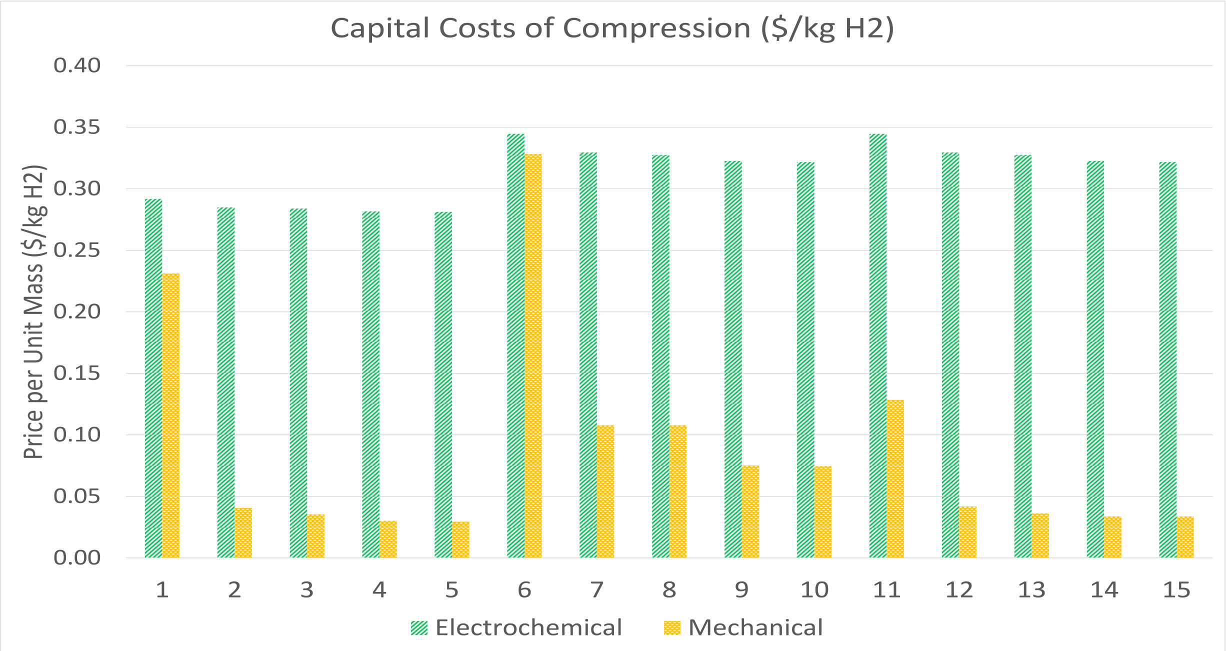
Accomplishments since June 2023

- CAPEX cost models were developed to compare electrochemical vs. mechanical hydrogen compression to determine optimal electrolyzer output pressure.
- A Single Cell URFC Stack was operated for 66 cycles.
- A Multi-Cell URFC Stack was operated for ~50 cycles.
- An energy storage techno-economic model was developed.
- Utility review of energy storage model with recommendations for early URFC applications was completed.
- "Understanding Reversible Fuel Cells in Energy Storage Applications" webcast was held

URFC system as modified

Hydrogen Compression CAPEX Models

- Mechanical and Electrochemical compression was evaluated for each input/output pressure and flow case
- Electrochemical compression to full pressure is, in general not competitive with mechanical compression
- Optimal output pressure for the electrochemical compressor to be cost competitive with mechanical compression is represented in Case 6 (5 bar input, 200 bar output at 10 kg/hr flowrate).
- Applications requiring higher flowrates (>10 kg/hr) would be better served by a 5 bar output electrolyzer paired with mechanical compression for 30+ bar output pressures.



Capital Cost of Compression Comparisons

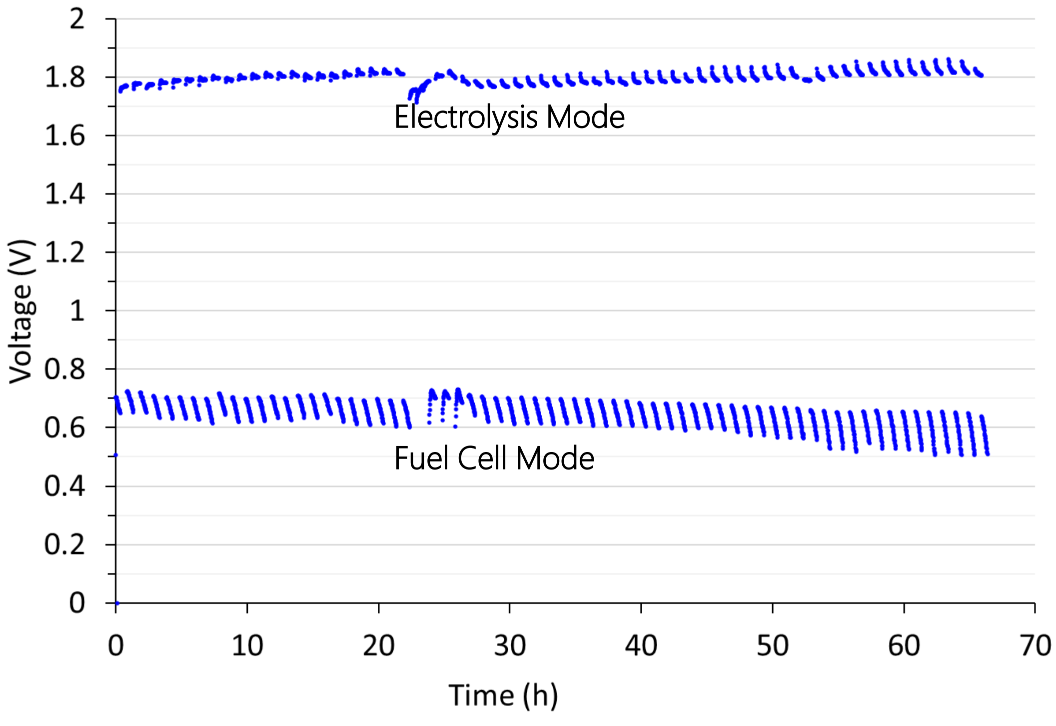
Case	Ps (Bar)	Pd (Bar)	Flow (kg/hr)
1	5	30	10
2	5	30	300
3	5	30	600
4	5	30	6,000
5	5	30	10,000
6	5	200	10
7	5	200	300
8	5	200	600
9	5	200	6,000
10	5	200	10,000
11	30	200	10
12	30	200	300
13	30	200	600
14	30	200	6,000
15	30	200	10,000

Electrochemical compression approaches mechanical compression cost

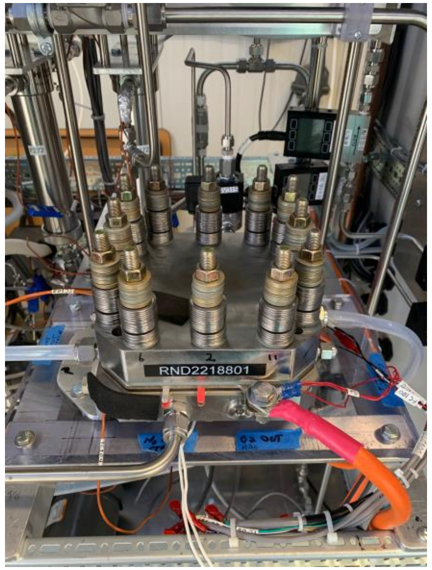
Input/Output Pressure & Flow Cases

Analysis by Gaia Energy Research Institute

URFC Single Cell Cyclic Testing



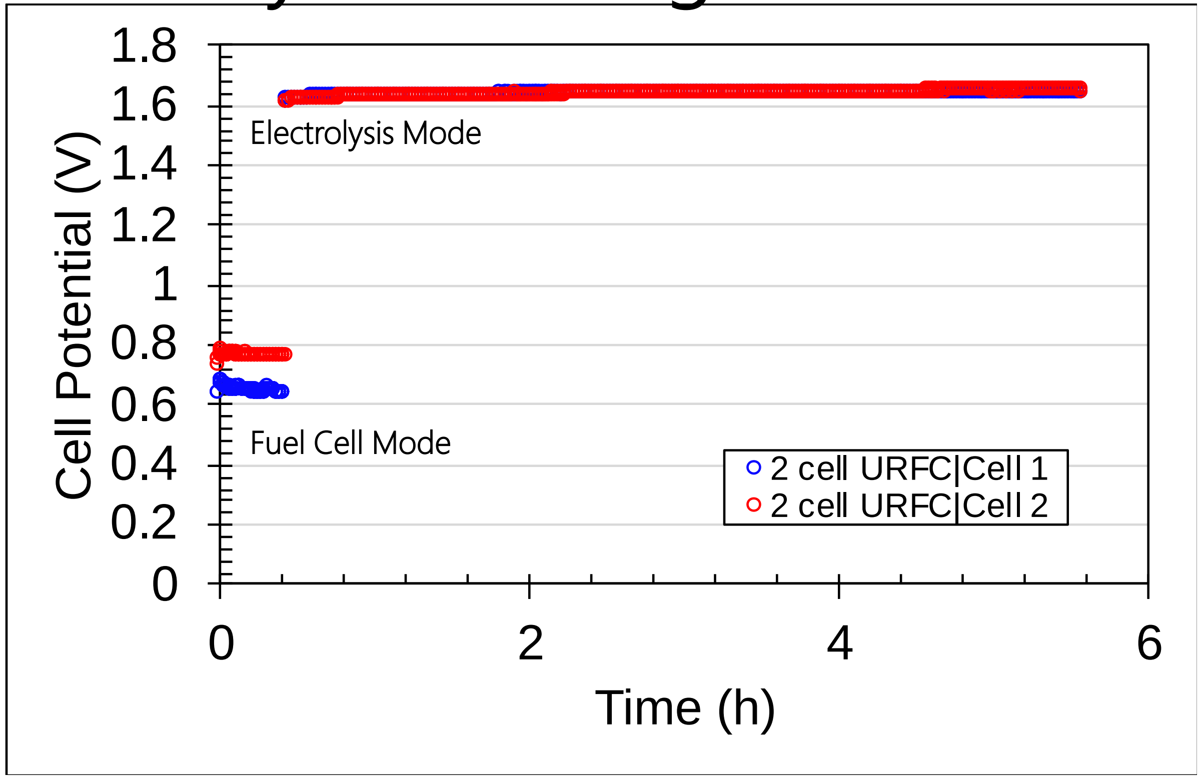
Cyclic testing of Single Cell URFC Stack



- The single cell URFC stack was baselined in discrete electrolysis and fuel cell modes
- The stack was run for 66 cycles* with a peak roundtrip efficiency of 43%
- Recoverable fuel cell performance decay in fuel cell over time was observed due to cell flooding

**1 Cycle = 30 minutes Electrolyzer mode, 30 minutes Fuel Cell mode*

URFC Multi Cell Cyclic Testing

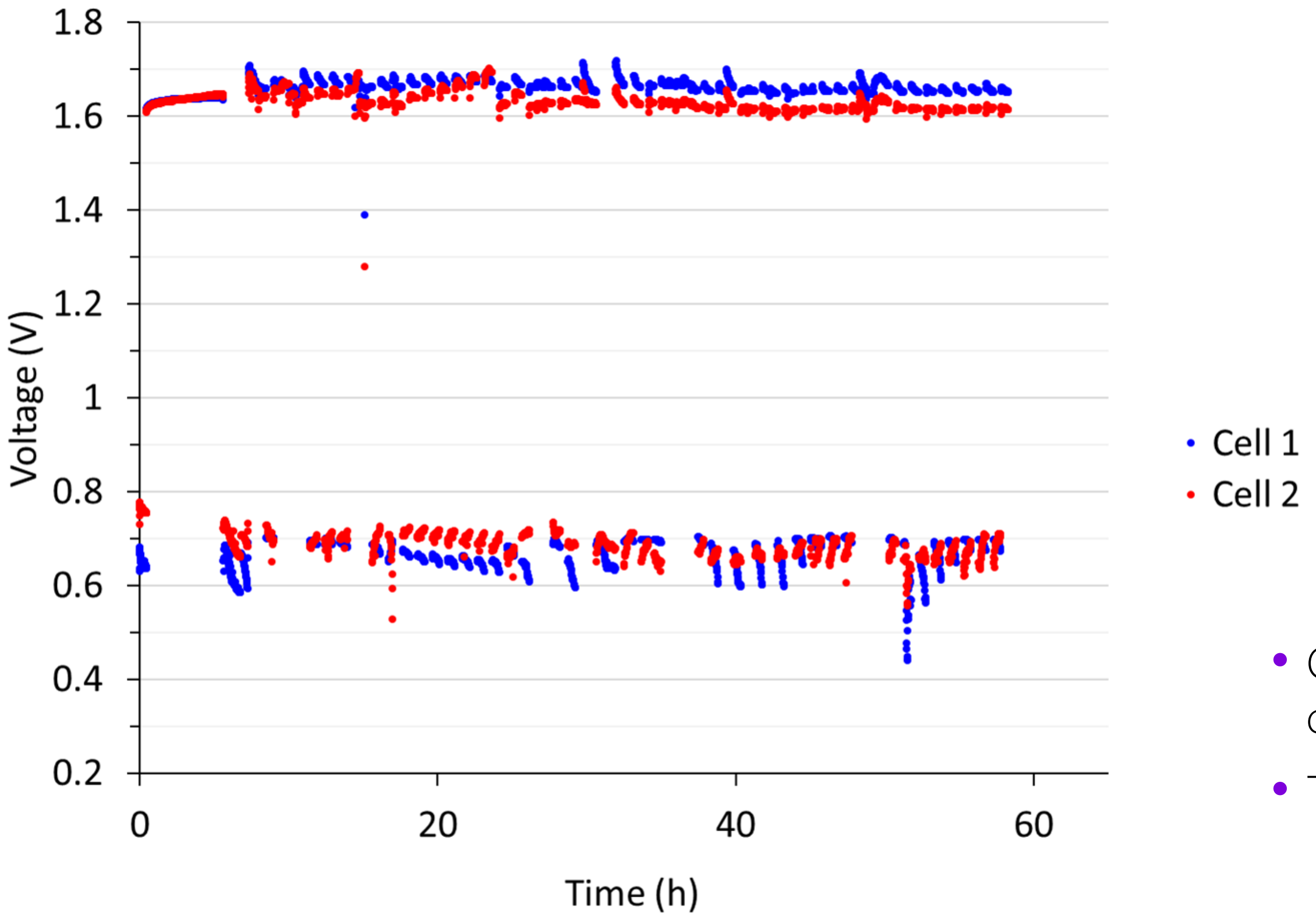


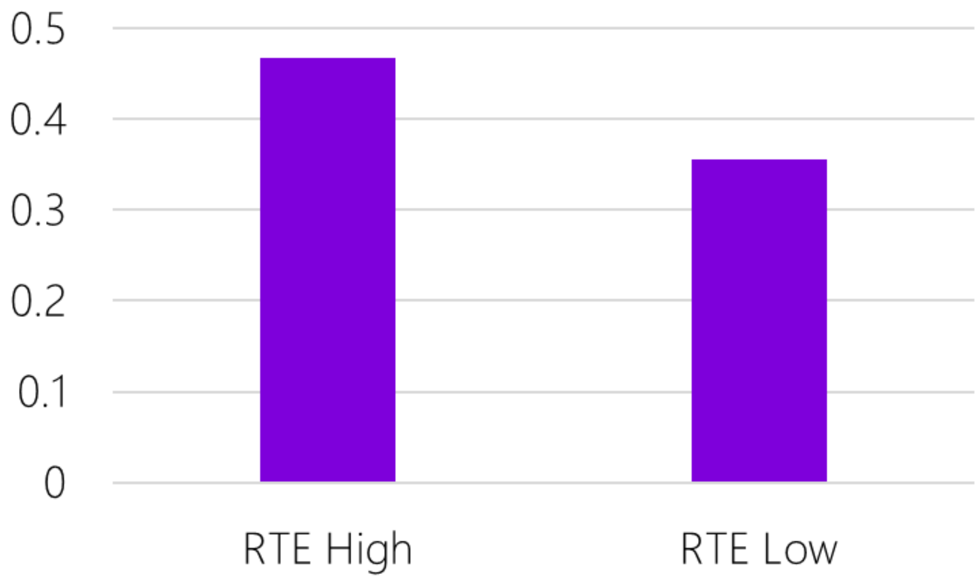
Discrete testing of 2-Cell URFC Stack

- A 2-cell URFC stack was baselined in discrete electrolysis and fuel cell modes (average RT efficiency – 42%)

**1 Cycle = 30 minutes Electrolyzer mode, 30 minutes Fuel Cell mode*

Multi-Cell Cycling





- Cyclic testing was stopped due to a test stand component failure
- Testing will resume following test stand repair

URFC Test Stand Challenges

- Thermal management issues
    - Mismatch in reactant feeds and stack temperature resulted in condensation (cell flooding) during fuel cell testing
- Component Failures
    - Scroll compressor failures
        - Bypass in oxygen and hydrogen feed compressors due to component wear
    - DI water feed pump
- System shutdown alarms during transients
    - Pressure buildup
    - Cell flooding
- Plan to restart test stand after facility upgrades are complete.
    - Direct feed H2 and O2 from compressed cylinders
    - Replace DI pump
    - Tune system controls

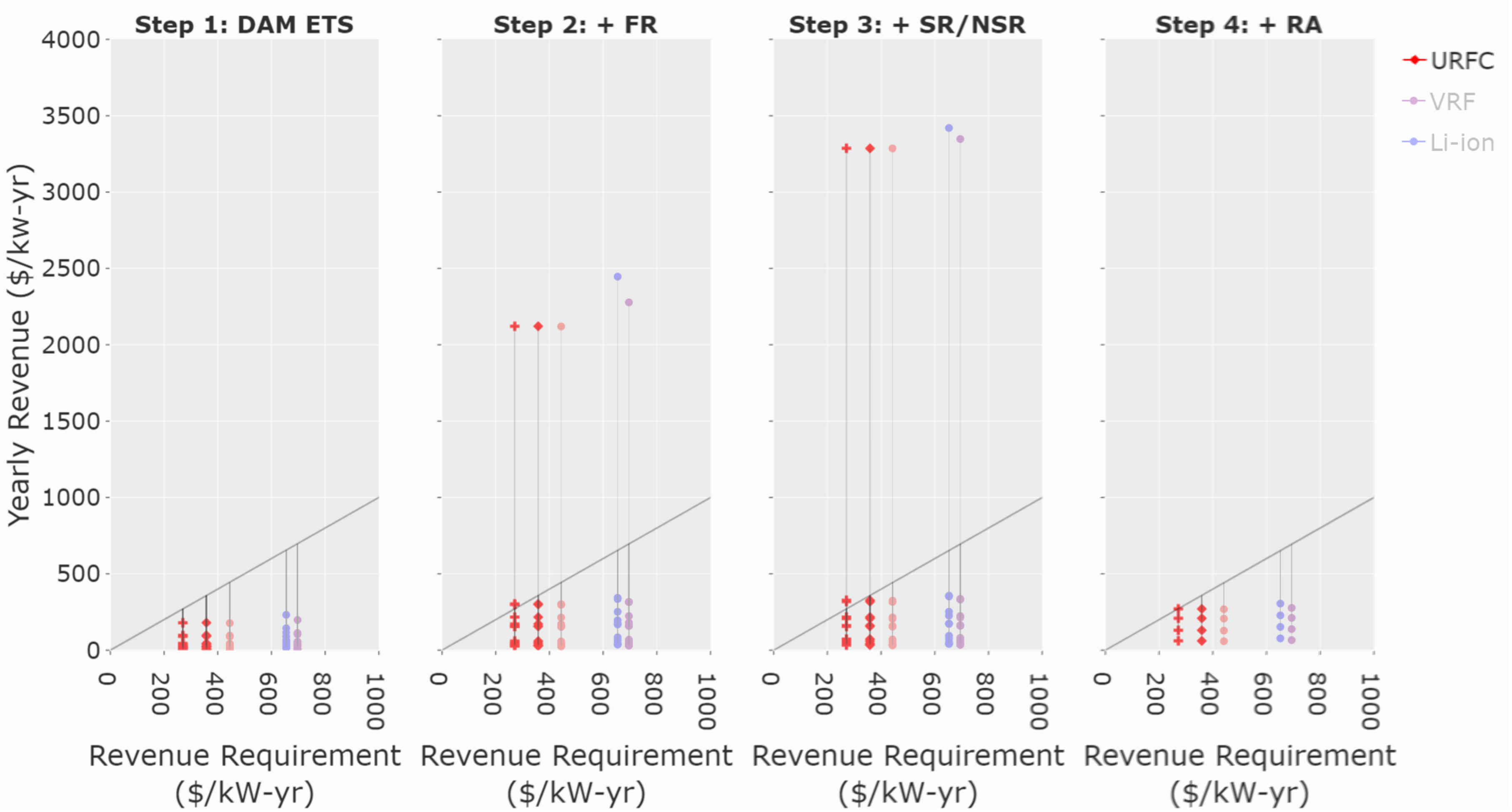
Energy Storage Techno-Economic Model- Overview

- 3 ISOs/RTOs Evaluated
  - CAISO, ERCOT, MISO
- Services
  - Step 1: Day-Ahead Market Energy Time-Shifting (DAM ETS)
  - Ancillary Services
    - Step 2: Frequency Regulation (FR)
    - Step 3: Spinning/Non-Spinning Reserves (SR/NSR)
  - Step 4: Resource Adequacy (RA)
- Sensitivities
  - Duration
  - Capital Cost
  - Round Trip Efficiency

Parameter	Scenarios
ISOs	ERCOT, MISO, CAISO
Comparison Technologies	Lithium Ion, Vanadium Redox Flow
Services	Day-Ahead Market Energy Time-Shifting, Ancillary Services
Sensitivities	
Capital Costs	**5250 $/kW - Prototype System Cost**, 3500 $/kW - Low Volume Production System Cost, 1750 $/kW - Target Production System Cost
Durations	12 h, **24 h**
Round Trip Efficiency	40%, **50%**
*Bold represent baseline case	

DER-VET™ provides an open-source platform for calculating, understanding, and optimizing the value of distributed energy resources based on their technical merits and constraints: www.der-vet.com

Cost Sensitivity ($3500/kW and $1750/kW vs $5250/kW)



Price Steps:

- Prototype System Cost – 5,250 $/kW
- Low Volume Production System Cost – 3,500 $/kW
- Target Production System Cost – 1,750 $/kW

Target cost ($1,750/kW) tips additional scenarios into cost recovery space

Energy Storage Techno-Economic Model: Conclusions and Considerations

- DAM ETS alone does not provide significant revenue
  - Pairing with ancillary services and/or industrial uses necessary for positive NPV
  - Achieving $1,750/kW CAPEX target makes URFC competitive with existing energy storage technologies
  - 40% vs. 50% Round-trip efficiency does not significantly impact value proposition
  - Use of hydrogen molecule can add additional value over existing energy storage technologies

- Review of modeling results with Southern Company identified early use cases could benefit from offtake of Hydrogen for:
  - Difficult to electrify industrial processes
  - Onsite fuel cell forklift re-fueling


Steel Mill Ladle Heater


Metal Reheat Furnace

Fuel Cell Forklift

Outreach

- Hosted five webcasts targeted at Electric Utilities:
  1. Intro to hydrogen: History, current and future uses (March 30, 2021)
  2. Hydrogen Production - An Overview (July 1, 2021)
  3. Hydrogen Applications - An Overview (October 28, 2021)
  4. Hydrogen Safety (January 10, 2022)
  5. Understanding Reversible Fuel Cells in Energy Storage Applications – DER-VET Modeling Insight (January 25, 2024)

- Planned Webcasts
  - Understanding Reversible Fuel Cell Technologies – Development and Performance Testing Results (Q2'2024)

EPRI ELECTRIC POWER RESEARCH INSTITUTE

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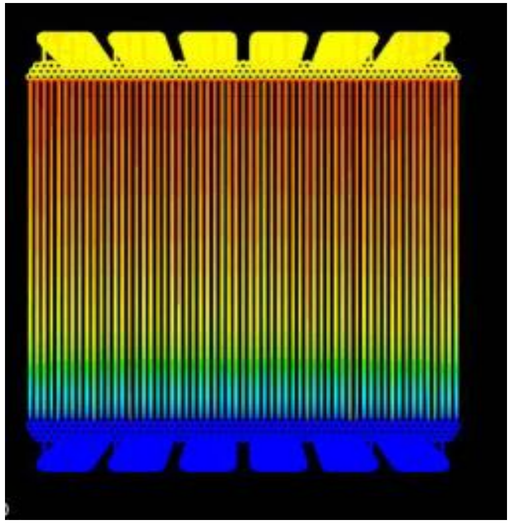
Collaboration

Partners	Project Roles
Electric Power Research Institute	System analysis, outreach
Southern Company	System analysis, outreach
Gaia Energy Research Institute	Techno-economic analysis
Lawrence Berkeley National Laboratory	Multi-physics transport modeling

Gaia Energy
Research Institute

Challenges and barriers

- Electrolyzers currently use thick membrane to tolerate the high differential pressure
  - Retuning of the cell design to enable the use of more efficient, thinner membranes
- Fuel cell operation is more sensitive to flow field geometry and gas-diffusion layer wettability
  - Leverage Nel cell optimization experience to make cell stack design compatible with efficient fuel-cell operation
  - Utilize basic Computational Fluid Dynamic modeling (CFD) to optimize flow field geometry
  - Use LBNL model to understand the water transport in the URFC cell with respect to membrane properties and operating conditions



Planned future work

- Upgrade key URFC test stand components
- Demonstrate up to 250 hours of operation under down-selected duty cycle with 50% roundtrip efficiency
- Recommendations for future projects:
  - Conduct a technoeconomic analysis of a unitized reversible fuel cell (URFC) vs. discrete electrolyzer and fuel cell stack
  - Full scale system design comparison (URFC vs. Discrete)

	Unitized Reversible Fuel Cell (URFC)	Discrete Fuel Cell & Electrolyzer

Benefits	• Reduced CAPEX
	  • 1 Common Cell Stack
	  • Shared Balance of Plant
		• Reduced OPEX
		  • Higher efficiency stacks
		• Simplified balance of plant controls complexity

Limitations	• Higher OPEX due to lower stack efficiency
	• Slower transitions from EL to FC (clear water from flow fields)
	• Increased balance of plant controls complexity
		• Higher CAPEX
		  • 2 Cell Stacks
		  • Addition balance of plant components

Summary

- Objectives:
  - Balance design and operating conditions for optimal electrolysis and fuel cell performance
- Relevance and impact:
  - Target 50% roundtrip efficiency
  - Projected costs below $1,750/kW
- Collaboration effectiveness:
  - Cross-functional project team actively working on project
  - Relevant use case studies for utility scale applications were developed
  - Webinars were presented to educate utilities about hydrogen

- Accomplishments:
  - CAPEX hydrogen compression cost models were
  - A Single Cell URFC Stack was operated for 66 cycles.
  - A Multi-Cell URFC Stack was operated at baseline conditions.
  - An energy storage techno-economic model was developed.
  - Utility review of energy storage model with recommendations for early URFC applications was completed.
  - "Understanding Reversible Fuel Cells in Energy Storage Applications" webcast was held
- Future work:
  - Upgrade key URFC test stand components
  - Demonstrate up to 250 hours of operation under down-selected duty cycle with 50% roundtrip efficiency
  - Recommend a TEA of unitized vs. discrete cell stacks

Response to Reviewers Comments

- Theme: Milestones and cost/durability targets are not clear; milestones for fuel cell durability and thermal management should be included
  - The milestones were set at the beginning of the project. Electrolyzer durability was the focus because the design deviation from a standard electrolyzer cell was wider than that for fuel cell. System optimization was out of scope based on the available budget but the team has tried to address the water management issues with the test stand as possible
  - URFC technology is still at relatively low TRL; while it is likely that megawatt scale systems should be the market target based on the work with EPRI and Southern, the technology is still at sub-kW scale. System level cost projections are therefore very difficult; however, at this scale, stacks are typically roughly 30-50% of total system cost.
- Theme: having Nel work on both the electrolyzer and fuel cell is surprising.
  - Nel has experience with hydrogen-oxygen fuel cells and static feed fuel cells dating back 20 years and has done many programs through NASA and NSF.
- Theme: Modeling does not clearly show the benefit of having only one stack
  - Agree that a more detailed comparison of unitized and discrete fuel cell systems, including system cost, is needed as a next step of any URFC program. The learnings from this project and other recent projects (e.g. LBNL) will greatly inform the analysis. The analysis will also help set reasonable targets.

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Response to Reviewers Comments

- Theme: More details should be provided on the test conditions and models
  - Cell area was 86 cm2; this design is very parallel to Nel's 680 cm2 and 1570 cm2 designs. Catalyst loading is still relatively high since that was not a focus of the project – 2 mg/cm2 PGM on the oxygen side with Pt/Ir catalyst. The electrolyzer model was the focus since it was much less developed to start with; Adam Weber has done extensive fuel cell modeling and polarization curve fitting.

- Stack testing issues indicate a lack of priority
  - The test stand has had many more issues than anticipated, possibly due to the extended cycling and other stressful conditions (significant condensation, etc.). The technicians who are experts on this stand and have 30 years experience in mechanical and electrical work have spent months troubleshooting, swapping components, re-tuning, etc. to get the stand to run reliably and consistently for long periods. The delays related to the system relate more to the need to do more study/design on regenerative systems and their reliability (vs. only stack studies) than a lack of focus on the repairs of the stand.

- It is not clear what the partners are contributing
  - Gaia completed a comprehensive trade of mechanical and electrical compression which is presented this year. In addition to the webinar outreach, EPRI and Southern have worked together to model several use cases and comparisons of technologies, also presented this year. In addition to electrochemical modeling, LBNL did provide information from their URFC project which informed and guided work on the Nel project, although there are differences since LBNLs efforts leveraged the fuel cell cathode as an electrolyzer cathode, vs. electrolyzer anode as typical in URFC systems.

Response to Reviewers Comments

- Theme: Impact is not clear since the same objectives can be obtained by 2 stacks/systems
  - This depends on the performance that can be achieved. An important next step before launching new URFC experimental programs should be to do a full cost/performance trade on unitized vs. discrete systems, including the balance of plant, based on the data from this and other projects which give a much better assessment of the potential of the technology vs. previous efforts with very poor fuel cell performance or very low current densities which are only likely to be useful in niche applications like outerspace where weight and volume are more important than cost.
- Theme: it is unclear how the duty cycle is selected – should focus more on durability
  - Southern, EPRI, and Nel have worked together to determine cycles that could be of practical use. Durability under steady state and under relevant cycling conditions are both important. Additional durability testing will be needed to show viability for commercial applications, but development has to start with showing feasibility to hit performance targets, then cycles of durability testing and additional development to address degradation pathways. URFCs in general are still at a relatively immature stage of development.