Titanium-Cerium Electrode-Decoupled Redox Flow Batteries Integrated With Fossil Fuel Assets For Load-Following, Long-Duration Energy Storage

Project FE0032011

FY22 FECM Spring R&D Project Review Meeting: Energy Storage Program

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presented by:

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Team Introduction

Wash U (lead)

RFB Technology Creator

Vijay
Ramani
(lead PI)

Fossil Plant Cost
& Performance

Ben
Kumfer
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U. Texas – San Antonio

RFB Technology Creator

Shrihari
Sankarasubramanian
(co-PI)

Industry Partners

Technology Developer

Giner Labs

Dr. Hui Xu, CTO

Fossil Asset Owner

Ameren Missouri

Tom Callahan, Senior Manager

Challenges & Opportunities

- **Increased cycling of fossil plants and reduced capacity factor due to increased penetration of intermittent renewable sources**
  - Reduced efficiency, increased emissions
  - Increased maintenance and wear, reduced lifespan
- **Deployment of grid-scale energy storage required to enable additional renewable sources and balance generation w/ demand**
- **Fossil asset owners benefit from owning/operating storage plants**
  - Control over combined generation/storage system gives flexibility
  - Can keep fossil plants operating at high capacity with optimal efficiency
  - Better positioned to capture grid market opportunities
  - Co-locating storage and fossil plants give opportunities for systems integration, reduced costs.

Challenges & Opportunities, Cont.

- **U.S. storage deployments will reach nearly 7 GW annually with a $6.9 billion annual market by 2025 (Wood MacKenzie)**

- **Storage capability needs span multiple time scales**
  - **short duration (< 1 hour to hourly) for voltage and frequency support and spinning reserve reduction/elimination**
  - **intermediate duration (multi-hour to full-day) for peak load demand and arbitrage opportunities considering diurnal load profiles and weather forecasting**
  - **long duration (multi-day) to improve resiliency against prolonged interruptions and to capture large amounts of energy during periods of high renewables penetrations / low demand**

Project Objectives

Overall Goal:

To advance the integration of a titanium-cerium electrode-decoupled redox flow battery (Ti-Ce ED-RFB) system with conventional fossil-fueled power plants through detailed technical and economic system-level studies and component scale-up and R&D.

Objective 1:

- Increase TRL from 4 to 5, by building and demonstrating a ED-RFB cell stack with following performance characteristics:
  - 0.5 A/cm2 current density
  - 400 cm2 cell size
  - Capable of 48-hr cycle duration
  - <5% capacity loss in 1- week standby

Project Objectives, Cont.

Objective 2:

- Demonstrate a pathway to achieve following cost targets for a utility-scale system:
  - Capex values of < $500/kW (power) and < $ 50/kWh (energy)
  - Levelized cost of storage (LCOS) of < $0.05/kWh-cycle

Objective 3:

- Reveal and quantify the benefits of co-locating the storage system within the fence-line of a fossil plant.

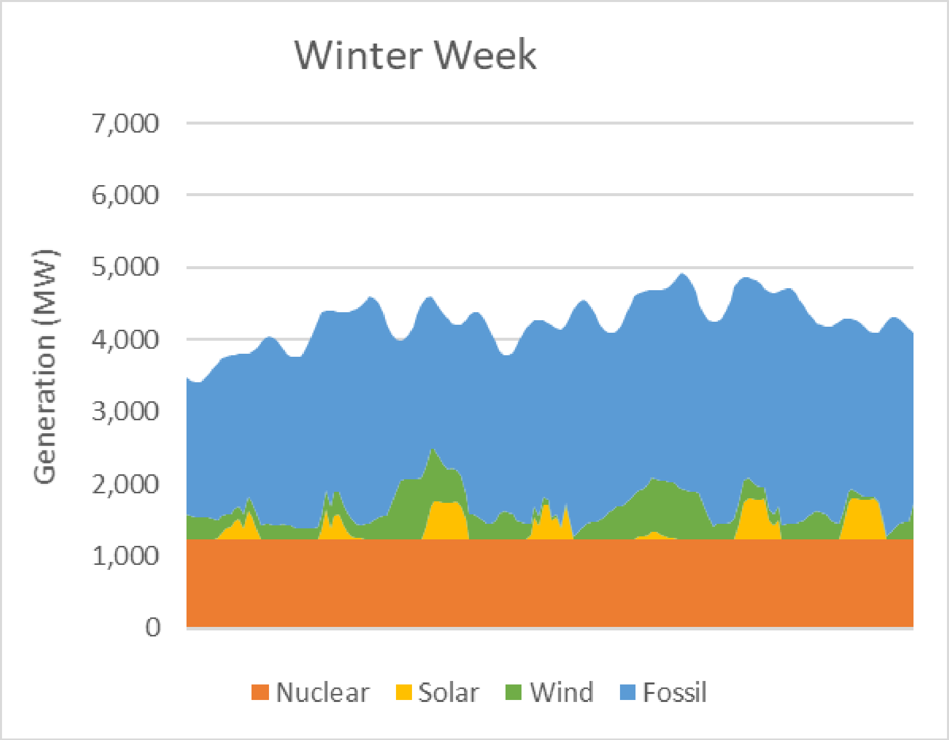
Objective 4:

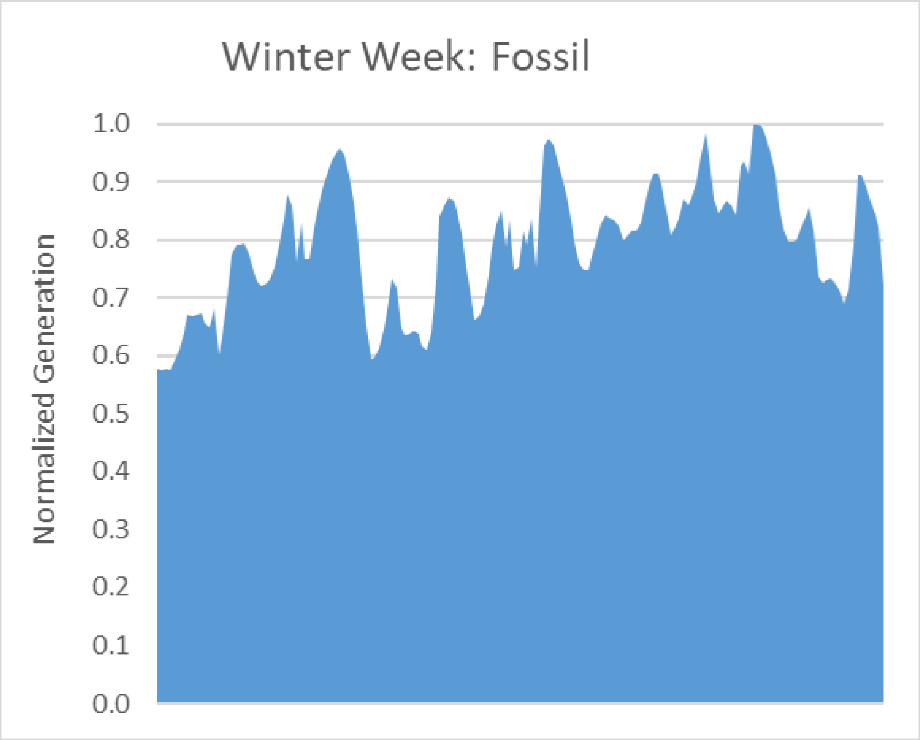
- Enable path to commercialization through market research, gap assessment, and technology maturation and commercialization planning

TEA Design Basis – Baseline Load Profile

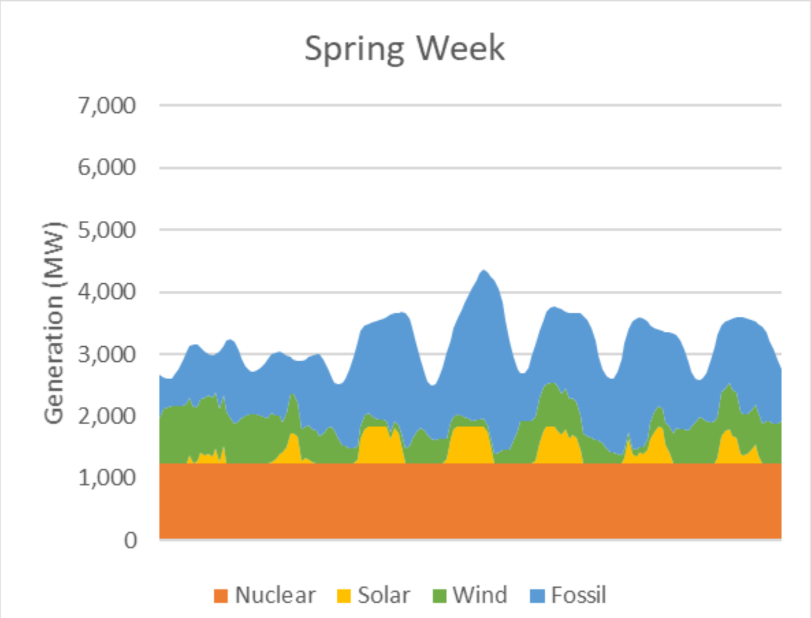
Hypothetical power generation fleet located in Midwest consisting of

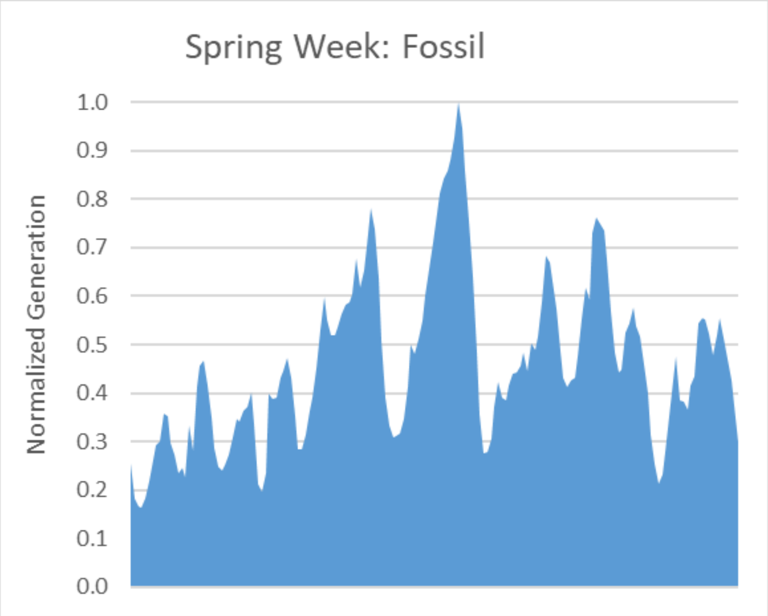
- 600 MW of solar (nameplate capacity)
- 1200 MW of wind (nameplate capacity)
- 1200 MW of baseline nuclear.

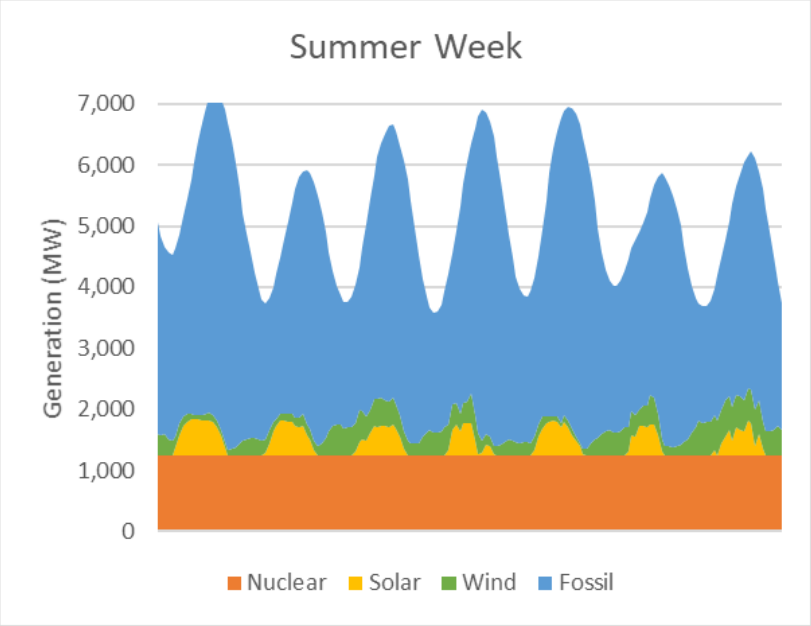


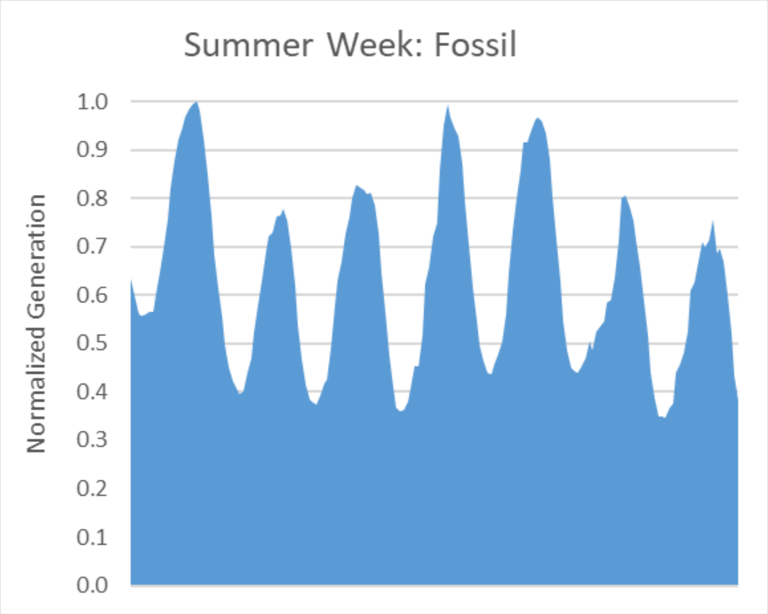


TEA Design Basis – Baseline Load Profile









TEA Design Basis – Case Summary

Fossil Plant	Scenario A: No Storage	Scenario B: Short Duration	Scenario C: Intermediate Duration	Scenario D: Long Duration
1. Reference NGCC NETL Baseline Case 31A	1A	1B	1C	1D
2. Reference NGCC w/CDR NETL Baseline Case 31B	2A	2B	2C	2D
3 VEC* CT (simple cycle)	3A	3B	3C	3D
4. VEC NGCC	4A	4B	4C	4D

*VEC: Venice Energy Center (Ameren MO)

<u>Short Duration (0-2 hours)</u>

<u>Intermediate Duration (2-24 hours)</u>

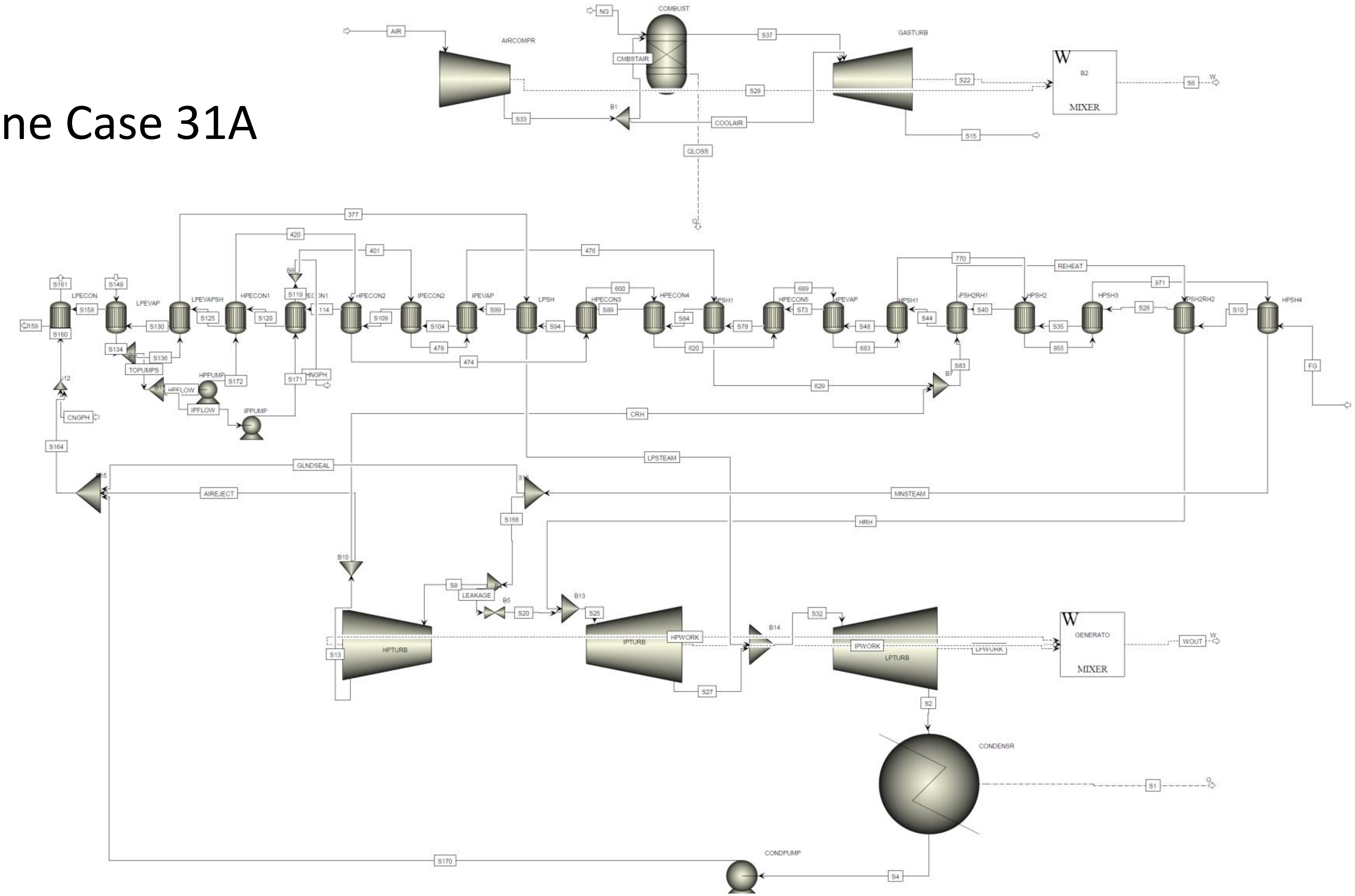
<u>Long Duration (24-48 hours)</u>

TEA Design Basis – Power Plant Specifications

Parameter	Ref. NGCC		VEC	
	Case 1	Case 2	Case 3	Case 4
Combust. Turbine gross output (MWe)	2 x 238		2 x 169	
HRSG Steam Cycle (psig/^{o}F/^{o}F)	2,393/1,085/1,085		N/A	1772/1050/1050
Steam Turbine Power (MWe)	263	213	N/A	185
CO_2 recovery load (MWe)	N/A	28	N/A	
Bal. of Plant Loads (MWe)	14	16	18	19
Plant Gross (MW)	740	690	338	523
Plant Net (MW)	727	646	320	504
LHV Plant Efficiency (%)	59.4	52.8	35.9	53.6
LHV Heat Rate (Btu/kWh)	5,743	6,462	9,493	6,363
LHV CT Efficiency (%)	39.0		35.9	
NOx Control	LNB & SCR		LNB	LNB & SCR
CT Turbine Specifications				
Type	F-Frame		F-Frame (501F-D2)	
Outlet Temperature (^{o}F)	1,156		1,116	
Plant Turndown Min Load (%)	22.0	N/A	50.0	22.0
Ramp Rate (MW/min)	80.0	N/A	tbd	tbd
Startup Time, RR Hot (min)	25	> 25	tbd	tbd
Electrical Specifications				
Grid Interconnect (kV)	345		138	

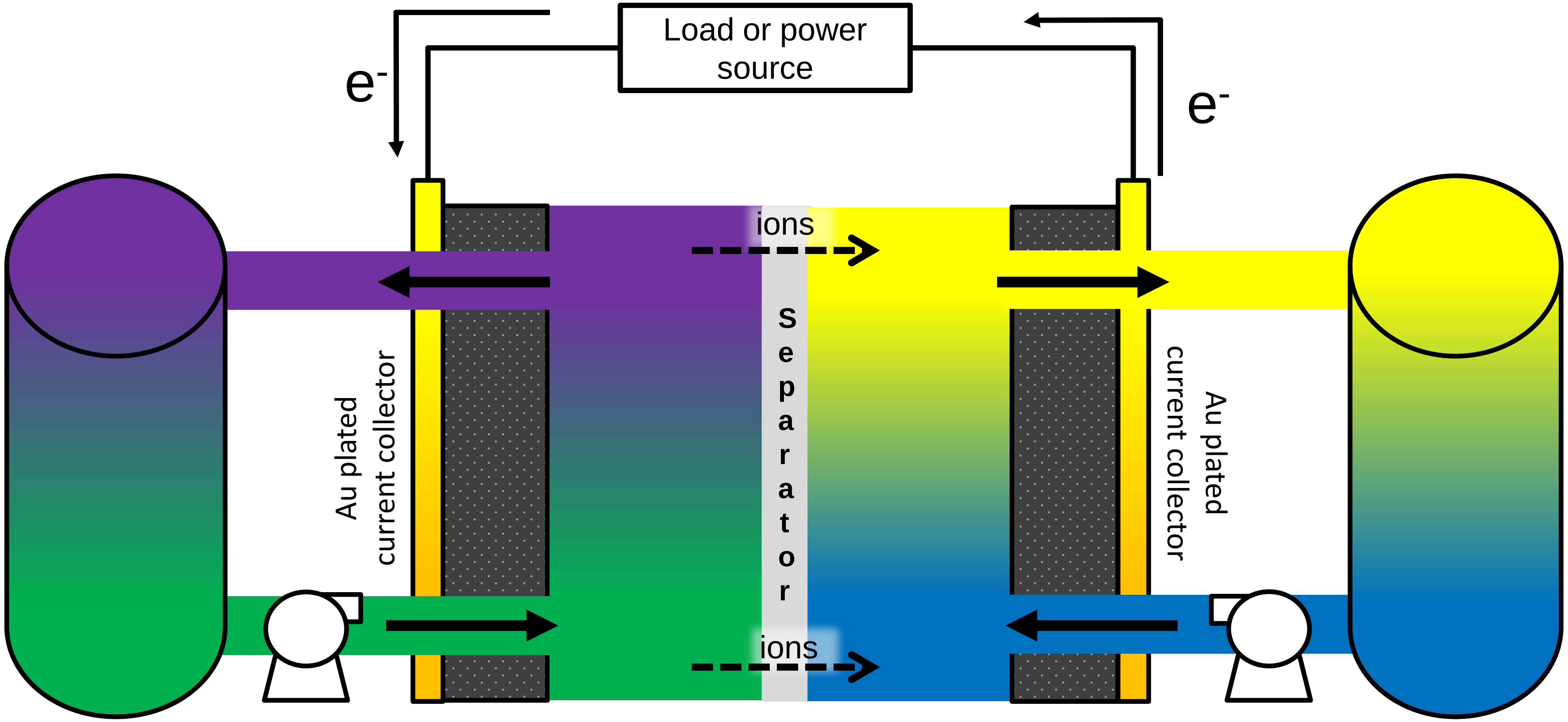
ASPEN Process Model

NGCC Baseline Case 31A

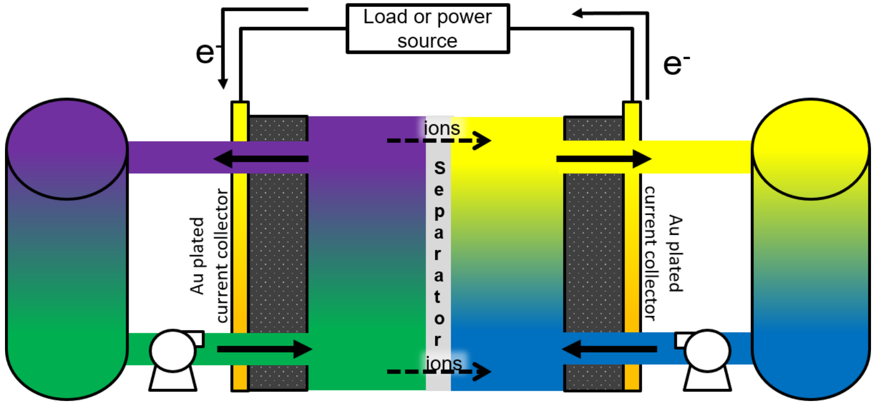


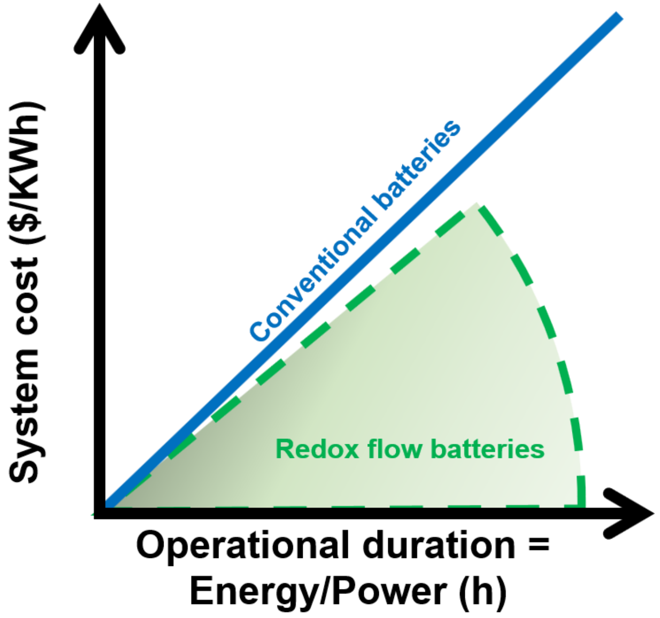
RFB Development & Testing (Shri)

Redox Flow Battery (RFB)



Advantages of RFBs

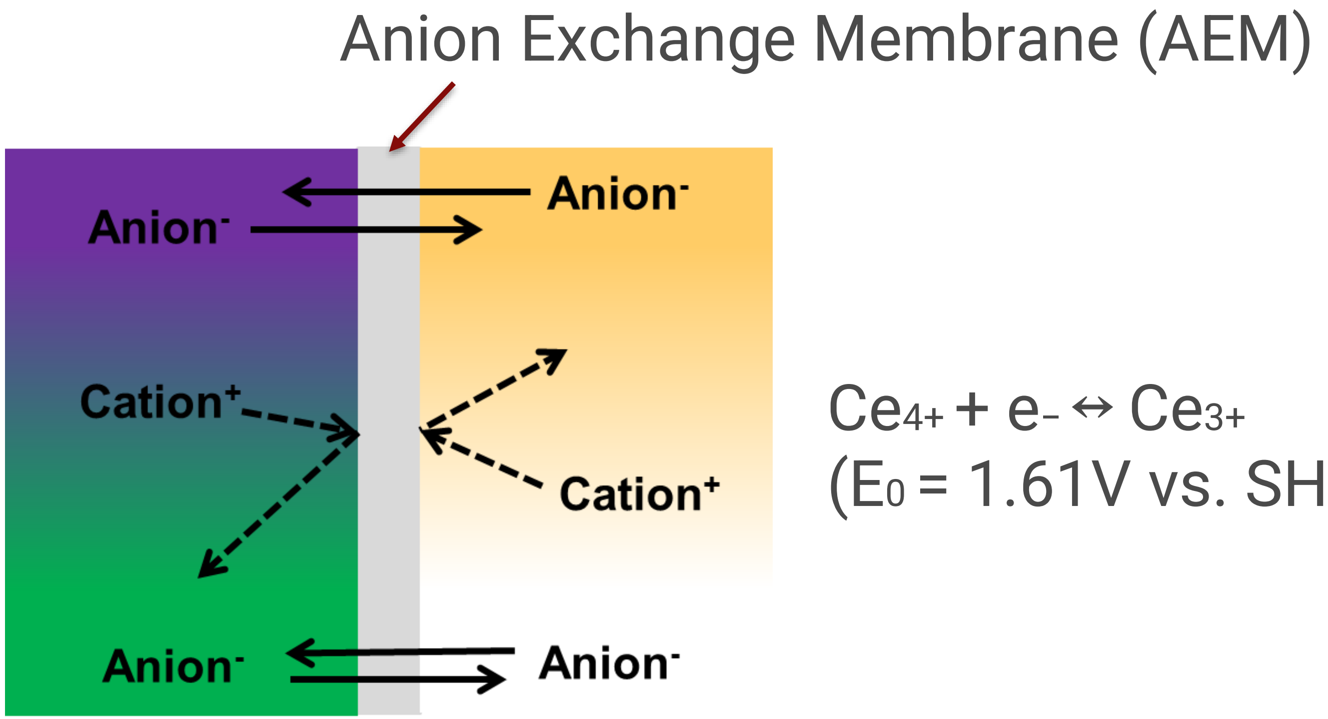




- Energy and power are decoupled
  - => greater design flexibility
  - => lower scale-up costs
- Rapid response
- Suitable for multiple time scales (minutes – weeks)
- Grid-scale demonstration projects underway (Vanadium type)

Ti-Ce electrode decoupled RFB

Ti^{4+} (as TiO^{2+}) + e^- ↔ Ti^{3+}
(E_0 = 0.19V vs. SHE)



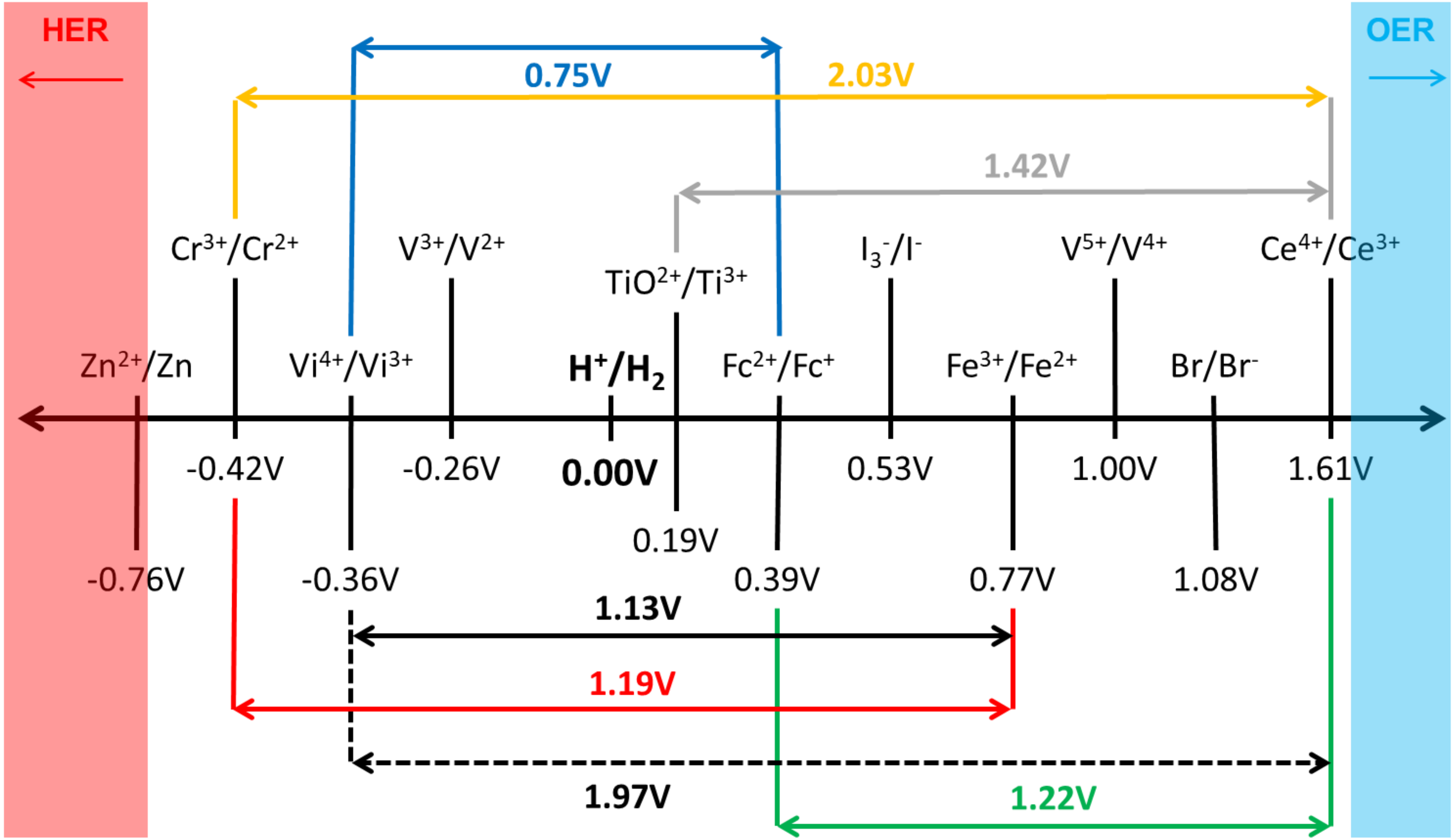
Ce^{4+} + e^- ↔ Ce^{3+}
(E_0 = 1.61V vs. SHE)

- Produced with H_2SO_4- or CH_3SO_3H-supported electrolyte
- Anion: SO_4^{-2} or $CH_3SO_3^-$

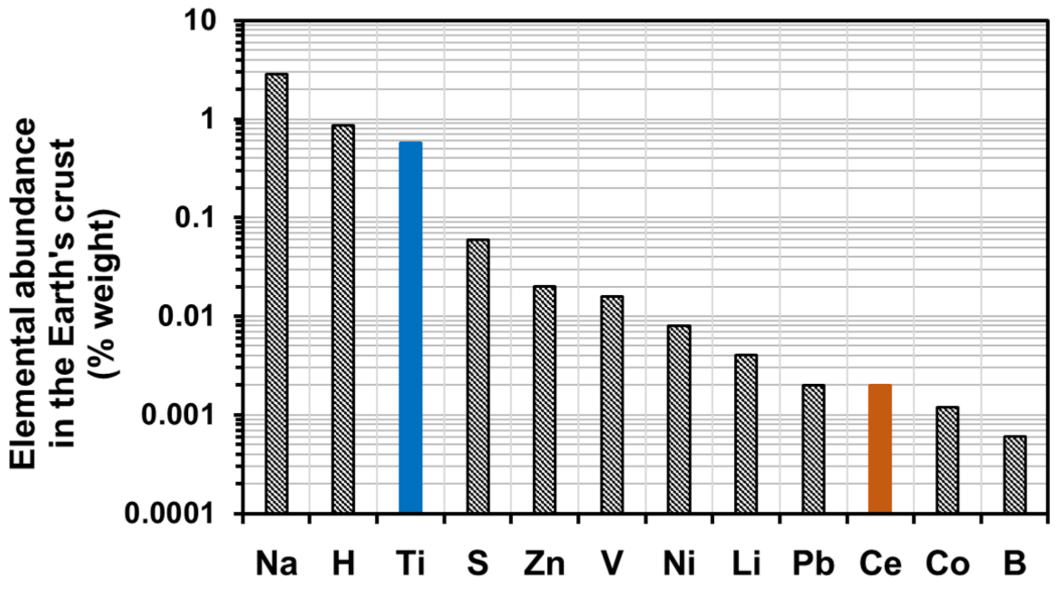
SHE: Standared Hydrogen Electrode

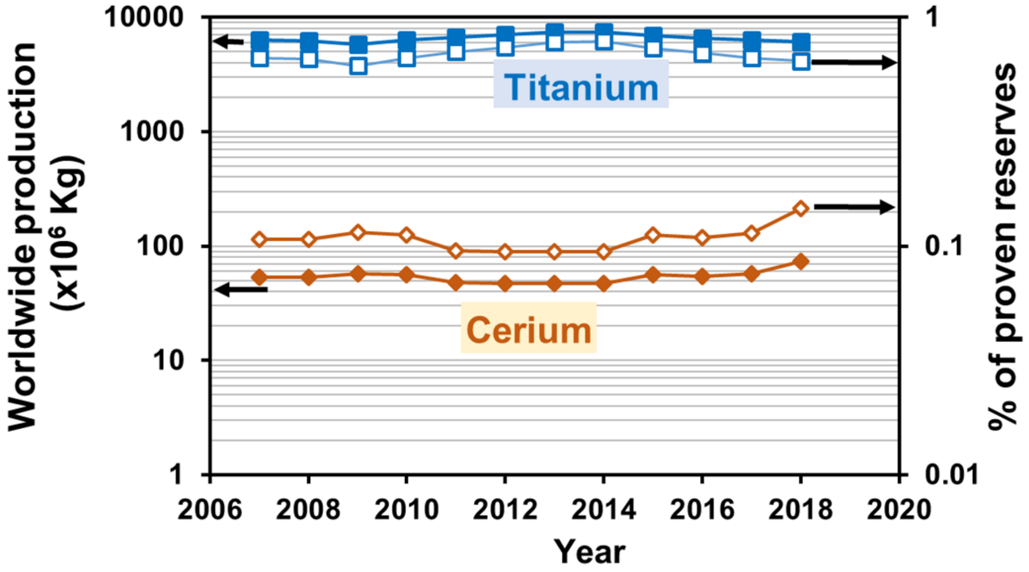
Advantages of Ti-Ce System

- ❑ Nominal Cell Voltage > 1V
- ❑ No phase change, solids precipitation
- ❑ Minimal potential for H_2 or O_2 evolution



Advantages of Ti-Ce System

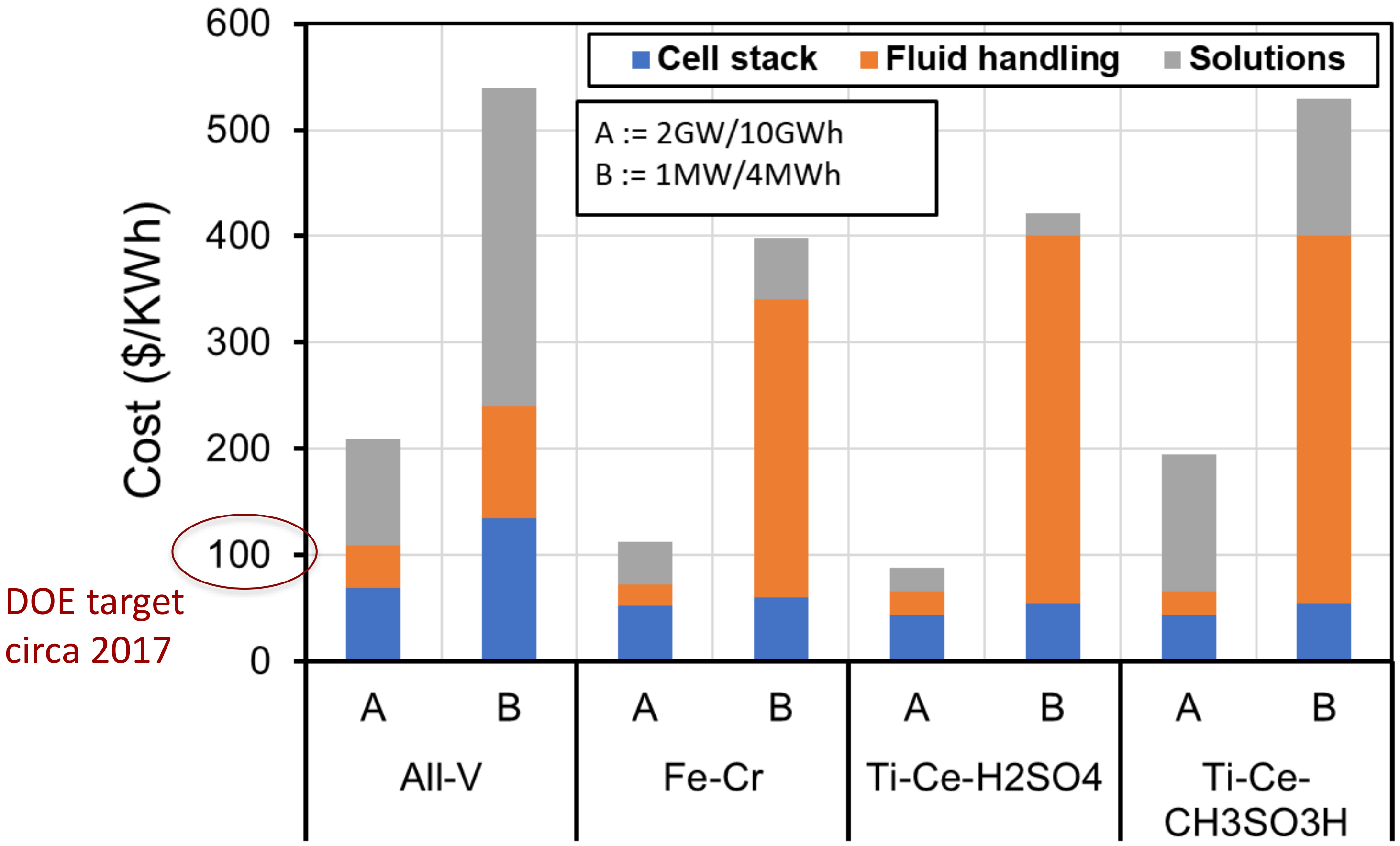




https://pubs.usgs.gov/fs/2002/fs087-02/

- ❑ Abundant active elements
- ❑ Lower material costs vs. All-V and V-Ce
- ❑ Proven reserves for >300x the total world electricity production (25,000 TWh/year)

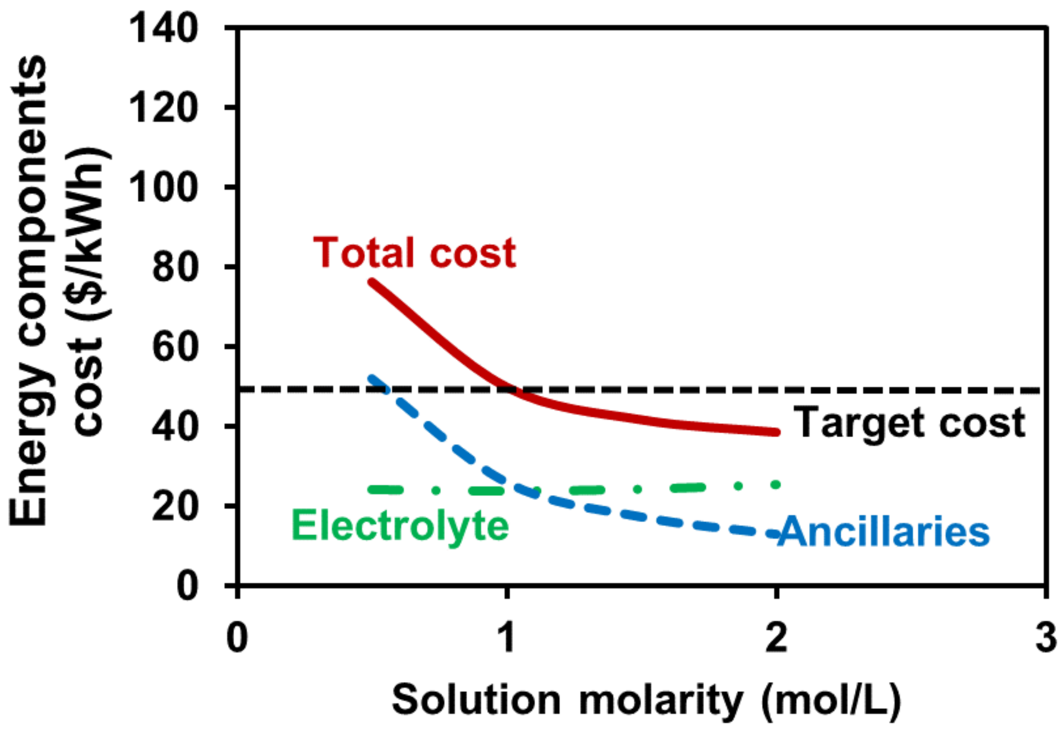
Scale-Up Cost Analysis

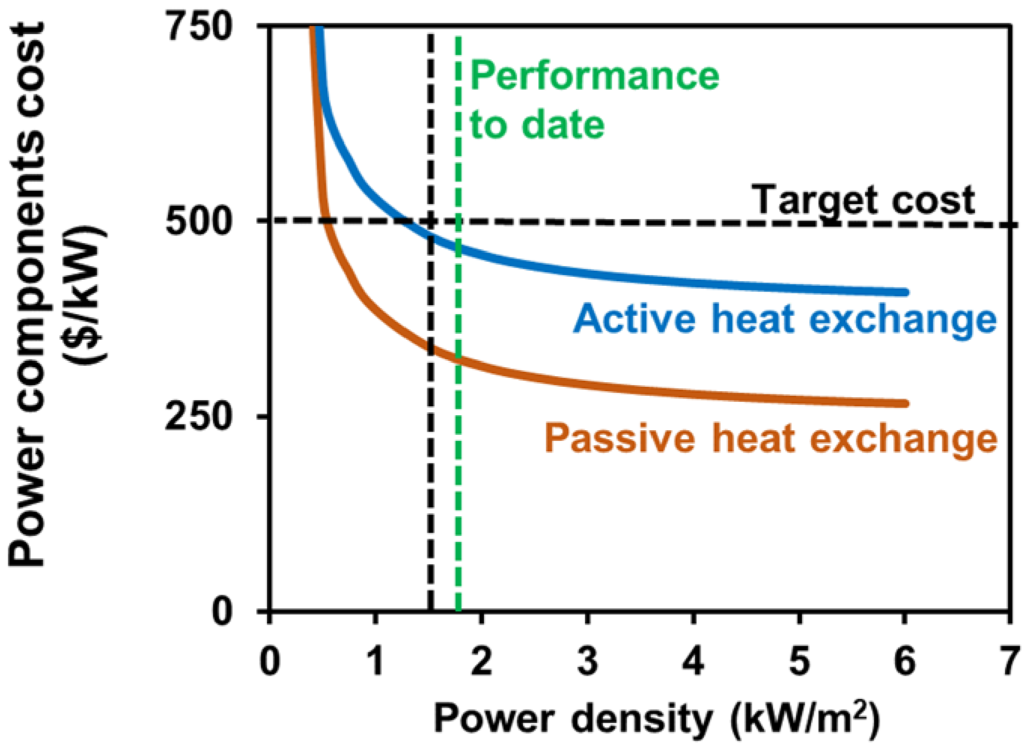


- Stacks costs are fairly static with scale.
- Solutions cost decrease in proportion to initial cost – economies of scale.
- Tankage and fluid handling are major factors at scale

The road to low cost, long-term energy storage in ED-RFB requires low cost, fairly dense (eg: 1.8g/cm^2 for H_2SO_4 vs. 1.16g/cm^2 for HCl) electrolytes

Scale-Up Cost Analysis





- Project target costs are $50/kWh for energy components and $500/kW for power components.

- Pathways exist for the Ti-Ce RFB to meet these targets.

Scale-Up Cost Analysis – present state

	1 MW/4 MWh System		10 MW/40 MWh System	
Estimate Year	2020	2030	2020	2030
DC system (with SB and container costs) ($/kWh)	$367	$299	$341	$278
PCS ($/kWh)	$22	$17	$17	$13
PCS markup ($/kW)	$2.2	$1.7	$2	$1
ESS equipment total ($/kWh)	**$391**	**$318**	**$360**	**$292**
Integrator margin ($/kWh)	$58	$48	$36	$29
Complete ESS equipment total ($/kWh)	**$449**	**$365**	**$396**	**$321**
EPC ($/kWh)	$101	$82	$79	$64
AC Installed Cost ($/kWh)	**$551**	**$447**	**$475**	**$386**

https://www.pnnl.gov/sites/default/files/media/file/RedoxFlow_Methodology.pdf

WUSTL Ti-Ce RFB cost estimates (supplier cost) – no optimizing assumptions

	1MW/4MWh	10MW/40MWh
DC system ($/kWh)	267	248
AC installed cost ($/kWh)	401	345

Our model matches DOE's all-V RFB model –

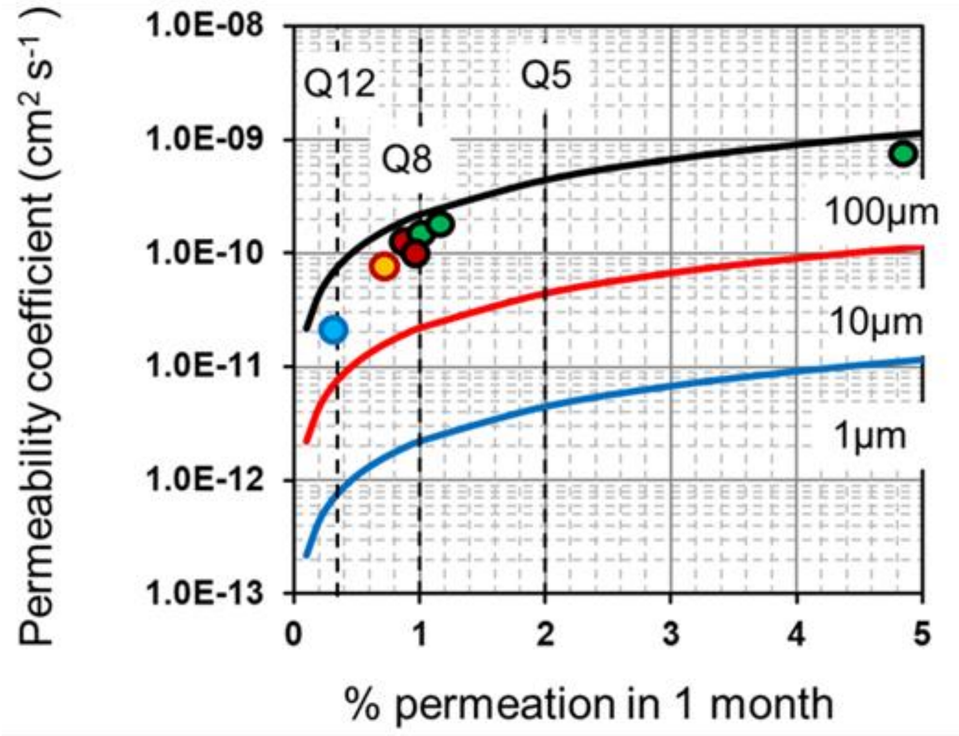
Power – 1MW; Duration – 4h; 1 molar electrolyte solution concentration; 100 mW/cm^2 power density.

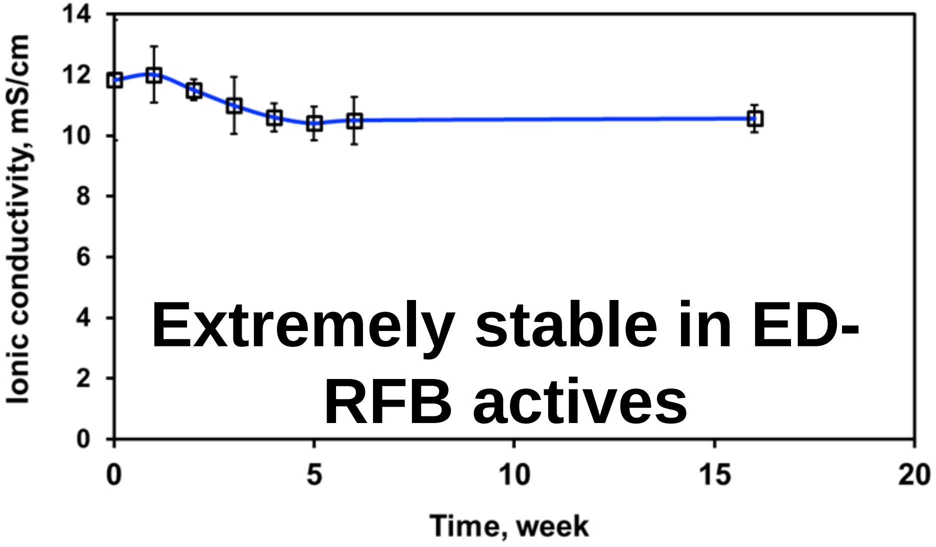
Same PCS, ESS and integrator margins assumed.

The unoptimized cost of the Ti-Ce RFB lower than the cost of all-V RFB systems today.

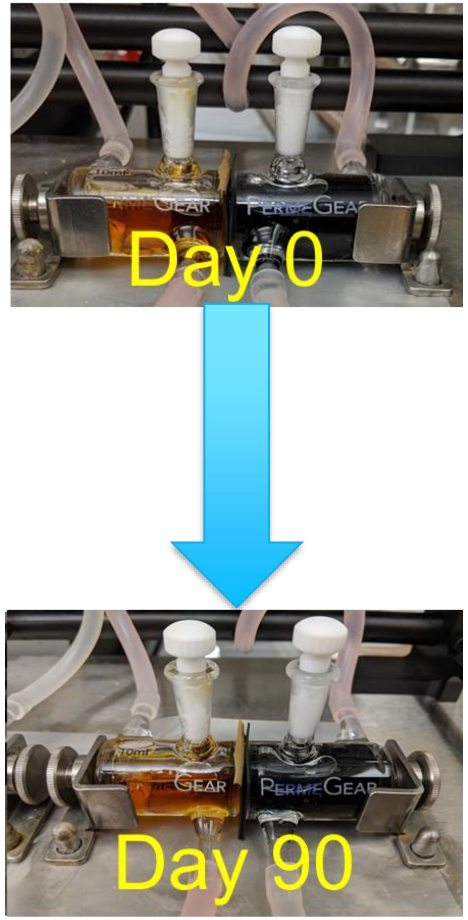
Anion Exchange Membrane (AEM)

- ❑ Key enabling technology
- ❑ Highly permselective to maintain separation of Ti and Ce species and prevent capacity fade





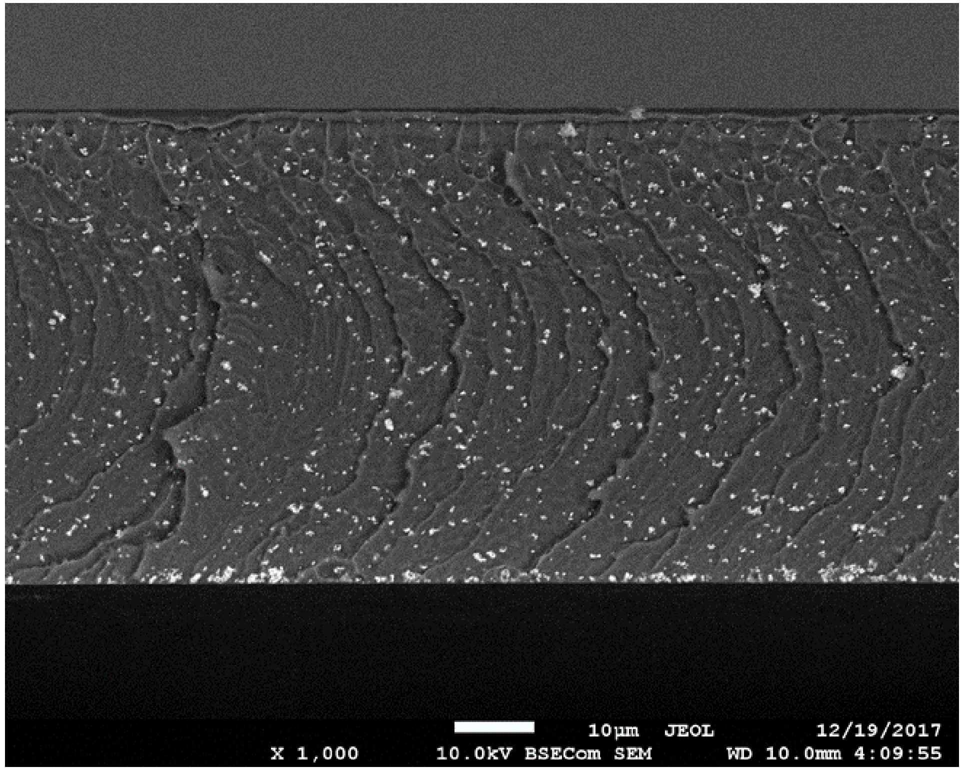
Highly selective



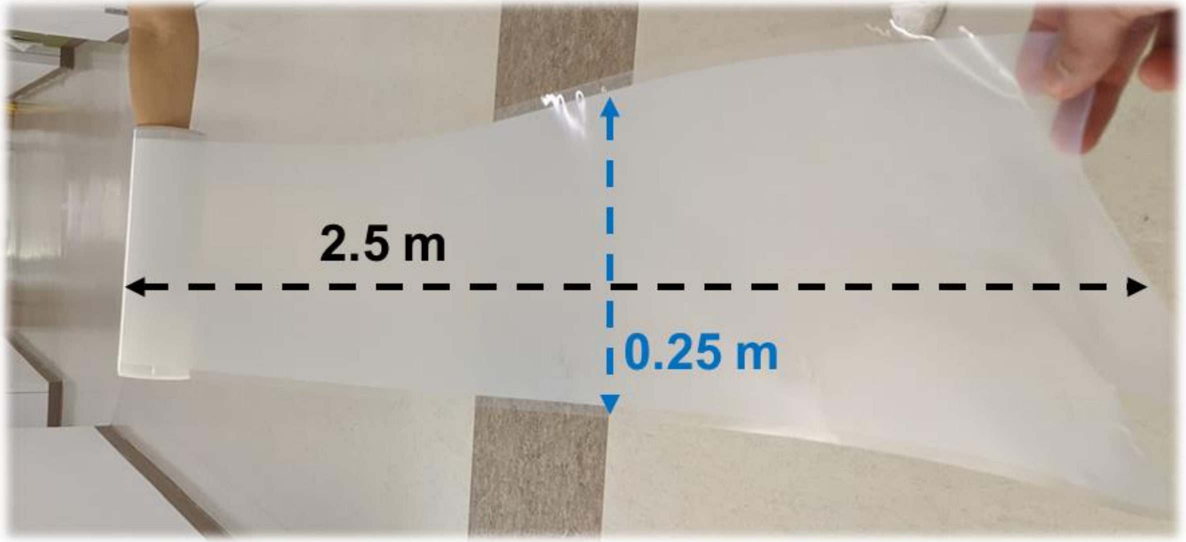
Developed under ARPA-E grant DE-AR0000768

Anion Exchange Membrane (AEM)

- ❑ Poly(ether ketone) doped with metal oxide nanoparticles to improve permselectivity



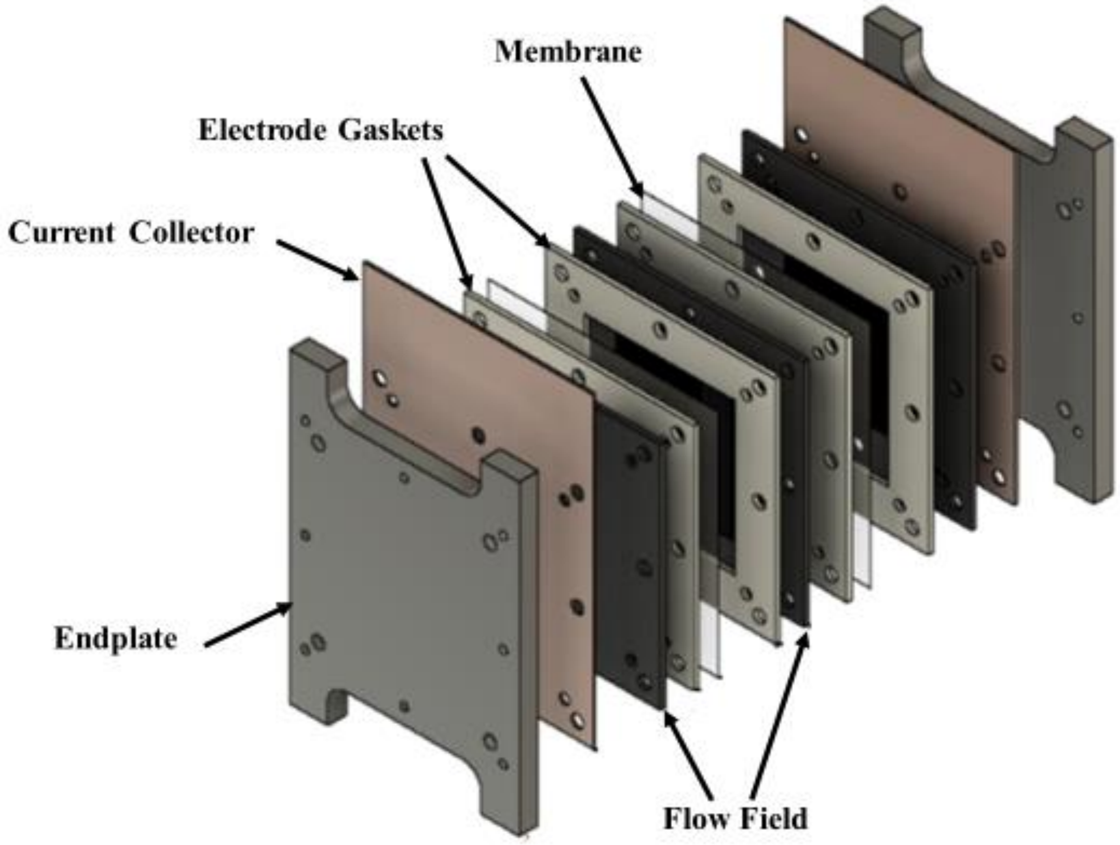
Made from 100cm^2 to roll-to-roll



Developed under ARPA-E grant DE-AR0000768

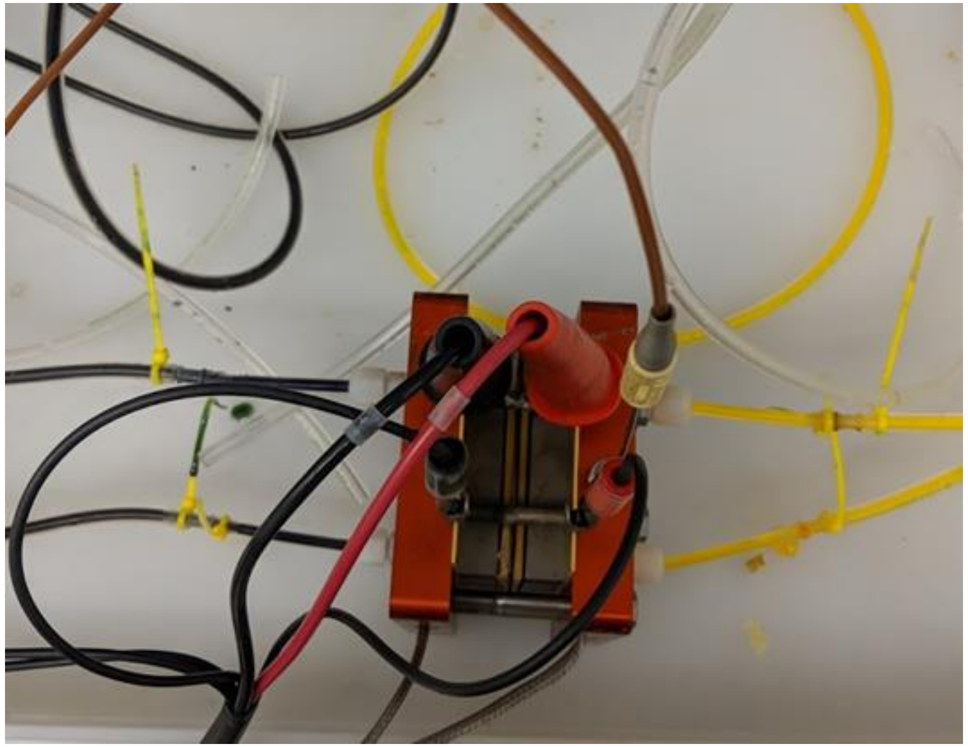
Task 2.0 – Component Testing, R&D

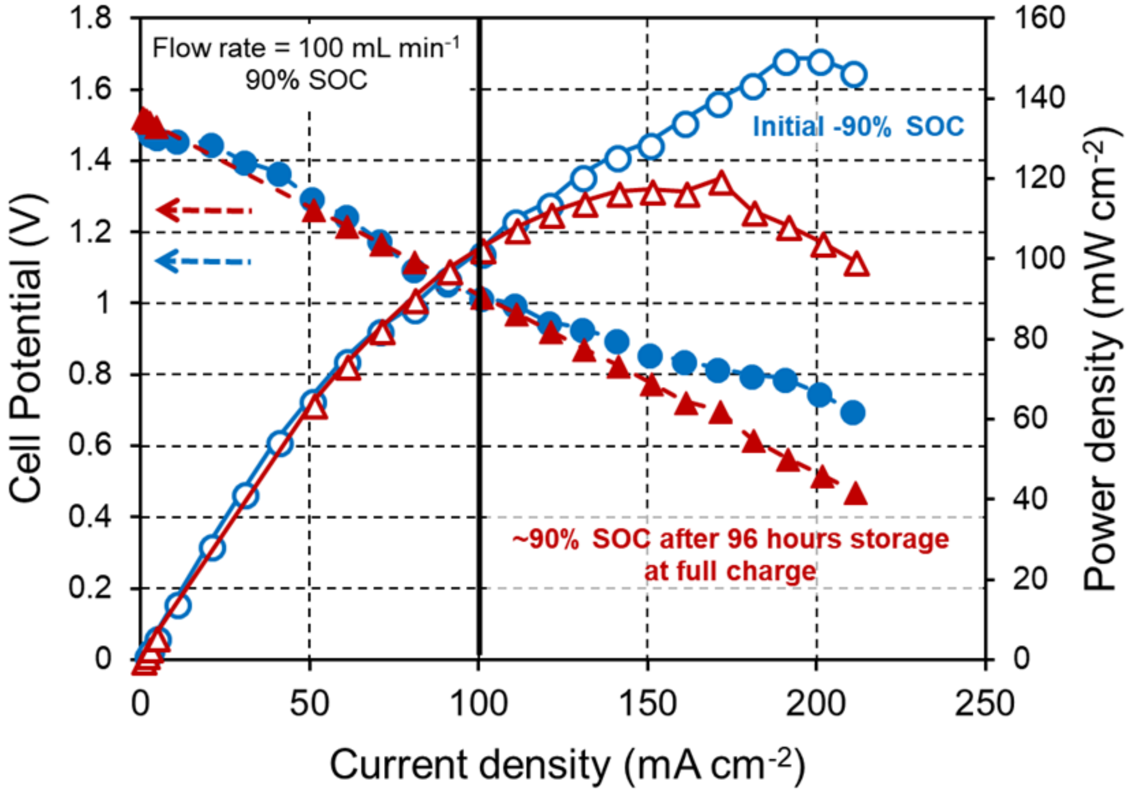
- **Test cell stack assembly**



Performance Test Results

Test Cell

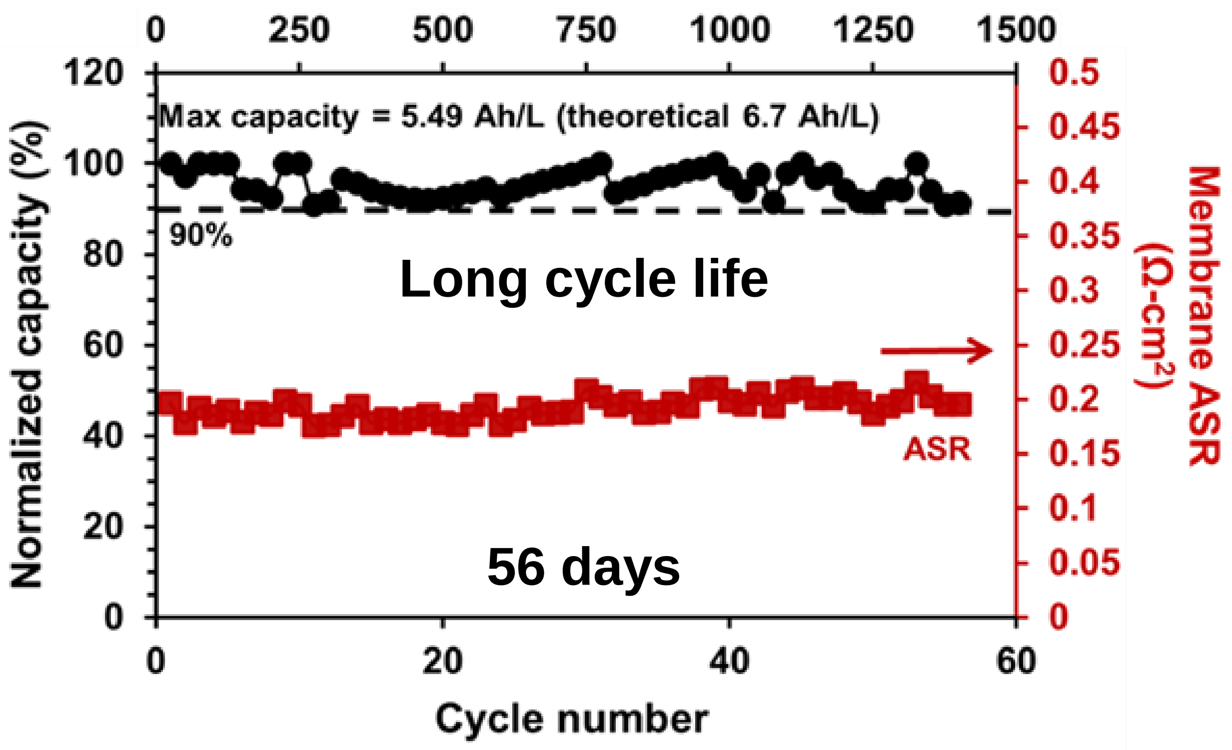


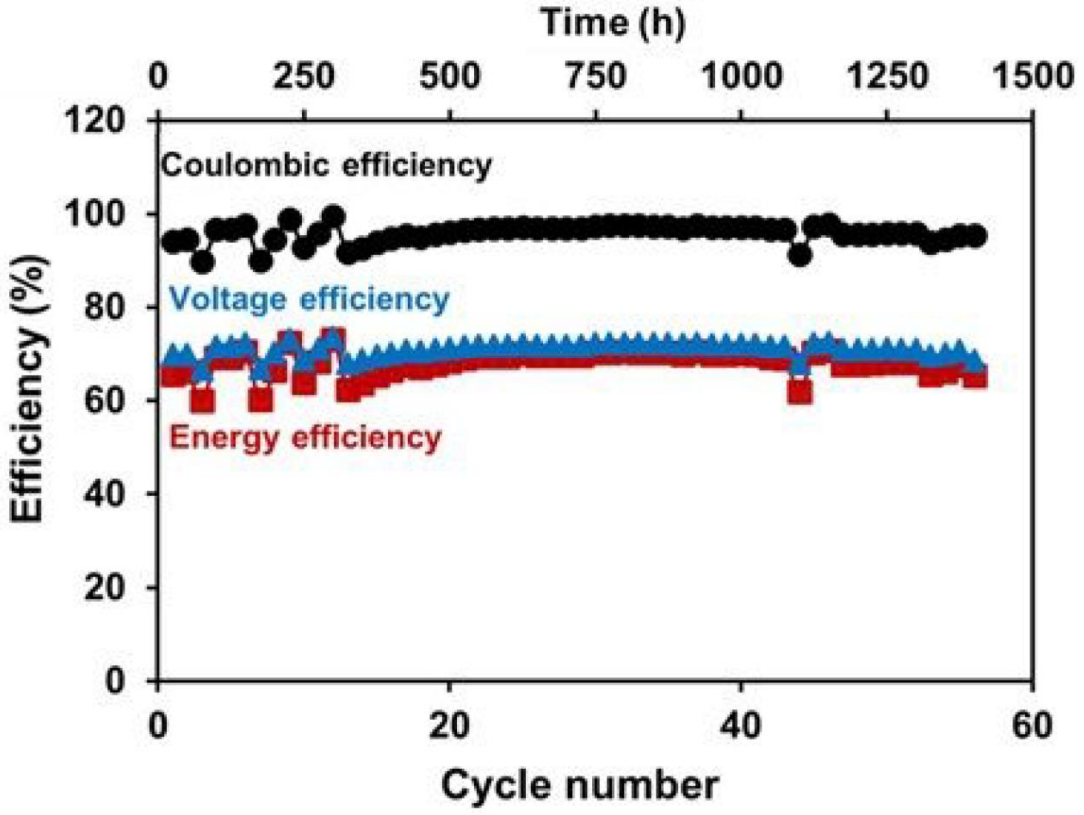


>3 day charge retention

Data obtained under ARPA-E grant DE-AR0000768

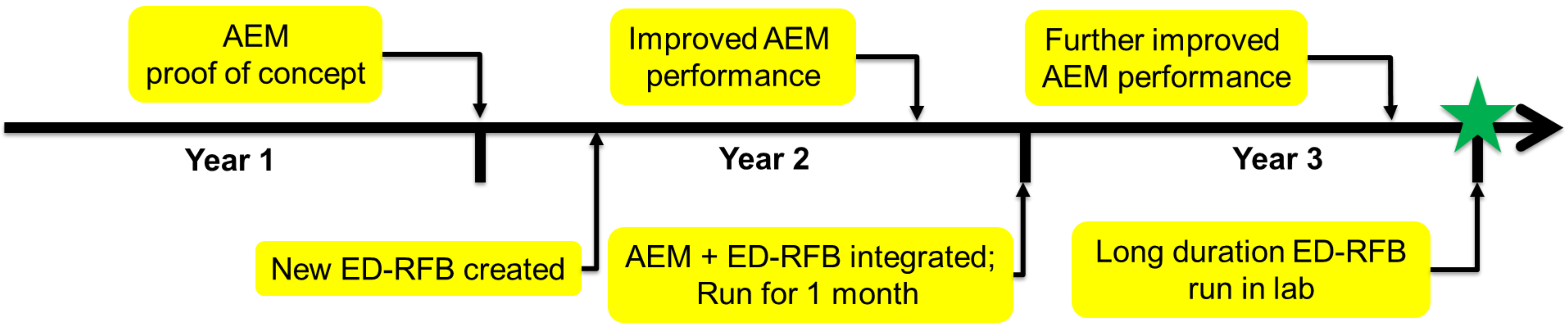
Cycle Performance Results



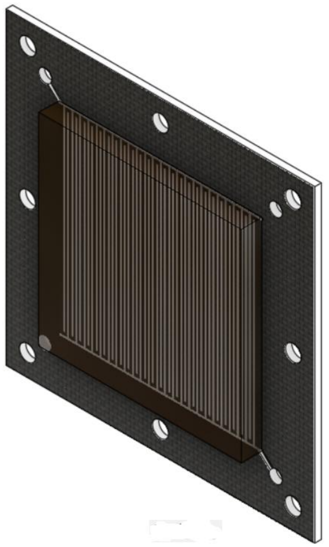


Summary of Prior/Ongoing R&D Activities

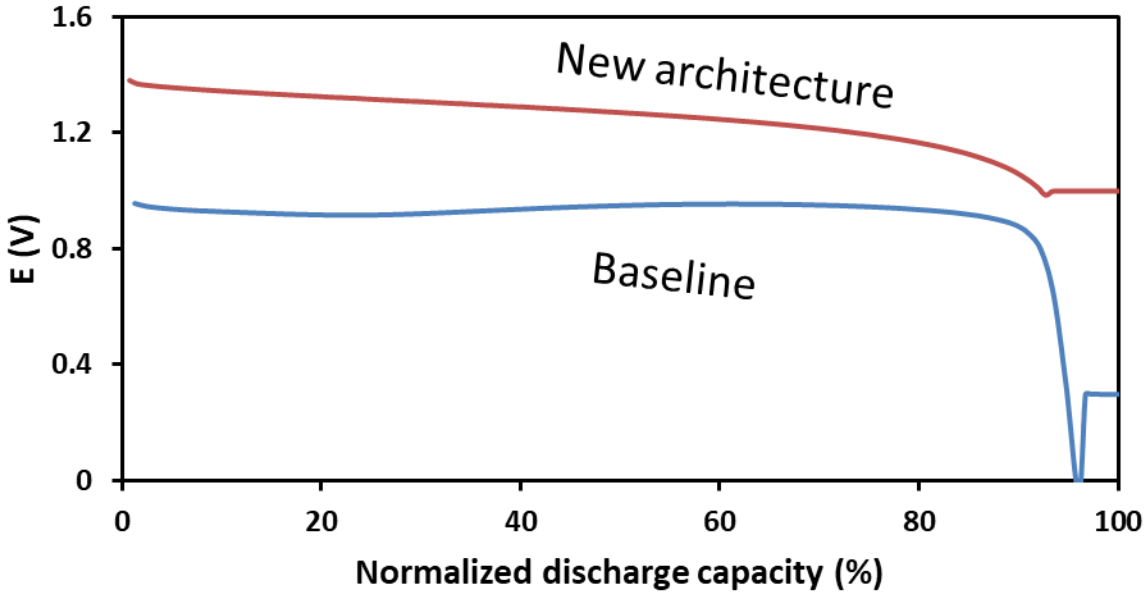
ARPA-E Ionics Program (DE-AR0000768)

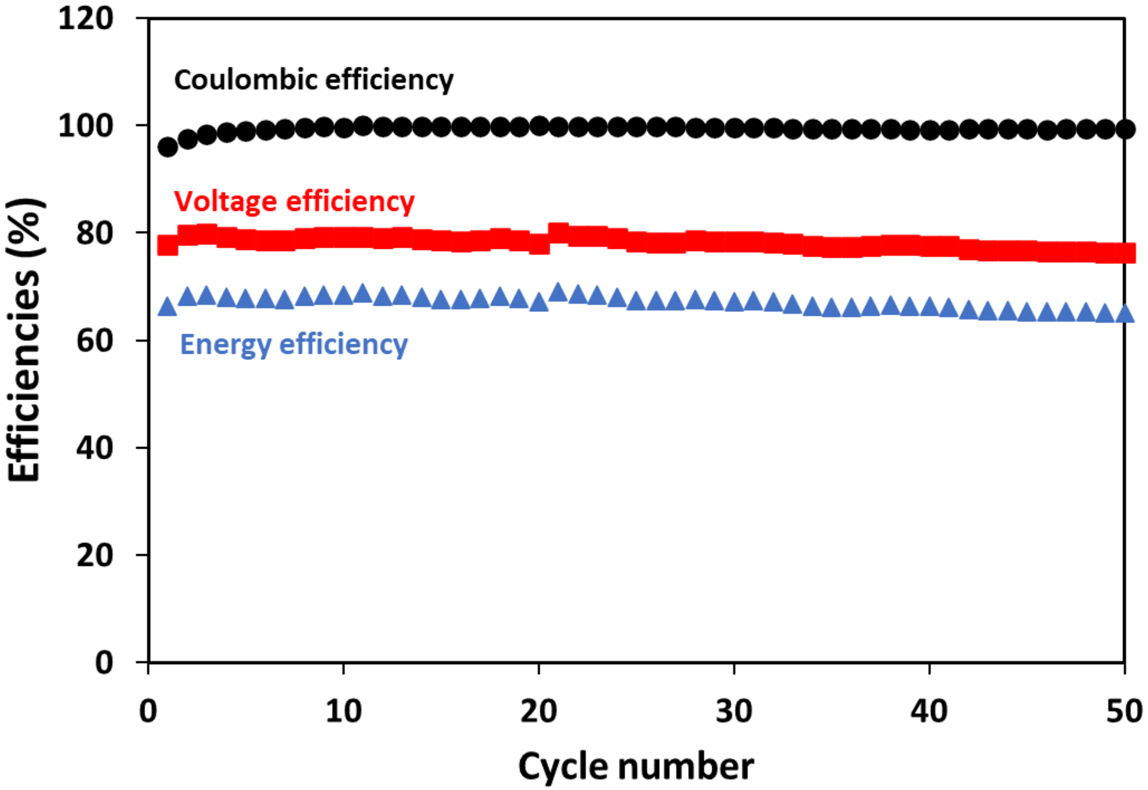


- ✓ AEM manufacturing and optimization
- ✓ Long duration performance testing (1300 hrs)
- ✓ Cost analysis
- ❑ Scale-up to 1.5 kWh
- ❑ Next generation electrolyte formulations
- ❑ Flow-field optimization



State-of–the art performance





- >50% increase in operating power density to 175 mW/cm^2 achieved without lowering the energy efficiency using a modified RFB architecture –
  - New electrode configuration used
  - New, economical electrode modification used

RFB Process Model Status

Inputs

Design Parameters:
- Parameters specific to stack configuration
- Parameter specific to electrolyte reservoirs
- Parameters specific to operating conditions

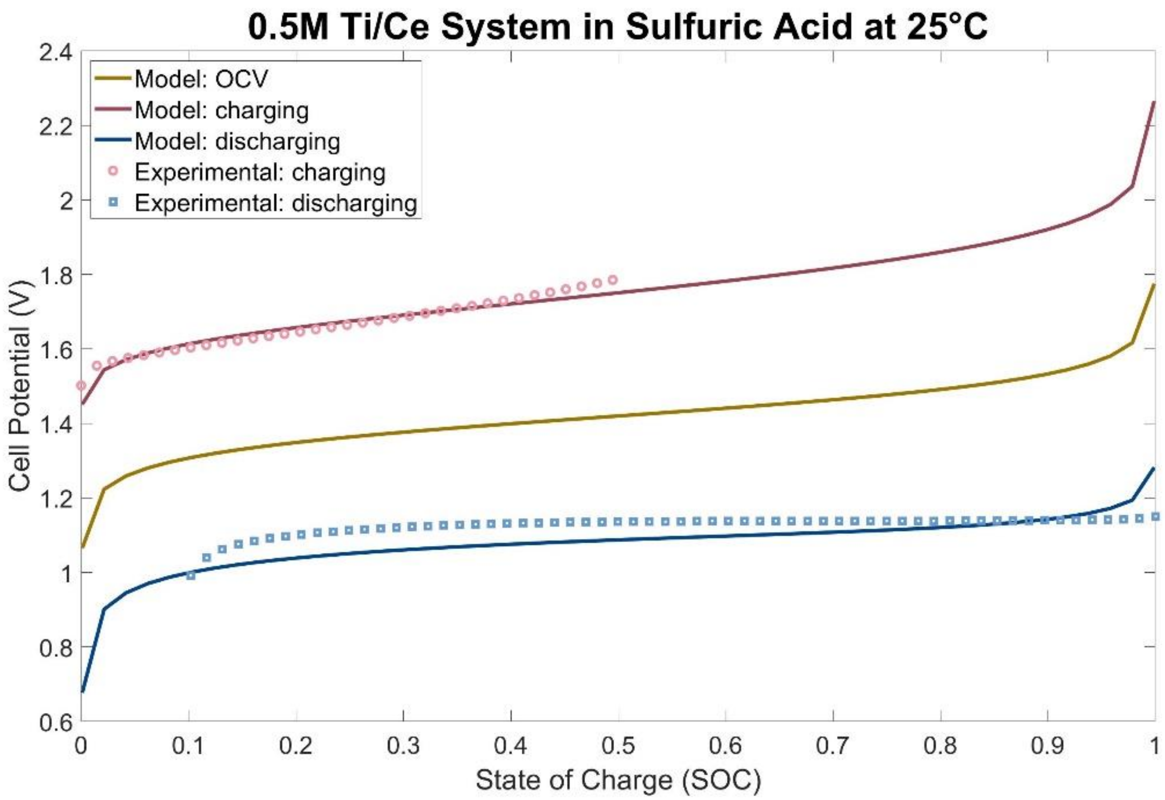
Material/Equipment Specifications:
- Parameters sourced from manufacturers
- Parameters sourced from literature
- Parameters measured experimentally

Model

- **Electrochemical model**
- Shunt current model
- Pumping loss model

Outputs

- **Cell potential vs. state of charge relation**
- Cell efficiency sensitivity to design parameters
- Flow channel cross-sectional area for minimal power losses



Thank You

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