Energy Storage Technology Advancement Partnership (ESTAP) Webinar:

Flow Batteries: New Efforts in R&D

March 23, 2016

Hosted by Todd Olinsky-Paul
ESTAP Project Director
Clean Energy States Alliance

Housekeeping

All participants are in “Listen-Only” mode. Select “Use Mic & Speakers” to avoid toll charges and use your computer’s VOIP capabilities. Or select “Use Telephone” and enter your PIN onto your phone key pad.

Submit your questions at any time by typing in the Question Box and hitting Send.

This webinar is being recorded.

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www.cesa.org/webinars

State & Federal Energy Storage Technology Advancement Partnership (ESTAP)

Todd Olinsky-Paul

Project Director

Clean Energy States Alliance (CESA)

Thank You:

Dr. Imre Gyuk
U.S. Department of Energy,
Office of Electricity Delivery and
Energy Reliability

Dan Borneo
Sandia National Laboratories

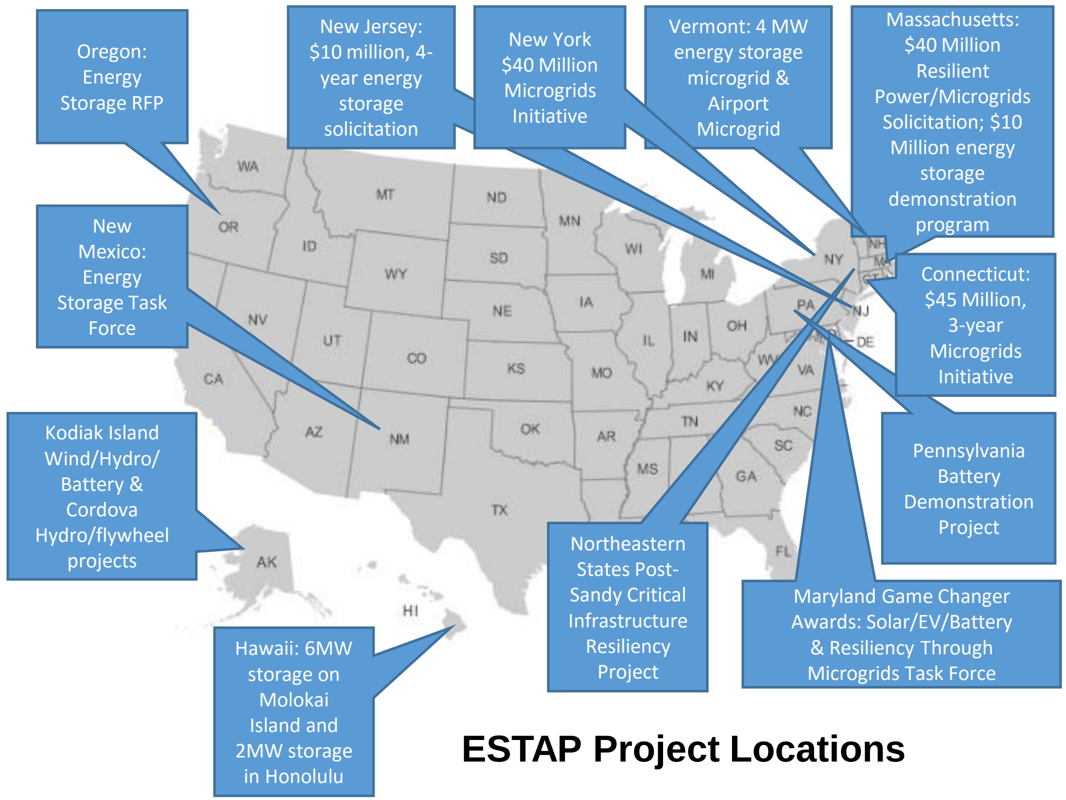
ESTAP is a project of CESA

Clean Energy States Alliance (CESA) is a non-profit organization providing a forum for states to work together to implement effective clean energy policies & programs:

State & Federal Energy Storage Technology Advancement Partnership (ESTAP) is conducted under contract with Sandia National Laboratories, with funding from US DOE.

ESTAP Key Activities:

1. Disseminate information to stakeholders
   - ESTAP listserv >3,000 members
   - Webinars, conferences, information updates, surveys.
2. Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment
3. Support state energy storage efforts with technical, policy and program assistance



ESTAP Project Locations

CleanEnergy States Alliance | Sandia National Laboratories | U.S. DEPARTMENT OF ENERGY

Energy Storage Technology Advancement Partnership

Overview
ESTAP Resource Library
ESTAP Webinars
ESTAP News
ESTAP Listserv Signup

ESTAP

Project Director: Todd Olinsky-Paul

Contact: Todd Olinsky-Paul, Todd@cleanegroup.org

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The Energy Storage Technology Advancement Partnership (ESTAP) is a federal-state funding and information sharing project, managed by CESA, that aims to accelerate the deployment of electrical energy storage technologies in the U.S.

The project's objective is to accelerate the pace of deployment of energy storage technologies in the United States through the creation of technical assistance and co-funding partnerships between states and the U.S. Department of Energy.

ESTAP conducts two key activities:

1) Disseminate information to stakeholders through:

- The ESTAP listserv (>2,000 members)
- Webinars, conferences, information updates

NEW RESOURCES

October 14, 2015
Resilience for Free: How Solar+Storage Could Protect Multifamily Affordable Housing from Power Outages at Little or No Net Cost
By Clean Energy Group

September 30, 2015
Webinar Slides: Energy Storage Market Updates, 9.30.15

UPCOMING EVENTS

December 16, 2015
ESTAP Webinar: State of the U.S. Energy Storage Industry,

More Events

LATEST NEWS

November 30, 2015
Massachusetts Takes the Lead on Resilient

Today's Guest Speaker

- **Dr. Wei Wang**, Senior Scientist, Pacific Northwest National Laboratory (PNNL)

Pacific Northwest
NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

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Next Generation Redox Flow Battery Development at PNNL

Wei Wang, Vincent Sprenkle, David Reed, Ed Thomsen, Zimin Nie, Bin Li, Xiaoliang Wei, Brian Koeppel, Baowei Chen, Alasdair Crawford, Vish Viswanathan, Patrick Balducci.

Pacific Northwest National Laboratory

Support from DOE Office of Electricity Delivery & Energy Reliability
Energy Storage Program

Flow Batteries: New Efforts in R&D Webinar
March 23rd, 2016

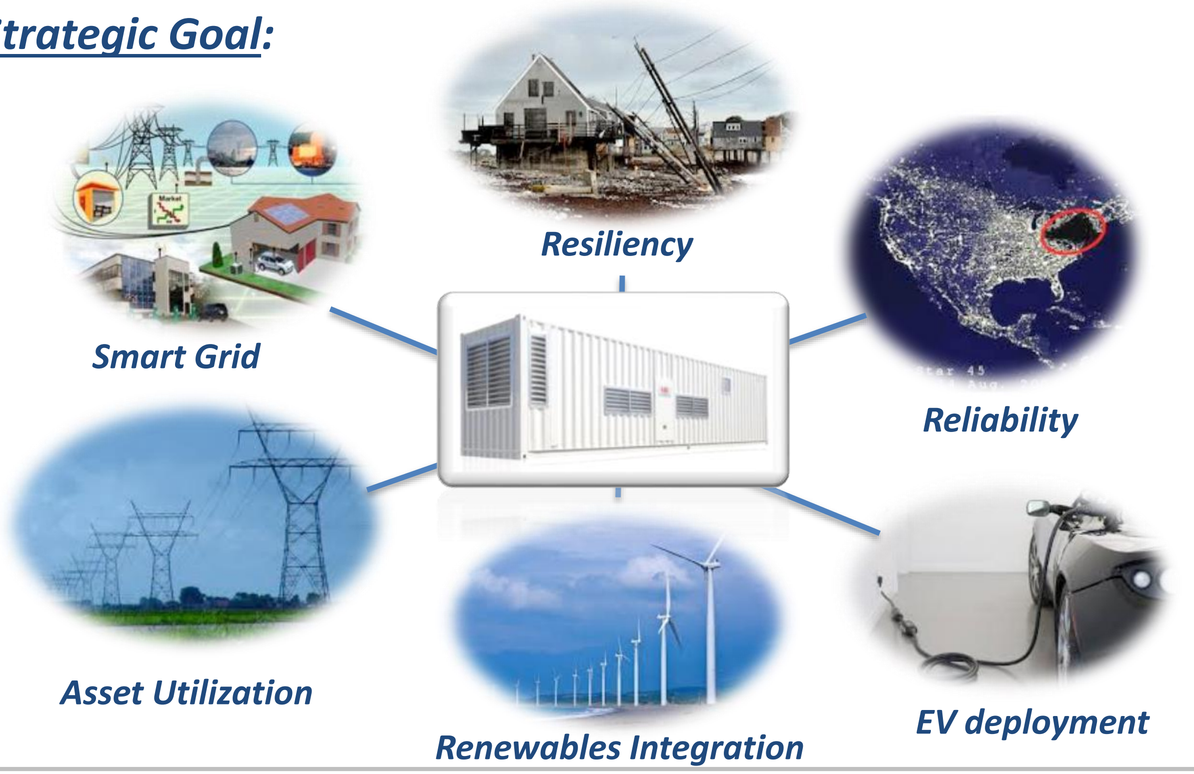
DOE OE Energy Storage Program

Challenges:

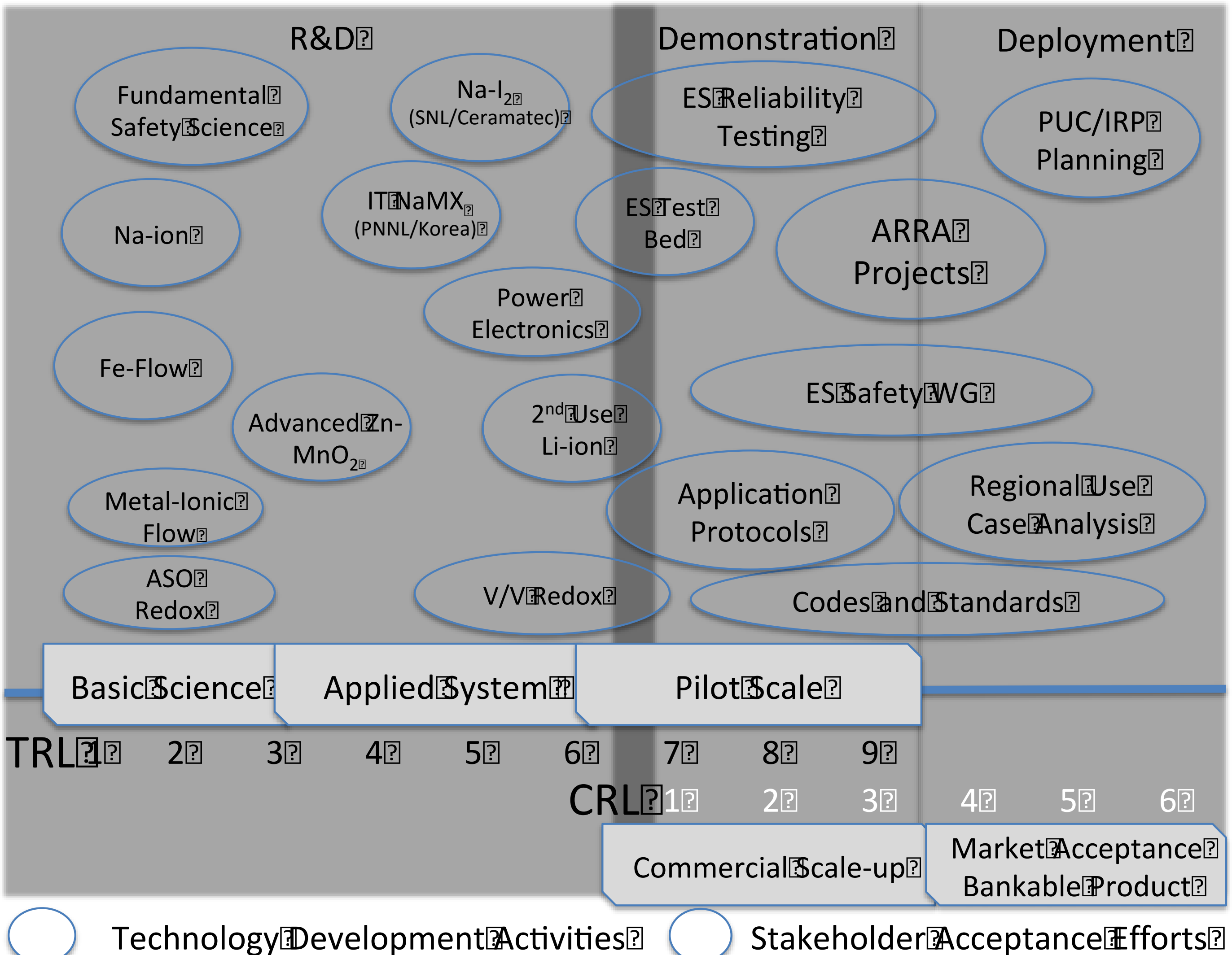
- **Cost competitive energy storage technologies**
  - Targeted scientific investigations of key materials and systems
- **Validated reliability & safety**
  - Independent testing of prototypic devices and understanding of degradation.
- **Equitable regulatory environment**
  - Enable Industry, Utility, Developer collaborations to quantify benefits provide input to regulators.
- **Industry acceptance**
  - Highly leverage field demonstrations and development of storage system design tools

Mission: To enable energy storage to provide multiple benefits for critical grid applications, DOE is accelerating adoption of energy storage through: improving the technology, field demonstrations, and innovative market design.

Strategic Goal:



OE Energy Storage Program Activities



Coordinated effort between Sandia National Laboratory, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory.

PNNL Stationary Energy Storage Development Approach

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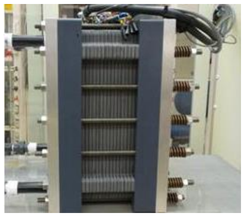
Competitive Technologies

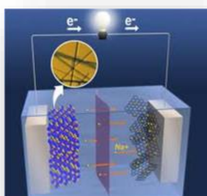
Mixed Acid VRB



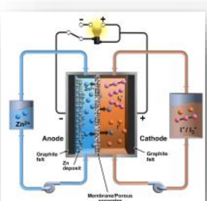
Na Metal Halide

Organic RFBs

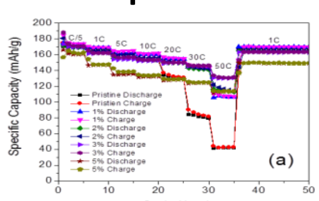
Na-ion

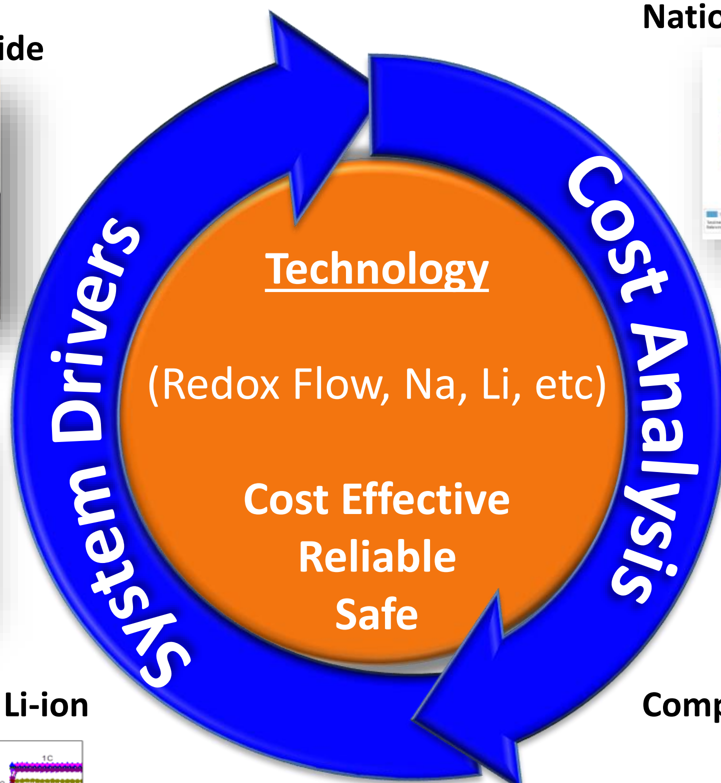


Zn-I RFB



Fast Response Li-ion

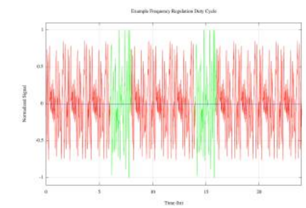




Market Acceptance

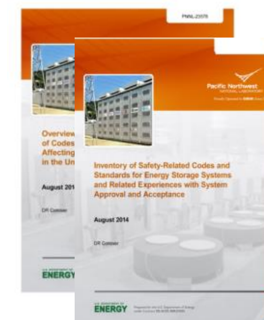
National Assessment

Performance Protocols

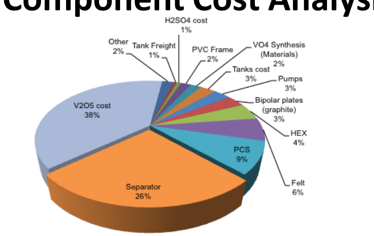


Bainbridge PSE Case

Safety Standards



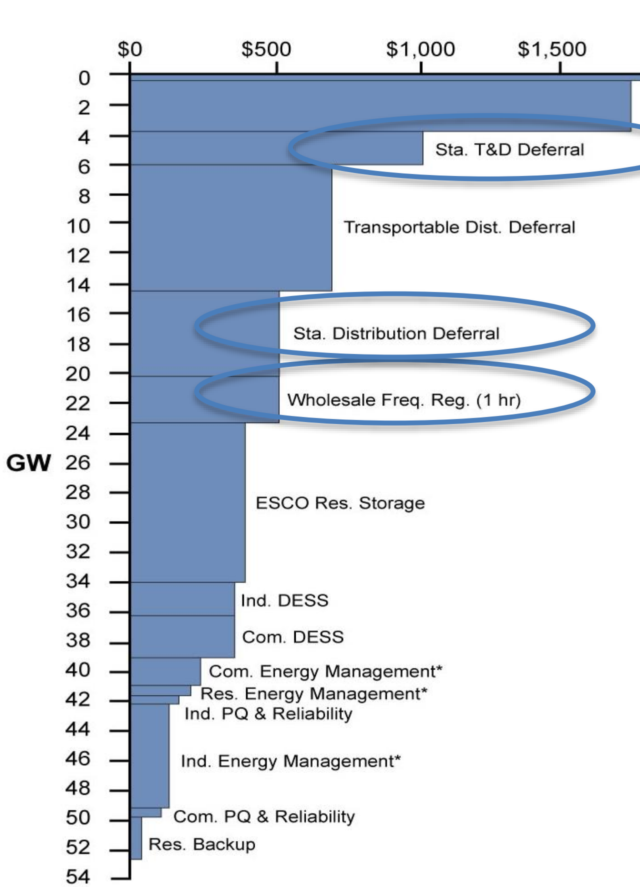
Component Cost Analysis



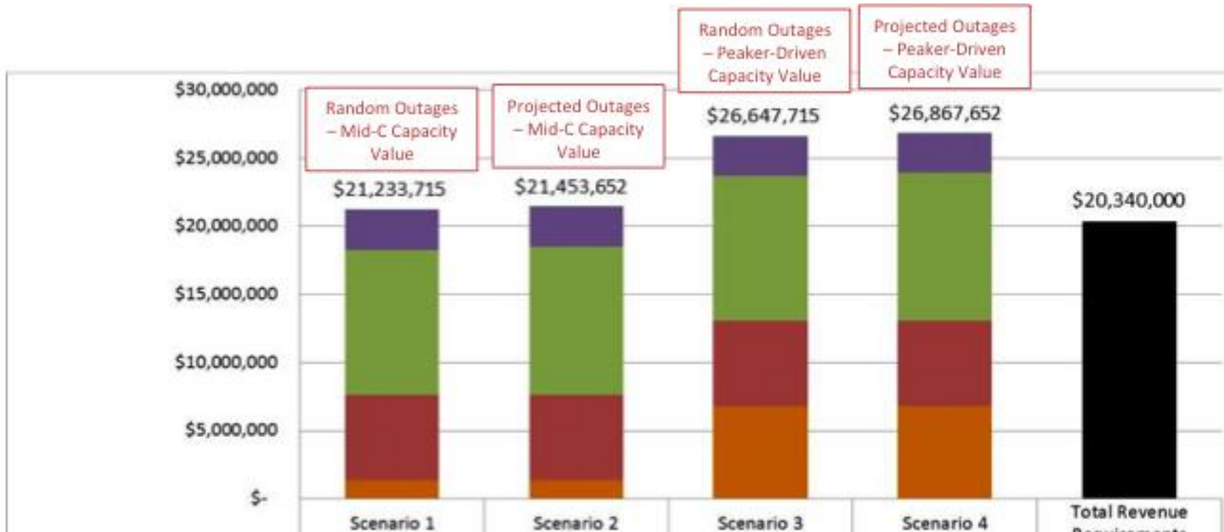
WA CEF

Developing deployable technologies to meet the cost/benefit requirements of the Grid.

Grid Energy Storage Diverse Markets Encourage Bundling and Cost Reduction.



EPRI – Electric Energy Storage Technology Options: A Primer on Applications, Costs & Benefits (2010)

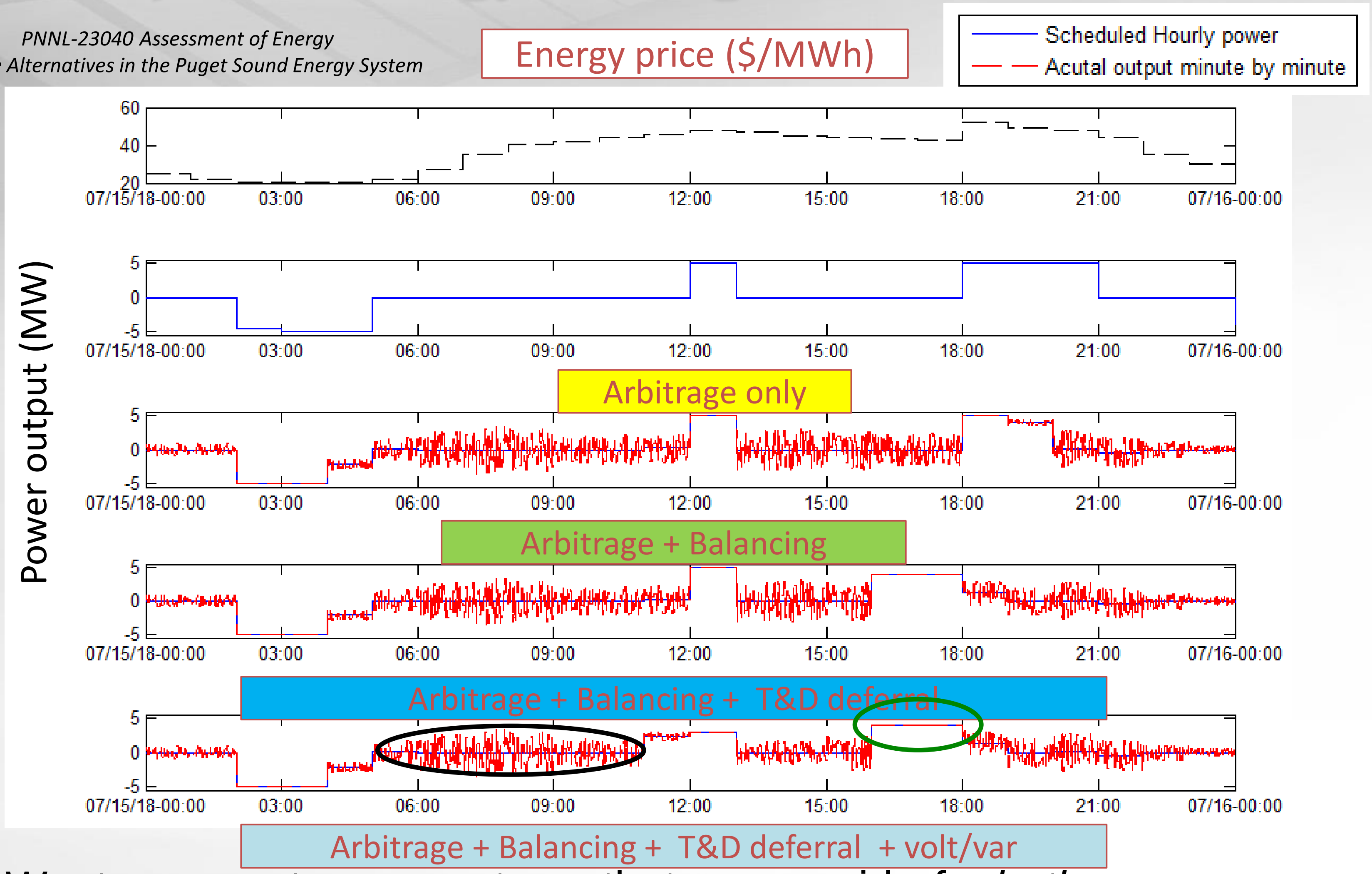


	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Total Revenue Requirements
Revenue Requirements					$20,340,000
Arbitrage and Energy Costs	$53,299	$40,833	$53,299	$40,833	
Balancing Services	$2,899,171	$2,898,352	$2,899,171	$2,898,352	
Outage Mitigation	$10,656,246	$10,889,467	$10,656,246	$10,889,467	
Distribution Upgrade Deferral	$6,252,000	$6,252,000	$6,252,000	$6,252,000	
Capacity Value	$1,373,000	$1,373,000	$6,787,000	$6,787,000	

PNNL-23040 Assessment of Energy Storage Alternatives in the Puget Sound Energy System

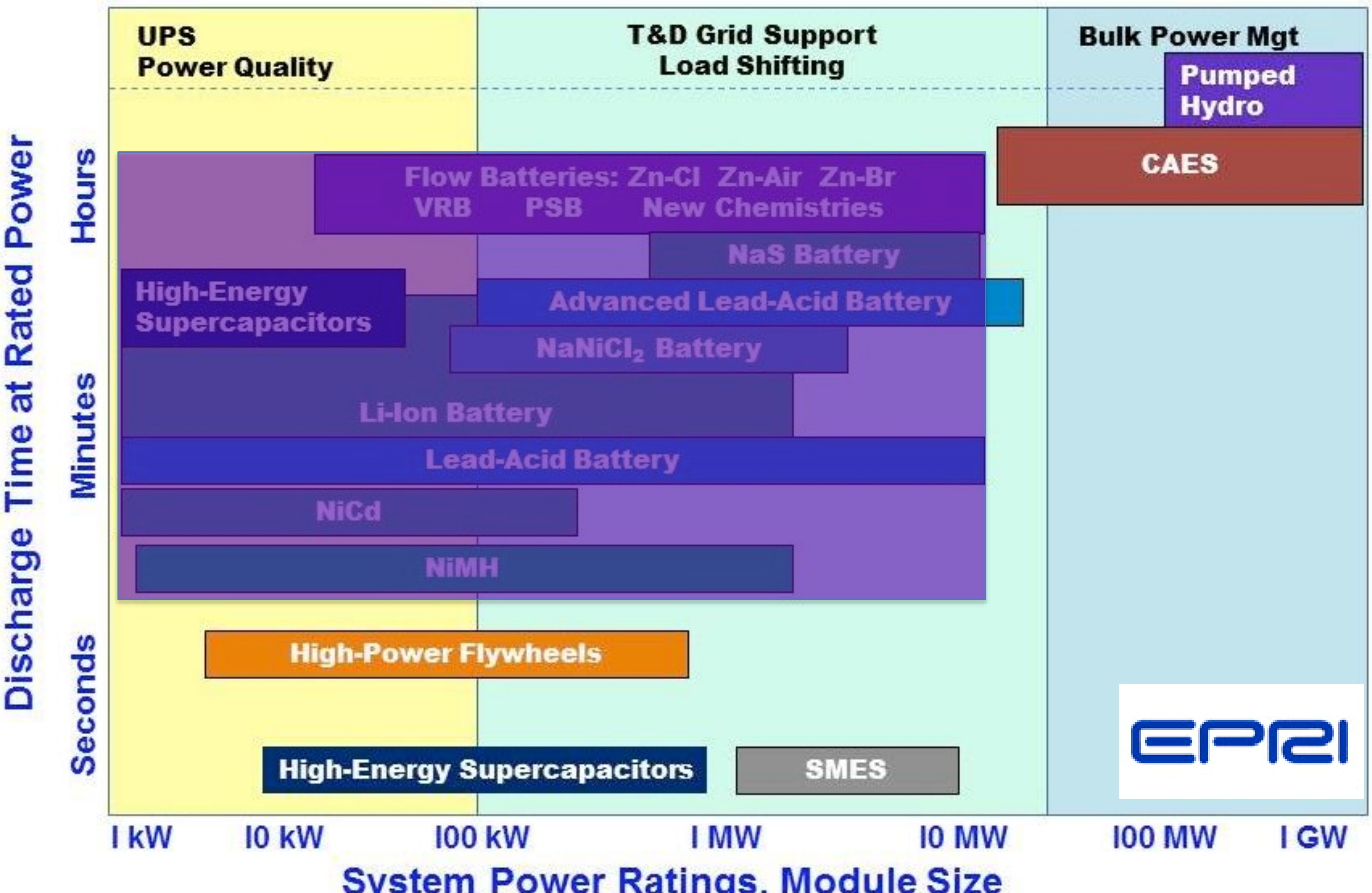
Bundled Services: High degree of flexibility needed from energy storage?

PNNL-23040 Assessment of Energy Storage Alternatives in the Puget Sound Energy System



- Want energy storage systems that can provide *for both*:
  - Fast response balancing services *and*
  - Longer duration (2^{+} hr) deferral and outage mitigation.

Electrical energy storage (EES) Options



EPRI - Electricity Energy Storage Technology Options 1020676

Why Redox Flow Battery?

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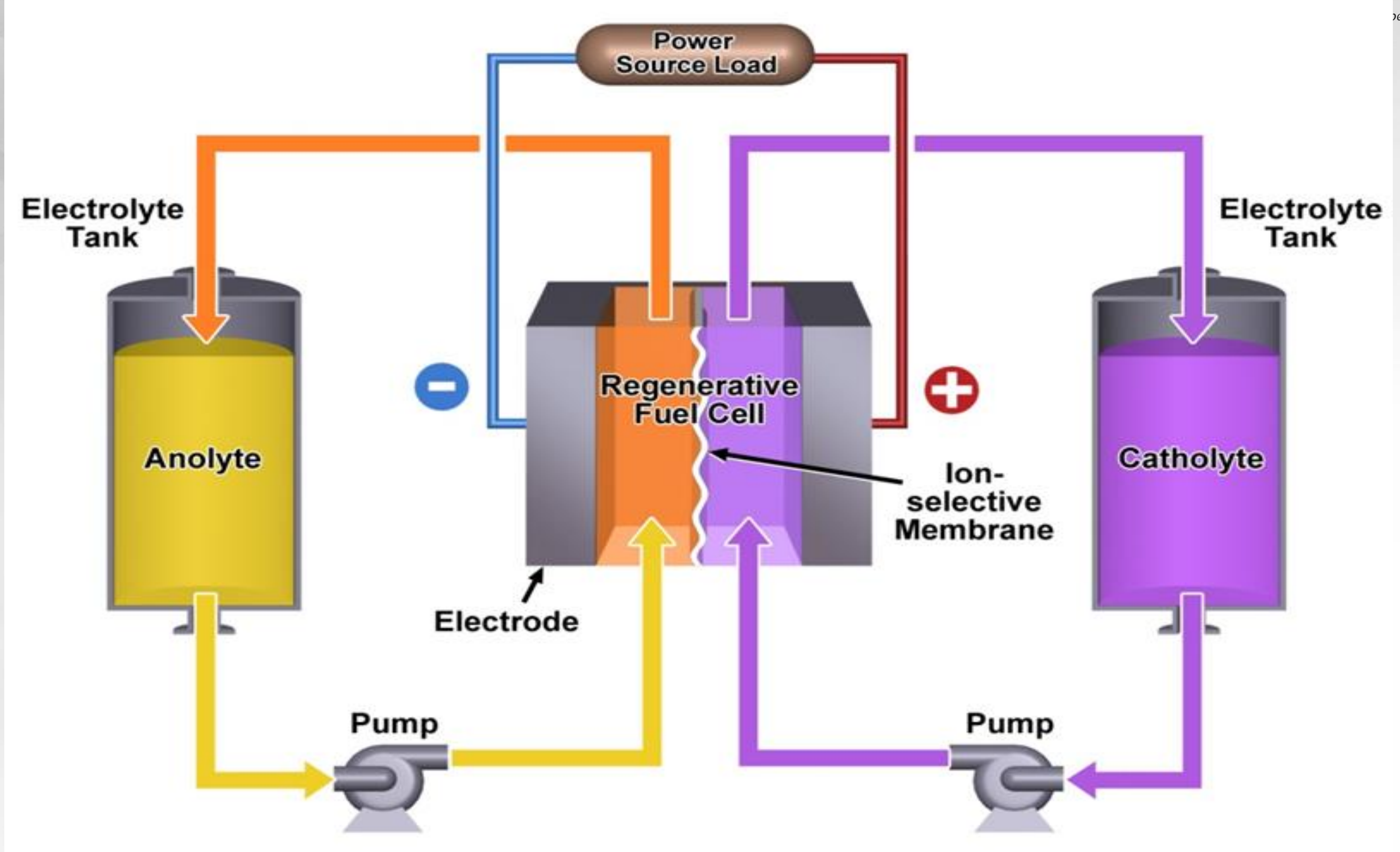

Key Aspects

- ***Power and Energy are separate enabling greater flexibility and safety.***
- ***High safety***
- Suitable for wide range of applications 10's MW to ~ 5 kw
- Wide range of chemistries available.
- Low energy density ~ 30 Whr/kg

Existing redox systems, advantages/issues

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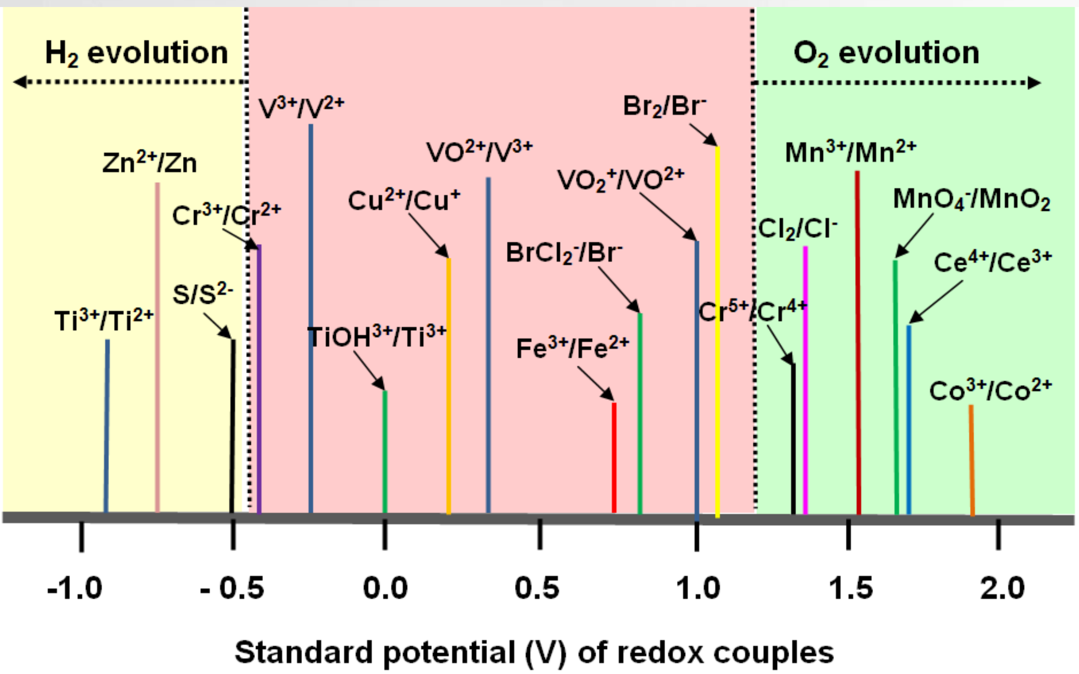
- ICB: Fe^{3+}/Fe^{2+} vs. Cr^{3+}/ Cr^{2+}
- VRB: V^{2+}/V^{3+} vs. VO_2^{+}/VO^{2+}
- PSB: Br^{2}/Br^{-} vs. S/S^{2-}
- ZBB: Br^{-}/Br^{2-} vs. Zn^{2+}/Zn

Multi-100 kW or MW demonstrated

Others:
V^{2+}/V^{3+} vs. $Br^{-}/ClBr_2^{-}$;
Ce^{4+}/Ce^{3+} vs. V^{2+}/V^{3+};
Fe^{3+}/Fe^{2+} vs. Br_2/Br^{-};
Mn^{2+}/Mn^{3+} vs. Br_2/Br^{-};
Fe^{3+}/Fe^{2+} vs. Ti^{2+}/Ti^{4+}, …



- Temperature stability
- SoC control
- Toxicity of Elements
- **Minimal Fire Hazard**
- **High Degree of Flexibility**

Challenge of traditional sulfuric-acid vanadium electrolyte

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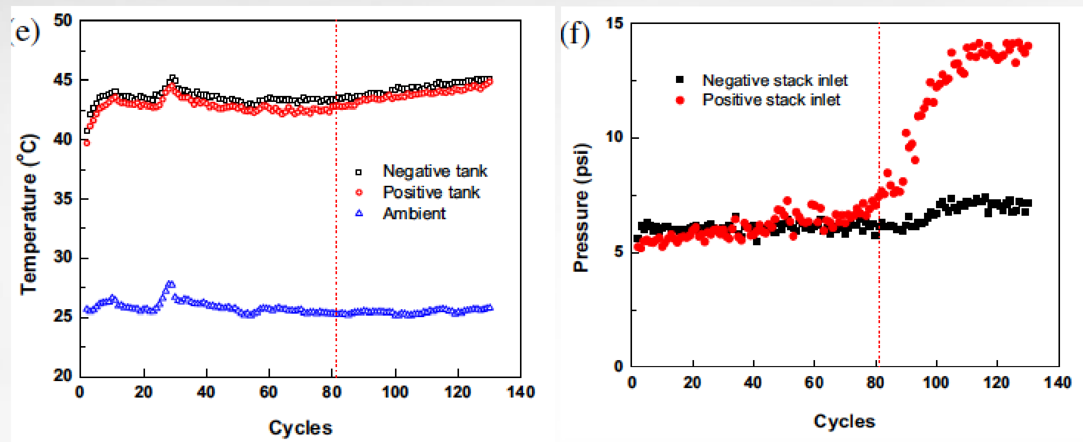
Problem of tradition VRB electrolyte

V concentration<1.5M

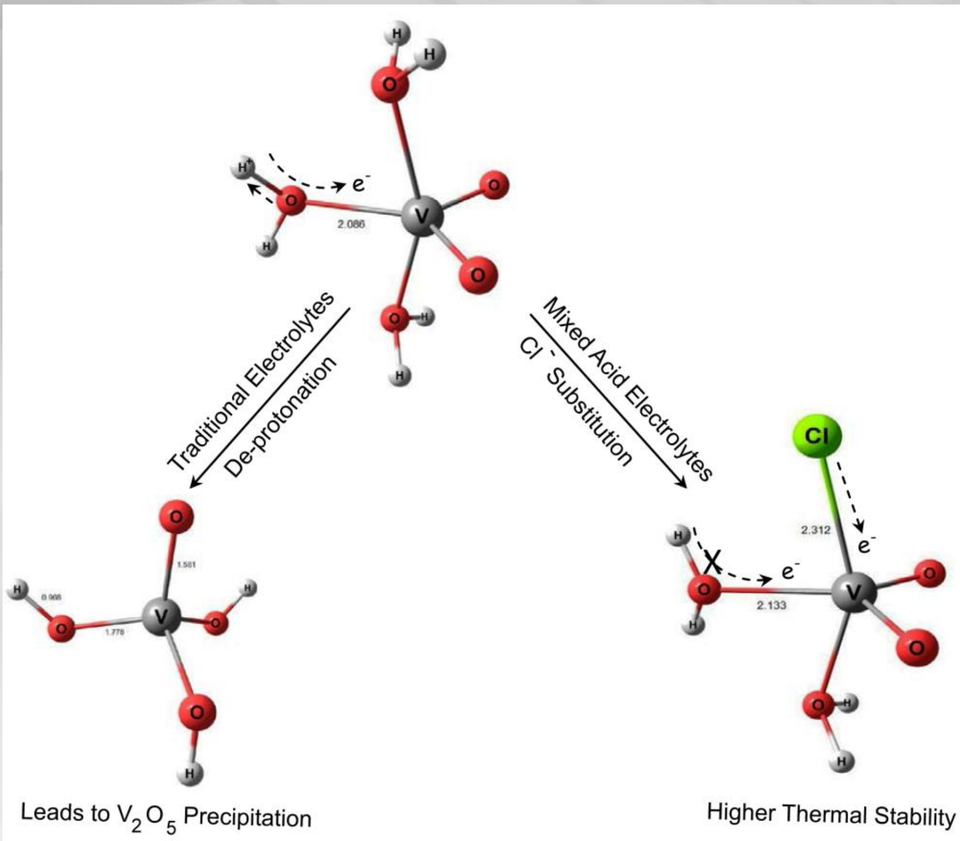
Temperature window 10~40°C

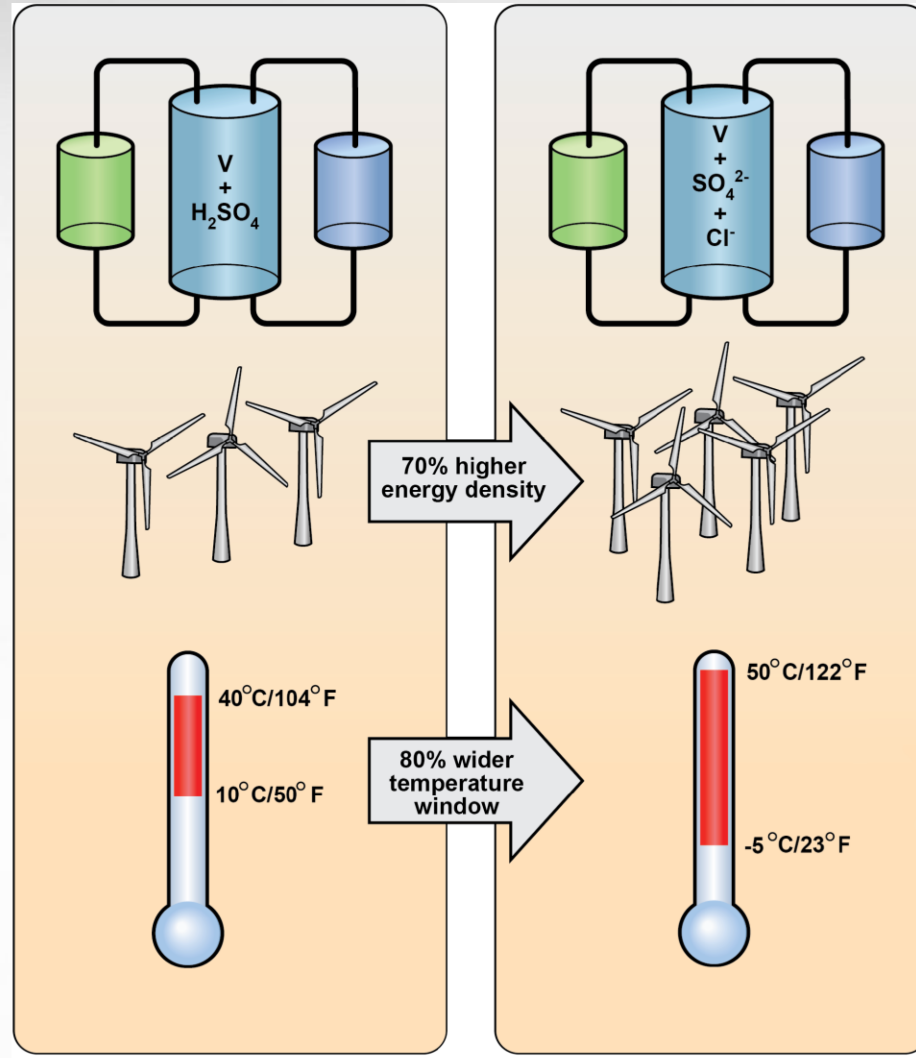
V specie	-5°C	25°C	40°C
	sulfate	sulfate	sulfate
V^{2+}	2M (419 h)*	2M	2M
V^{3+}	2M (634 h)	2M	2M
V^{4+} (VO^{2+})	2M (18 h)	2M (95 h)	2M
V^{5+} (VO_2^+)	2M	2M	2.0M (95 h)

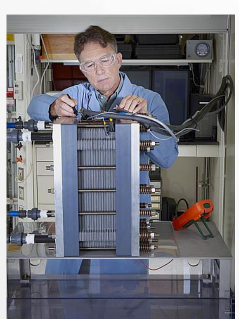
V^{5+} precipitation (1.5M @ ~43°C)



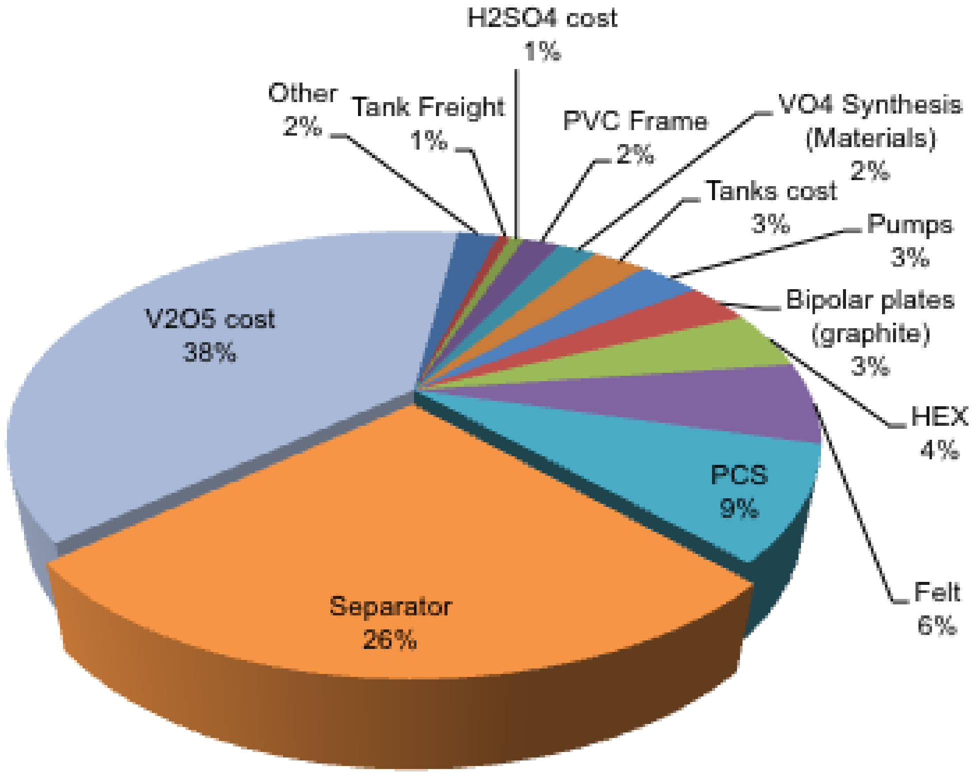
Solution Chemistry of the Electrolyte







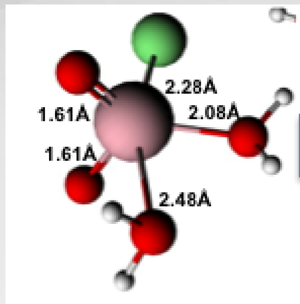
Redox Flow Battery Cost Projection



Gen 2 V-V 1 MW /4 MWh
At 80 mA/cm2

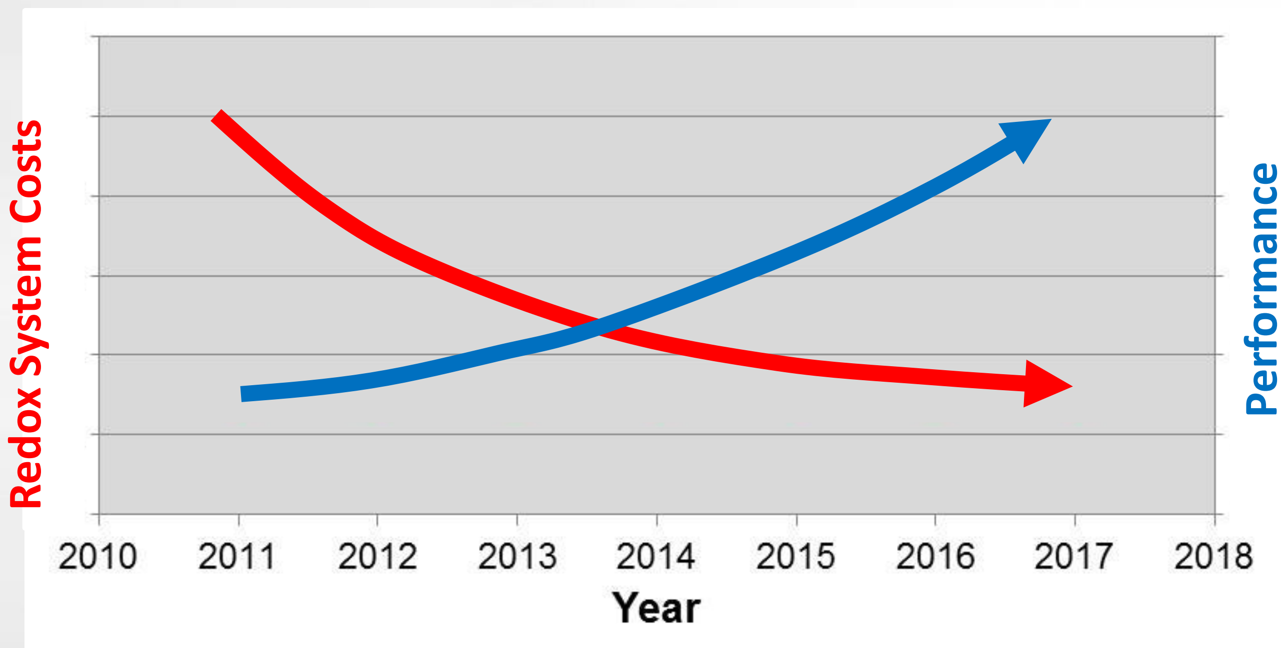
Redox Flow Battery Objectives

Develop the technologies, tools, and system understanding required to move the mixed acid electrolyte chemistry from basic chemistry to cost effective system solution.

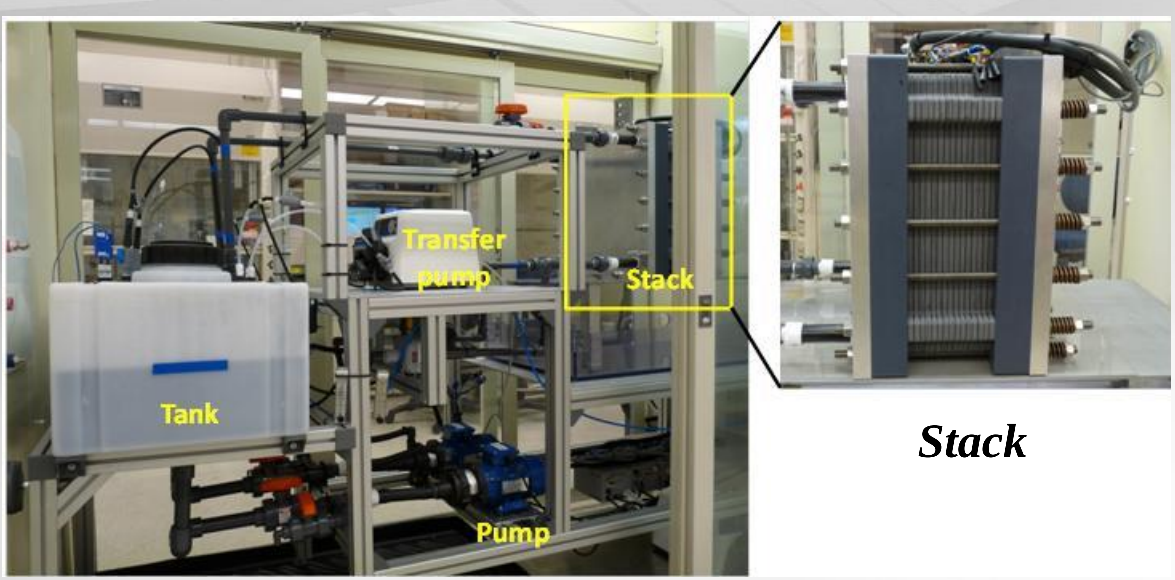


Basic Chemistry

Applied Systems



VRFB kW scale Stack Parameters



Stack

Test Parameters

- 780 cm^2
- 1-20 cell stacks
- 15-85% SOC
- Mixed acid electrolyte
    - 2M V, 2M S, 2M Cl
- Nafion® membrane
    - 212 (~ 2 mil)
    - j = 80 -320 mA/cm^2
- Modified interdigitated flow design
- 1-5 KW stack
- Chillers to control temperature

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20-cell Stack Performance

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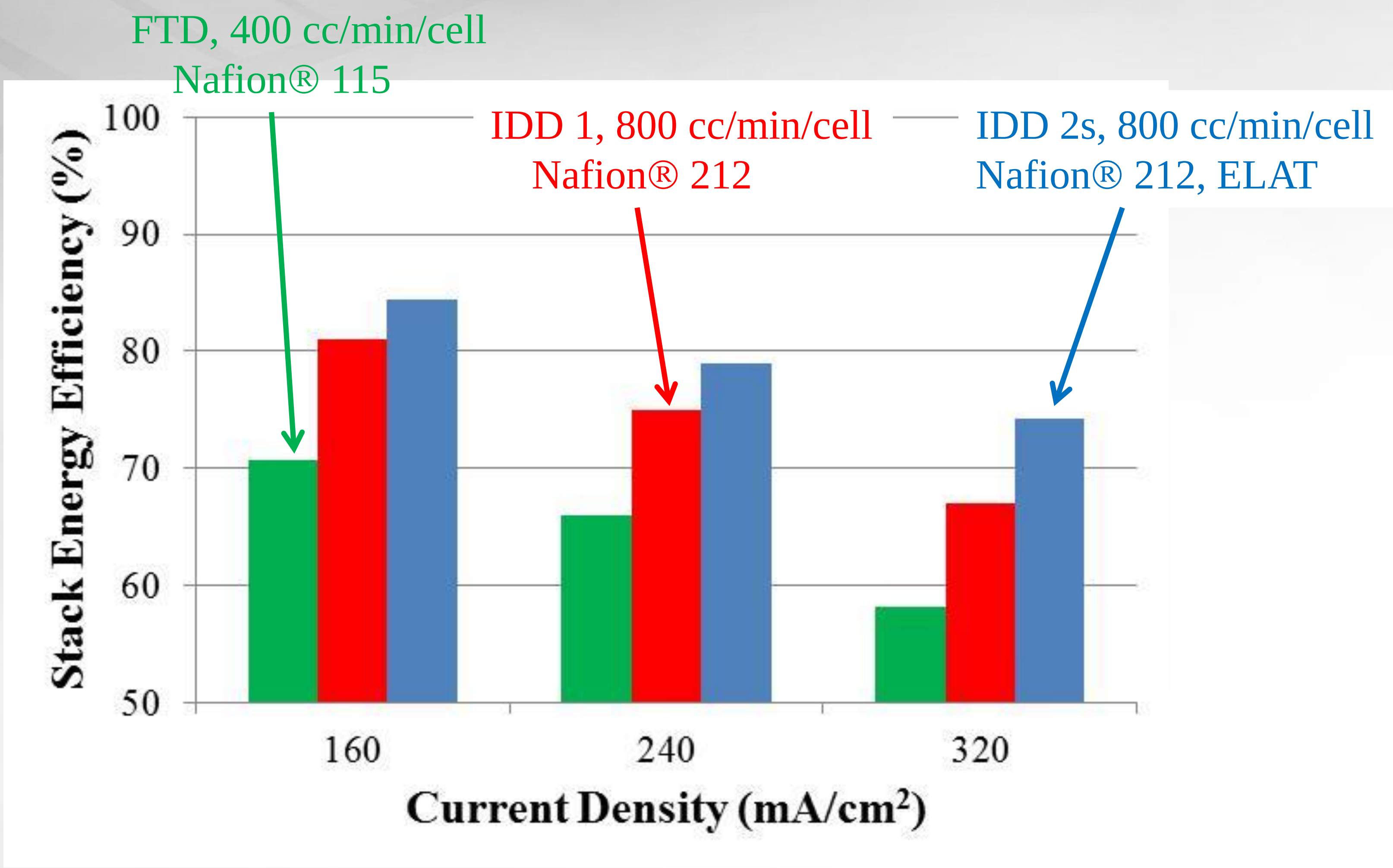
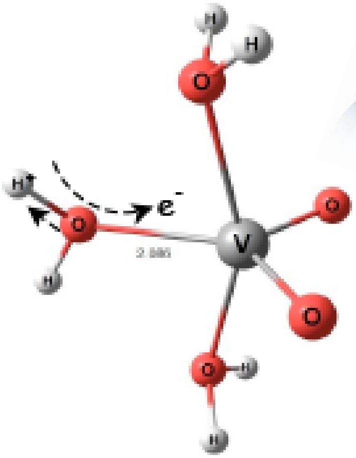
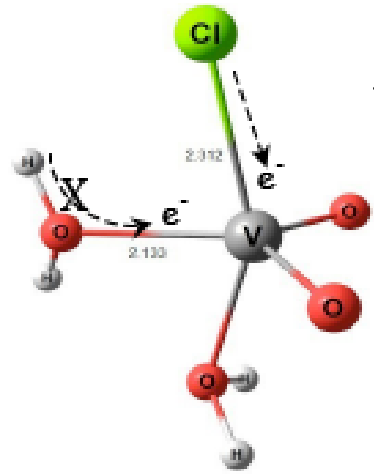


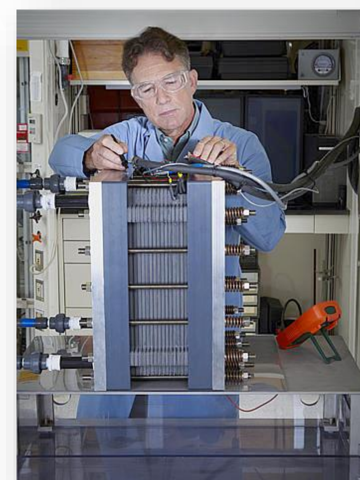
Mixed-acid VRB Development

Collaboration with EMSL/FCSD on standard sulfuric electrolyte: deprotonation leads to precipitation at elevated temperatures





HCl addition prevents deprotonation increasing temperature stability by 80% and energy density by 70%



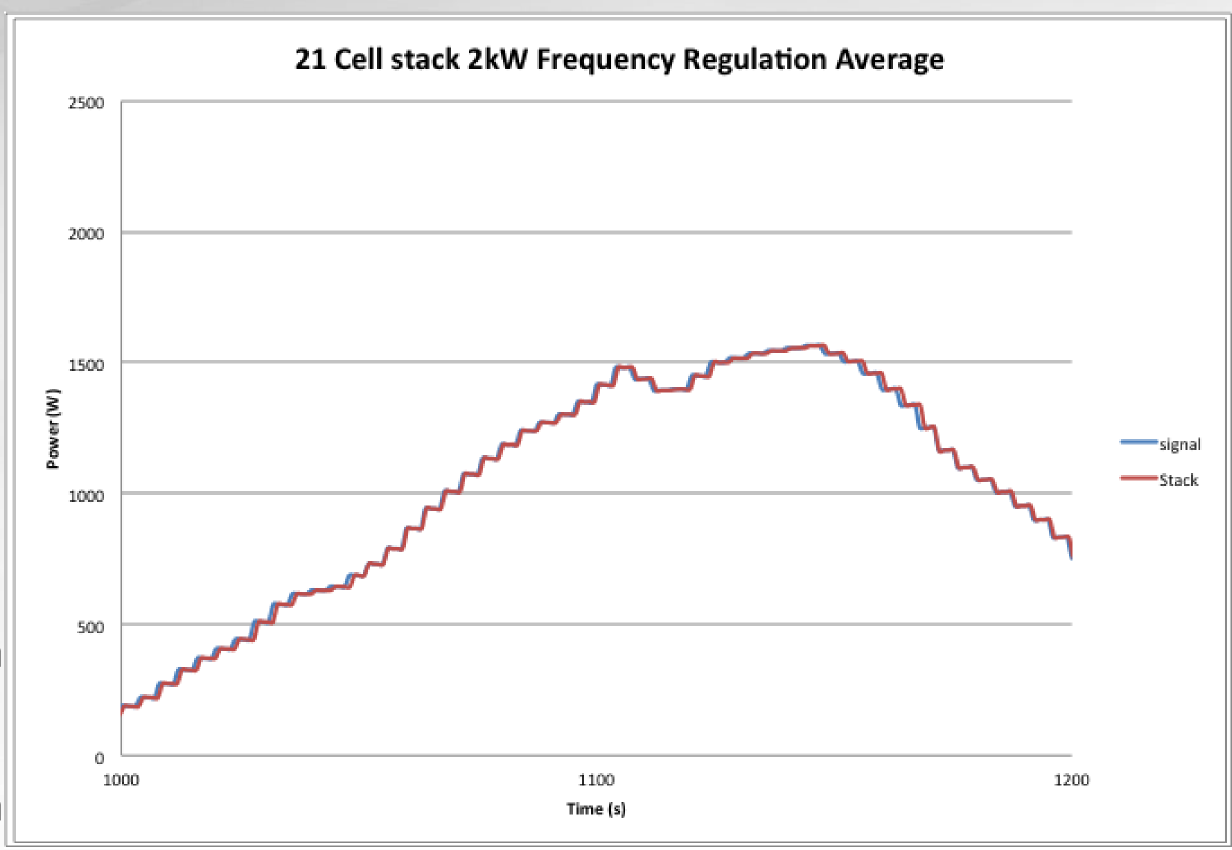
PNNL kW lab scale demonstration of technology

WA Governor Jay Inslee, UniEnergy CEO Gary Yang, OE Asst. Sec. Pat Hoffman at CEF kickoff June 2014

Avista/UniEnergy 1 MW/4 MWh System installation February 2015, commissioned in June.

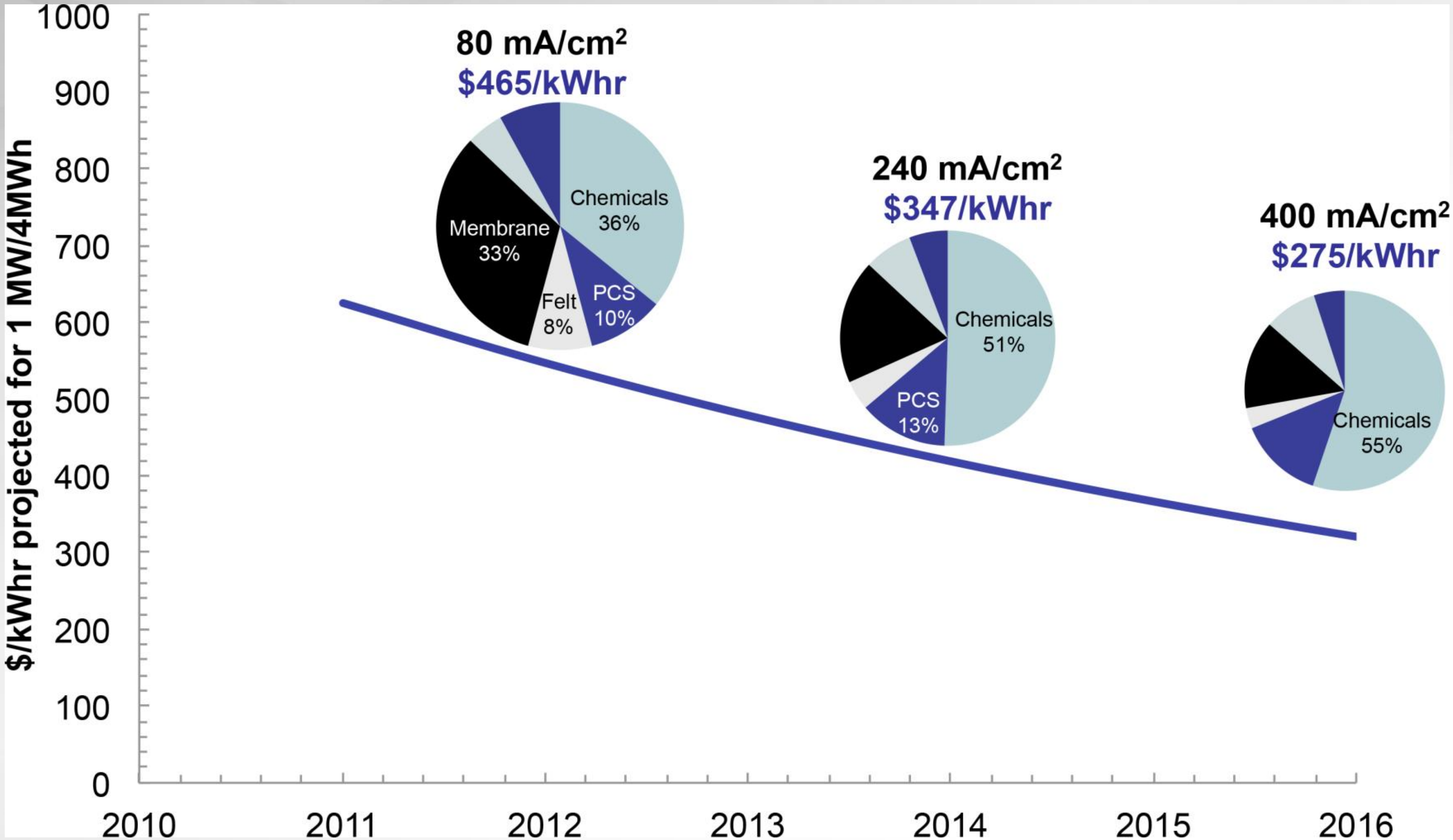
21 cell VRFB stack under Frequency Regulation protocol

- FR duty cycle determined from PJM balancing signal for year 2011
- Signals grouped into low, average and high standard deviations
- Representative 2-hour intervals with average standard deviation and 2-hour intervals with high standard deviation chosen
  - each being energy neutral
- Duty cycle consisted of three 2-hour average standard deviation (SD) signals followed by one 2-hour high SD signals, three 2-hour average standard deviation (SD) signals followed by one 2-hour high SD signals and four 2-hour average SD signals

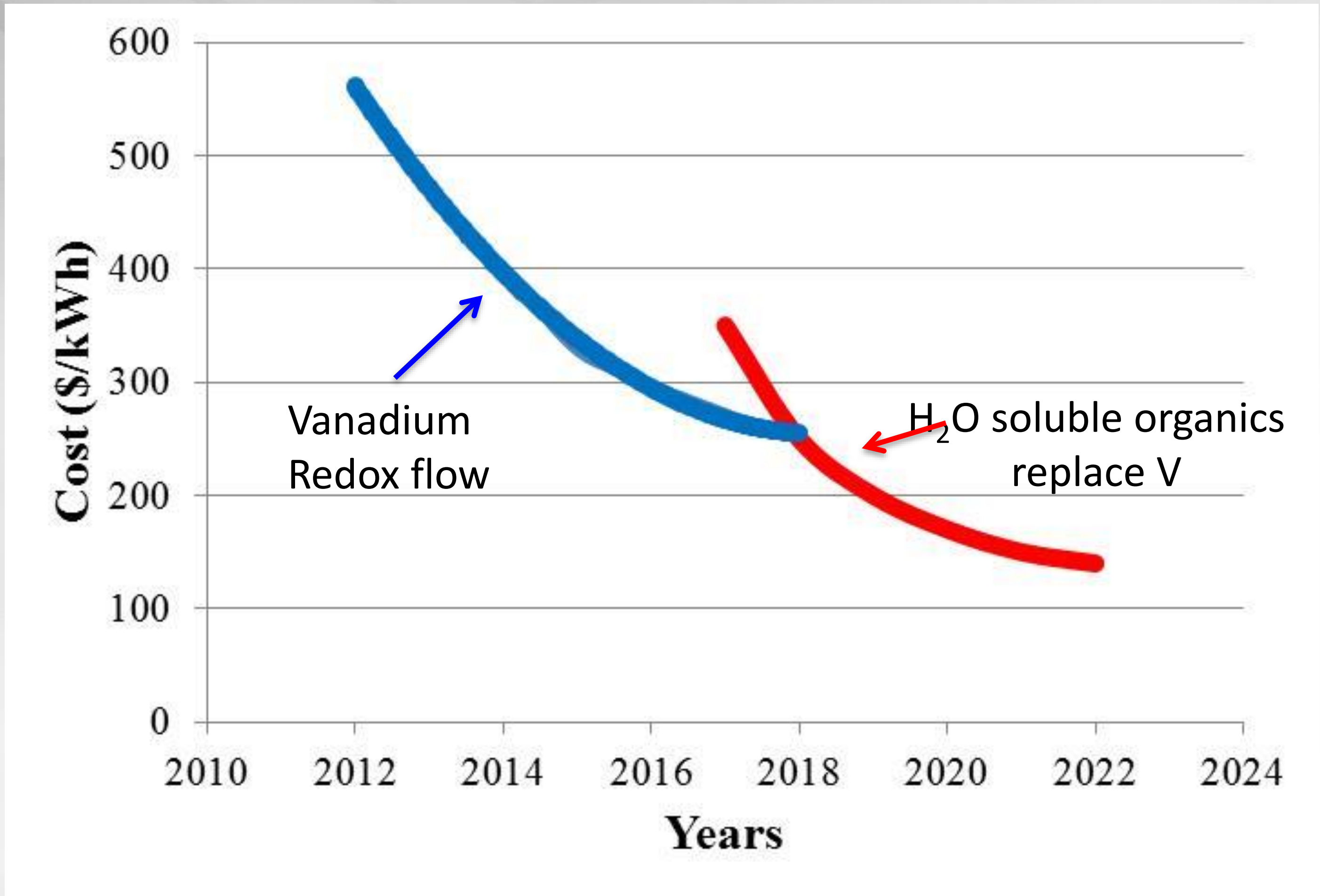


*DC only

Remaining Challenges - Cost Reduction



Next Generation Redox Battery Development



Low-cost aqueous organic RFBs

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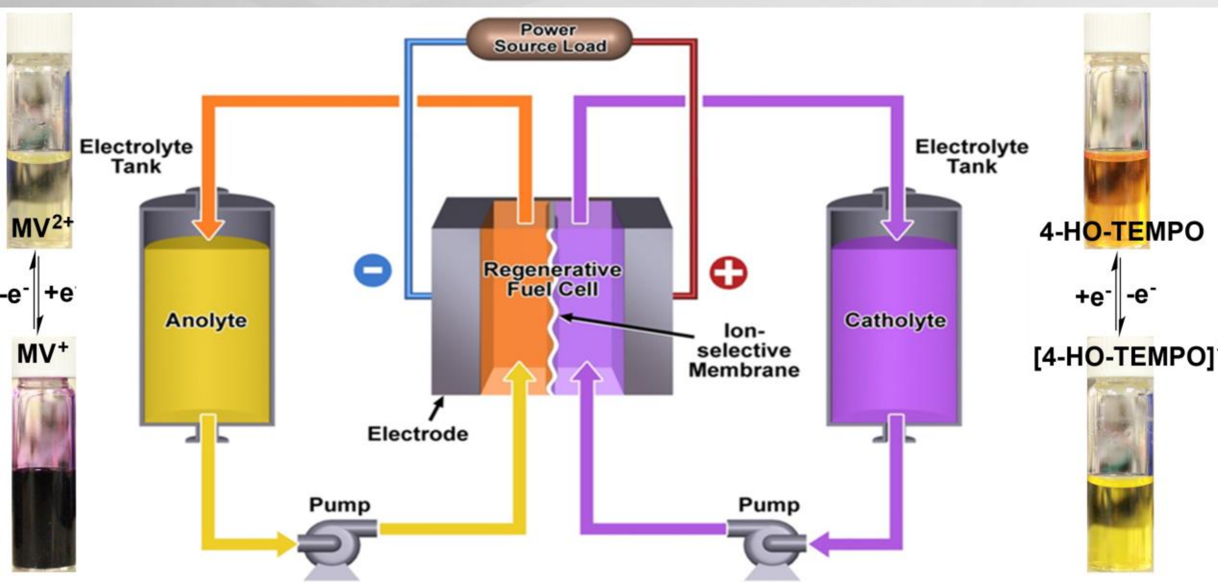
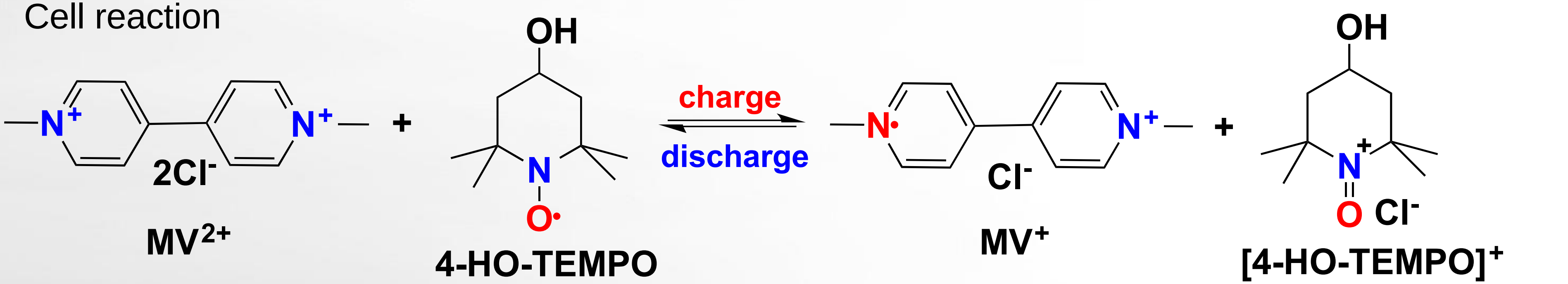


Advantage:

- Low-cost redox couple;
- Low-cost supporting electrolyte;
- No resource constraints;
- Less corrosive and toxic.

Cell reaction



Voltage of Aqueous Redox Flow Battery

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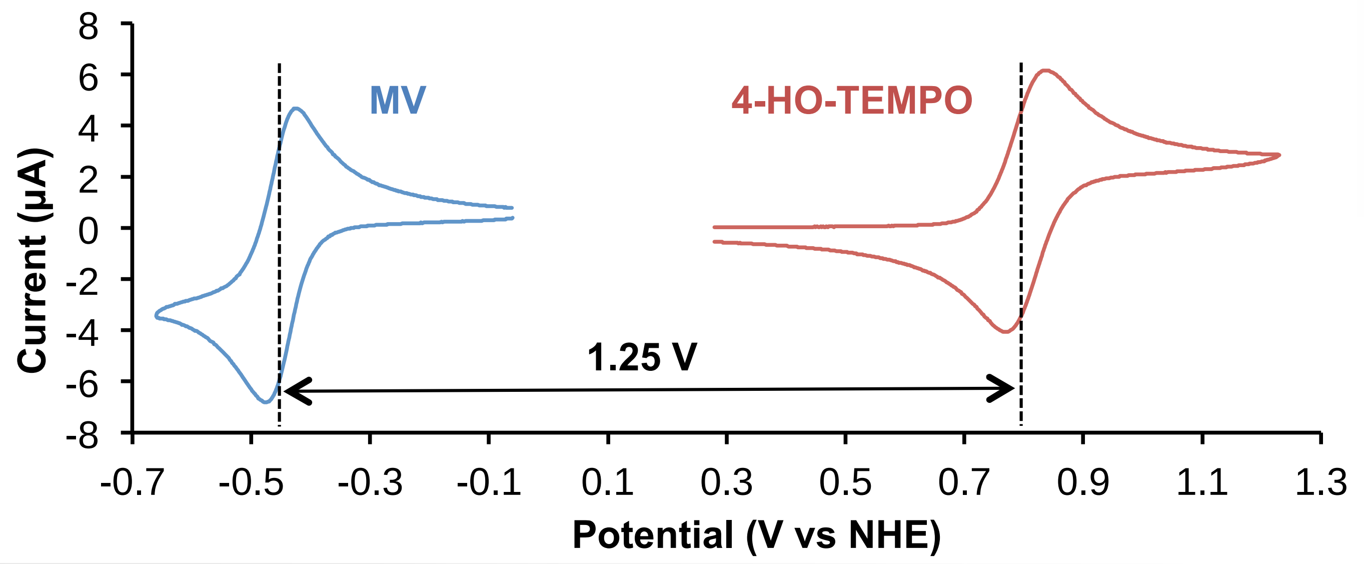
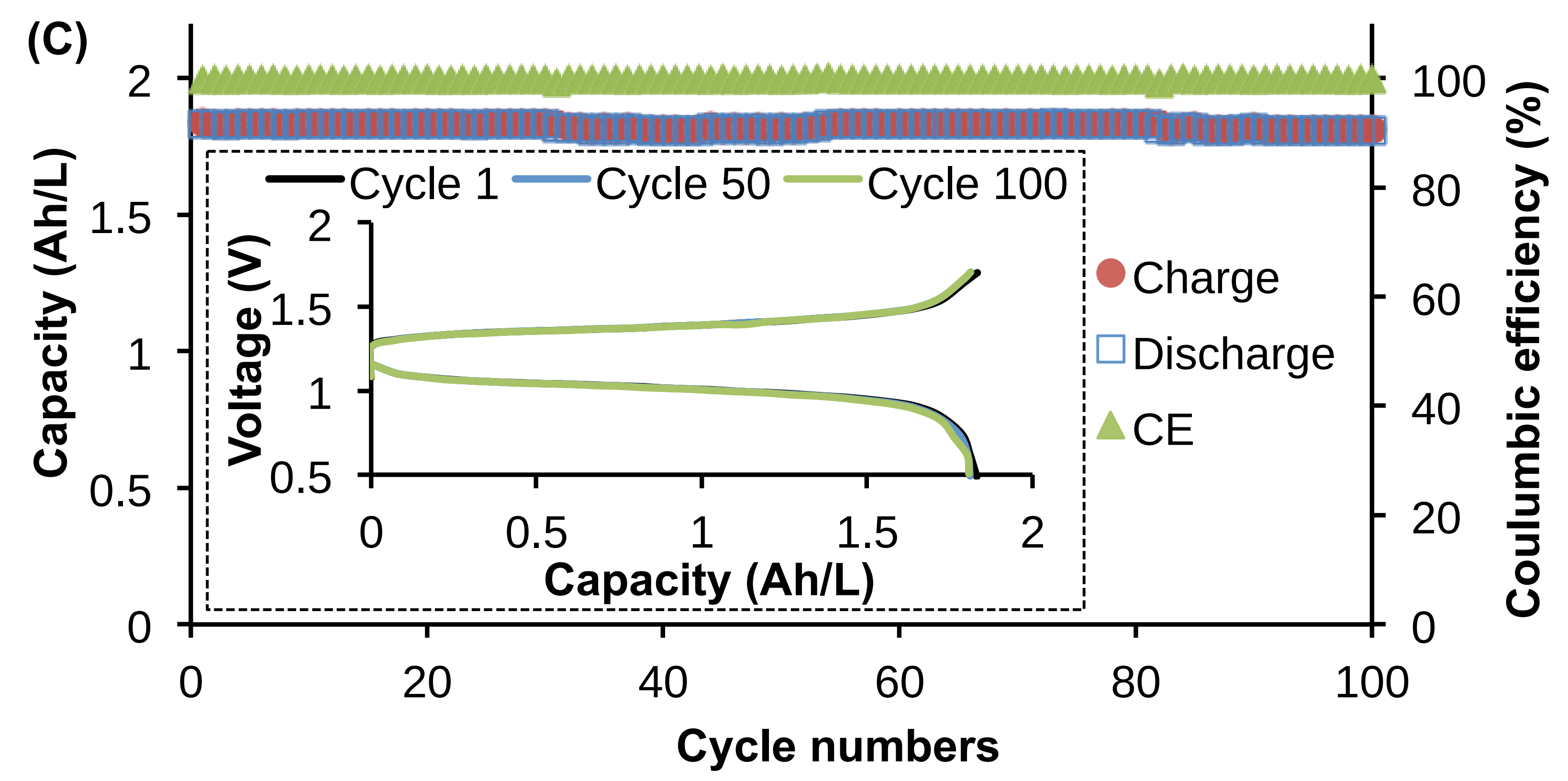
ARFBs (anolyte/catholyte)	Cell voltage (V)	Current density (mA/cm^2)	Supporting electrolytes	Membrane
$PbSO_4$/BQDS	**1.07**	10	H_2SO_4	Nafion 115
AQDS/Br_2	**0.96**	500	H_2SO_4 and HBr	Nafion 117
AQDS/BQDS	**0.76**	8	H_2SO_4	Nafion 112
MV/4-HO-TEMPO	**1.25**	60	NaCl	AME



Solubility in water:
MV > 3.0M
4-HO-TEMPO: >2.1M

Flow Cell Performance – Low Concentration



Capacity and coulombic efficiency vs cycling numbers of the cell at 40 mA/cm^2. Conditions: anolyte, 0.1 M **MV** in 1.0 M NaCl aqueous solution; catholyte, 0.1 M **4-HO-TEMPO** in 1.0 M NaCl aqueous solution; flow rate, 20 mL/min; AMV anion membrane. No remixing.

Redox flow battery with high energy density

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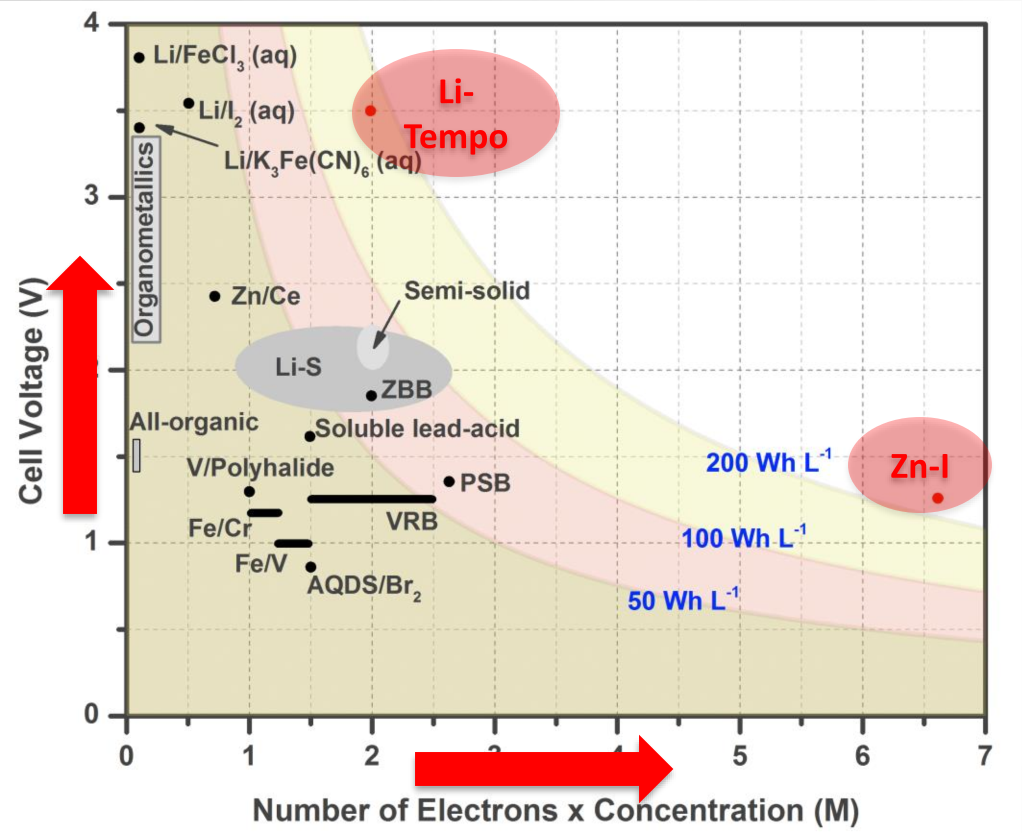
120MWh system, peak power ~15MW.
Each tank holds 1800m^3 of electrolyte.

- Large form factor/footprint
- Limited application

$$E = \frac{NC_a FV}{n}$$



E, system energy density
N, the number of electrons transfered
F, Faraday constant (26.8 Ah mol^{-1})

C_a, Max concentration of active redox species
V, Voltage of the cell
n, number of electrolyte tanks

- Hybrid flow battery design
- Ambipolar electrolyte
  Both anion and cation are active species.
- Bifunctional electrolyte
  Active species can act as charge carrier.

High energy density Zn-Polyiodide aqueous RFB

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Solubility of ZnI_2 is 7M in water → theoretical energy density ~322Wh/L

Identify high solubility redox active species

$$I_2(s) + I^- \leftrightarrow I_3^- \qquad K \approx 720 \pm 10 (298K)$$

$$Positive: 3I^- \underset{Discharge}{\overset{Charge}{\longleftrightarrow}} I_3^- + 2e^- (E_0 = 0.536V)$$

$$Negative: Zn^{2+} + 2e^- \underset{Discharge}{\overset{Charge}{\longleftrightarrow}} Zn (E_0 = -0.7626V)$$

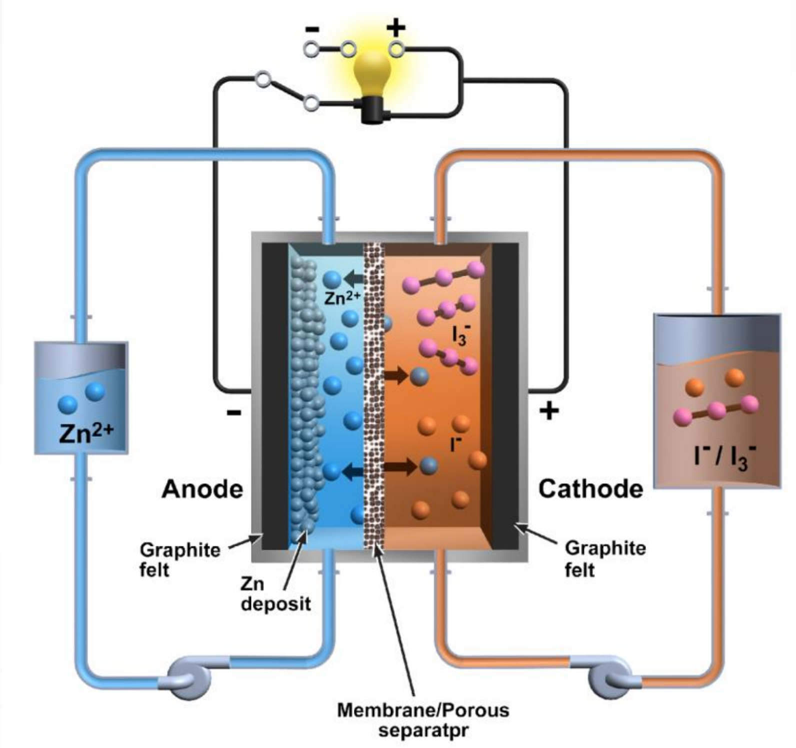
$$Overall: Zn^{2+} + 3I^- \underset{Discharge}{\overset{Charge}{\longleftrightarrow}} Zn + I_3^- (E_0 = 1.2986V)$$

Characteristics of the Zn-I_x RFB

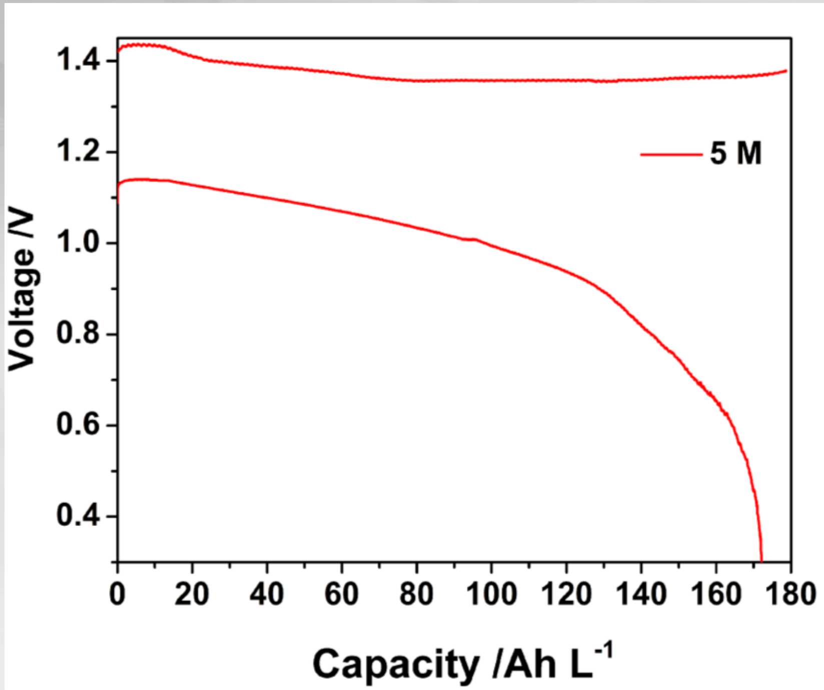
- Ambipolar electrolyte
- Bifunctional electrolyte
- High energy density
- High safety: PH value: 3~4

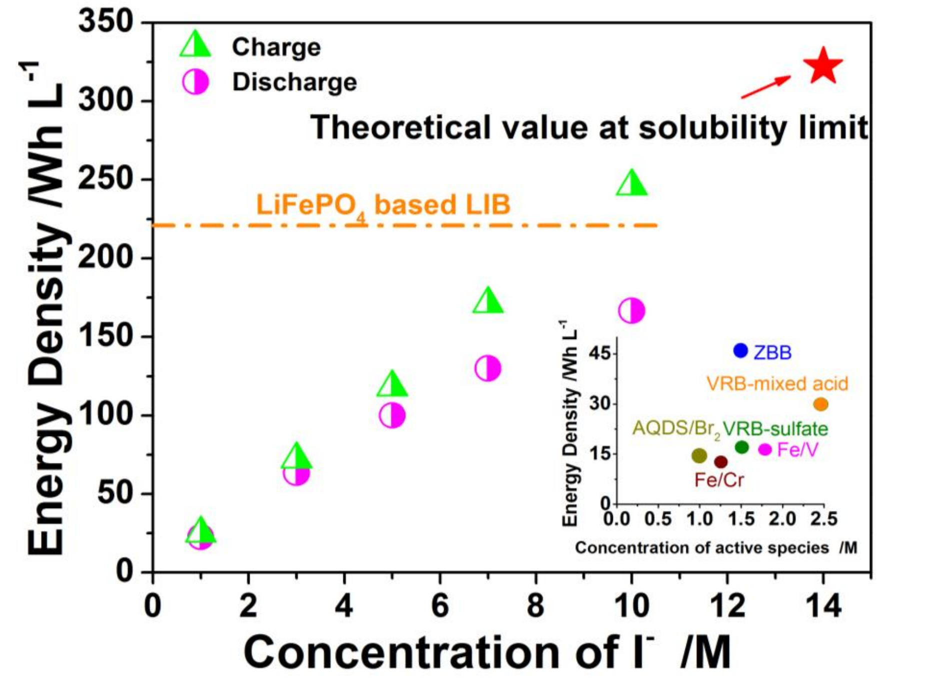
  No strong acid

  No hazardous materials



Electrochemical performance

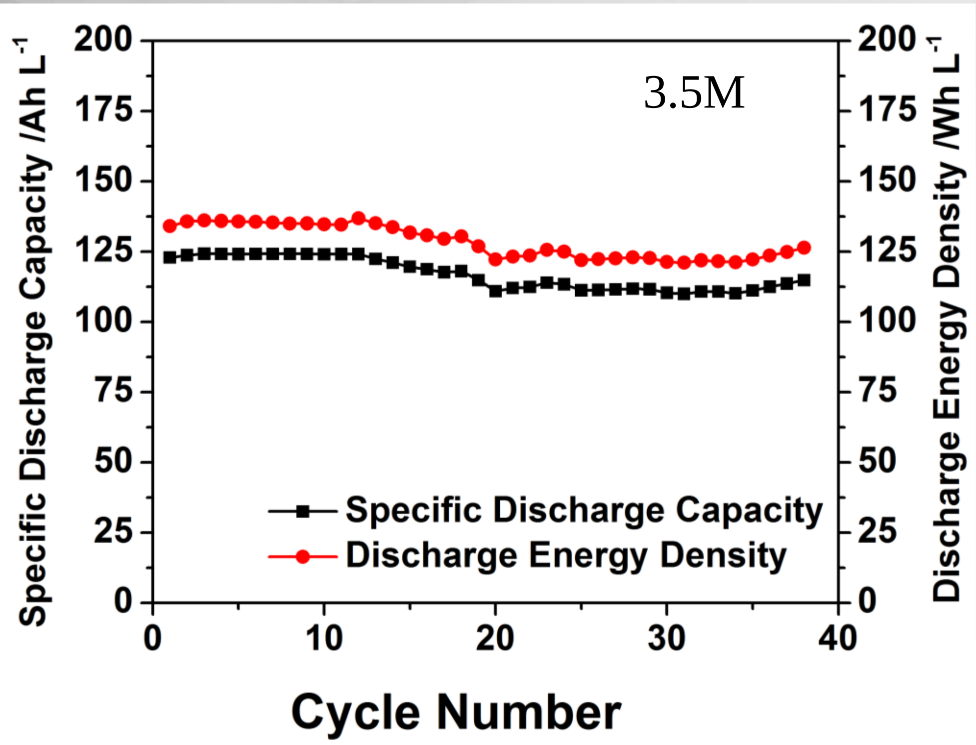




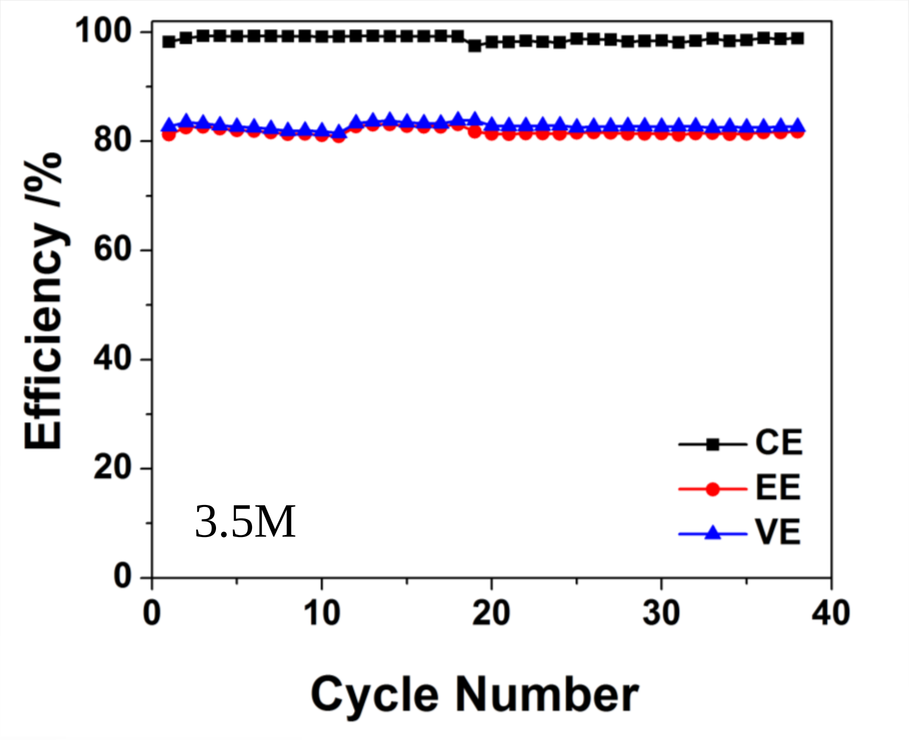
Charge/discharge curves for the cell with 5.0 M ZnI_2 and Nafion 115 as membranes operated at the current density of 5 mA cm^{-2}.

The charge and discharge energy density as a function of the concentration of I^-. The inset lists concentration vs. energy density of several current aqueous redox flow battery chemistries for comparison.

Cycling performance



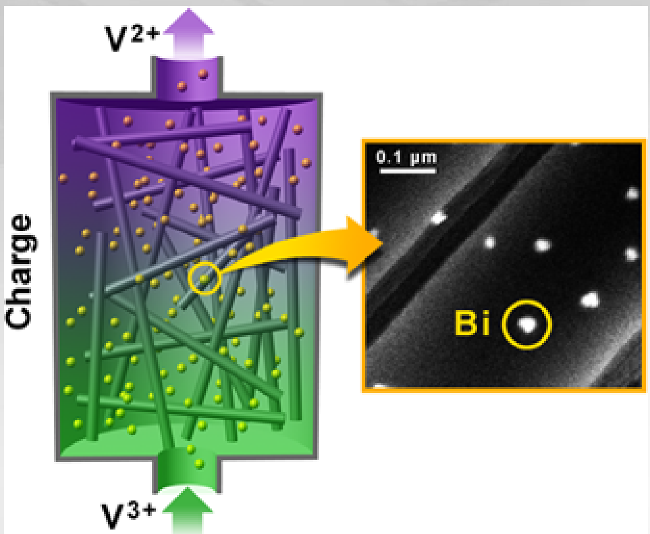
Capacities and energy density of the cell with 3.5 M ZnI_2 and Nafion 115 as membranes under the current density of 10 mA cm^{-2}.

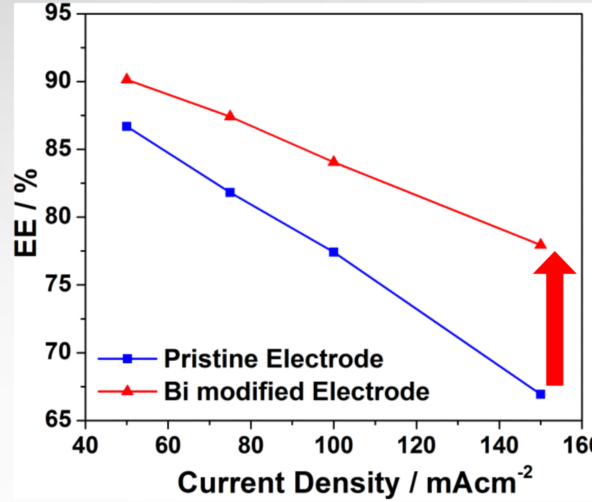


Efficiencies of the cell with 3.5 M ZnI_2 and Nafion 115 as membranes under the current density of 10 mA cm^{-2}.

Development in other areas – Advanced electrodes

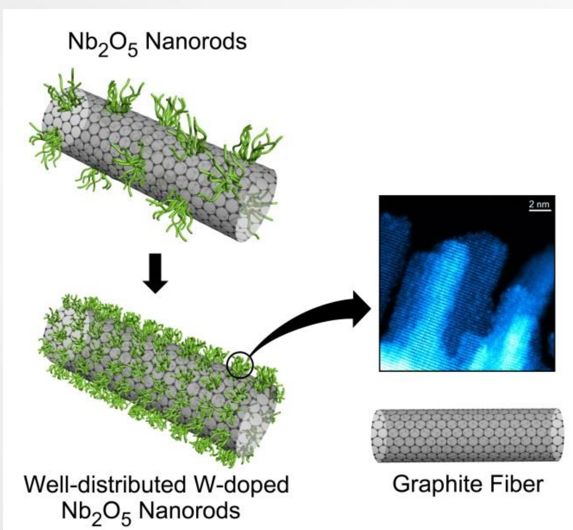
Bismuth nanoparticles

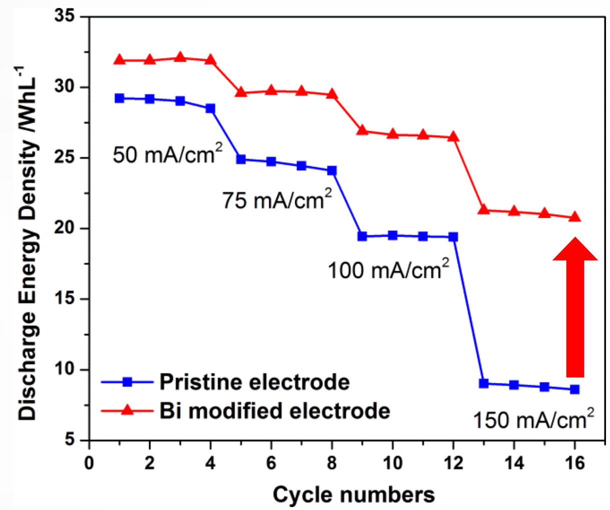




~17% increase

W-doped Nb_2O_5 nanorods





34% increase in vanadium utilization

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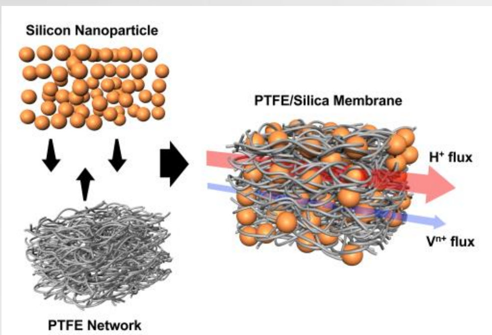
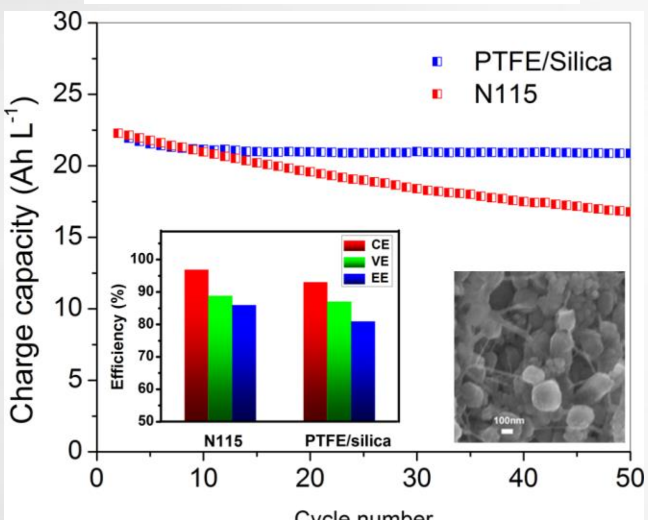
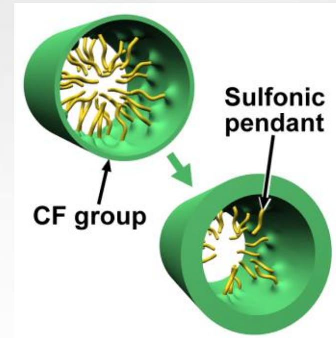
PNNL PTFE/SiO_2 separator

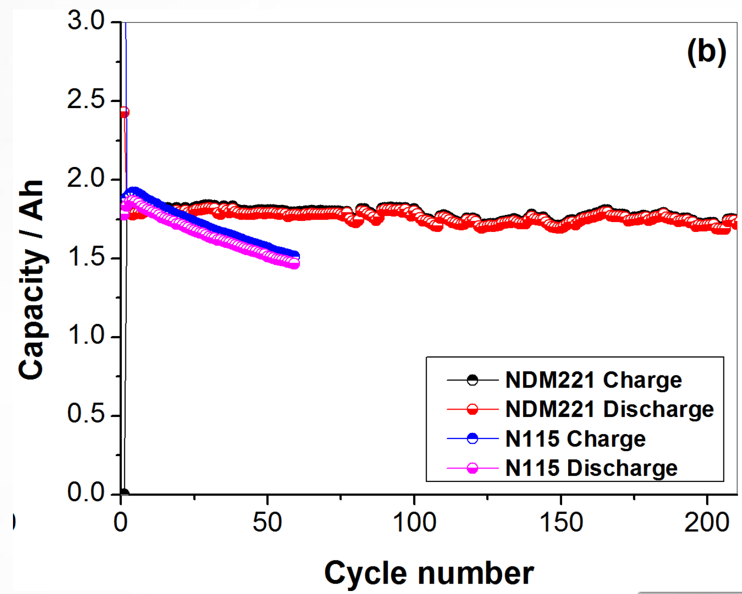
- Comparable efficiency
- Proven chemical stability
- No capacity decay
- Low cost (<5% of Nafion price)





Development of high selective PFSA membrane with Dupont





DUPONT

Chemours

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- External collaborators
  - Sandia National Laboratory
  - Oak Ridge National Laboratory
  - Chemours (Formerly Dupont)

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Webinar Archive: www.cesa.org/webinars

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Upcoming Webinar

- What are flow batteries and how can they improve resiliency, continuity and safety in urban installations? March 24, 1-2 pm ET

More information at www.cesa.org/webinars

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