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A Brief Overview of Flow Battery Construction and Operational Considerations

Reed Wittman, PhD

Sandia National Labs

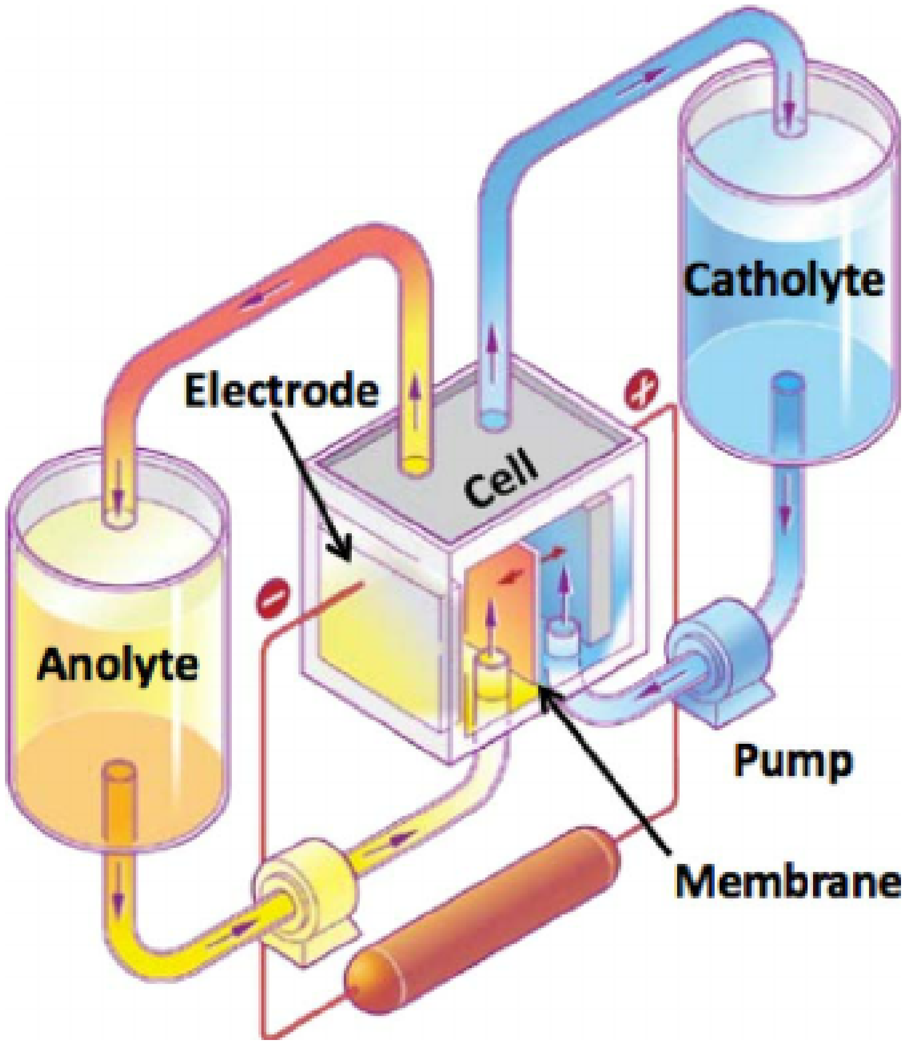
Rwittm@sandia.gov

Agenda

- Introduction to Flow Battery Operation
- Types of Flow batteries
  - Aqueous
  - Organic
  - Hybrid
- Considerations for Integration and Operation
- Use Cases Comparison
- Conclusion

Introduction to Flow Batteries

- Charged species is dissolved into electrolyte
- Pumped from storage tanks to electrode stacks
- Reaction takes place in the reactor stack and products are pumped back to storage tanks



Travis Anderson, Sandia National Laboratories, 2013

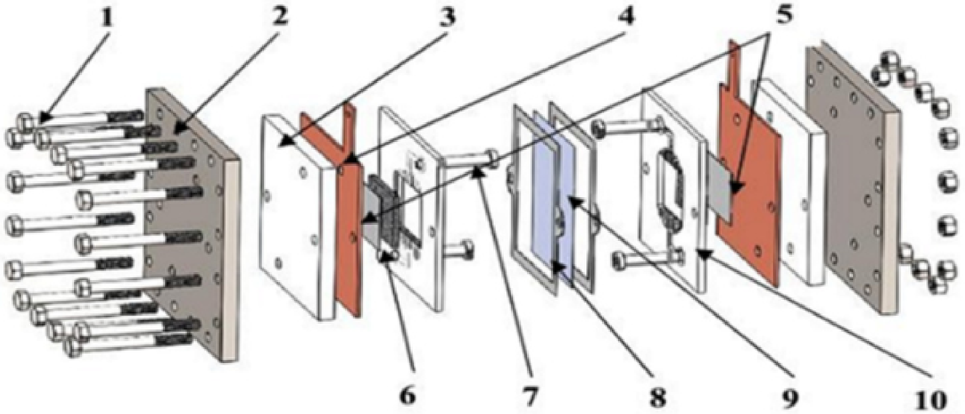
Key Distinctions from traditional batteries

- Charge carrying species (almost) always remains dissolved in the electrolyte
- Flow batteries flow electrolyte to and from the electrode stack during charge and discharge
- Electrolyte pumping rates need to be balanced with pumping losses
- Leaks become a larger concern
- Energy and power of the system can be decoupled
  - If you you need more energy add more electrolyte
  - if you need more power add more stacks
- Low energy density systems but generally lower costs particularly at longer durations

Flow Battery Components: Single Cell

- Single cell is generally composed of two porous electrodes sandwiching an ion exchange membrane
- Electrodes are often carbon felts or paper
- Common ion exchange membrane is nafion
- Bi-polar plates act as current collectors and distribute electrolyte to the electrodes

Ghimire et al, Batteries, 2021



1. Nut and bolt
2. End plates
3. Insulator plate
4. Current collector
5. Bipolar plate
6. Porous electrode
7. Nozzle for frames
8. Gasket
9. Membrane
10. Flow frame

Bi-polar plate

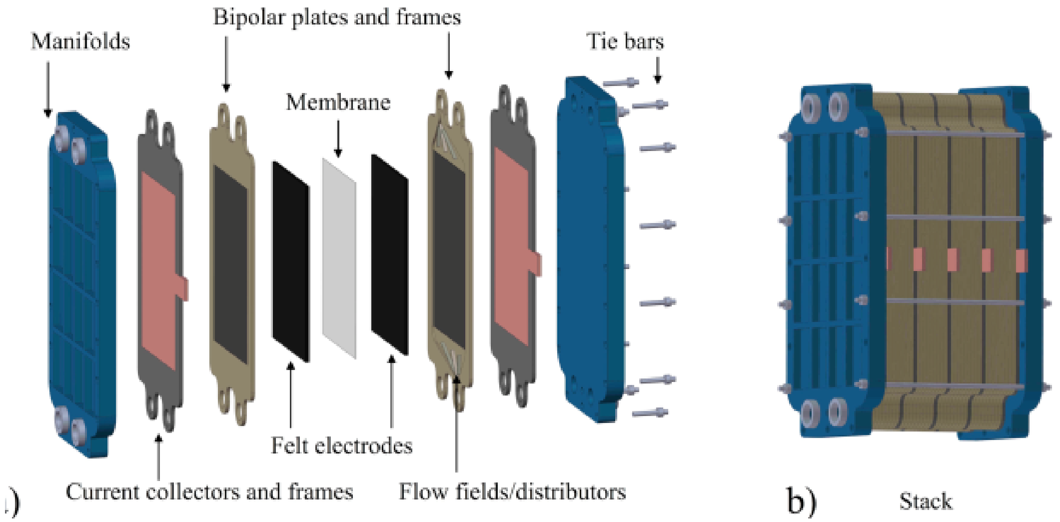
Carbon Felt

Fuel Cell Store

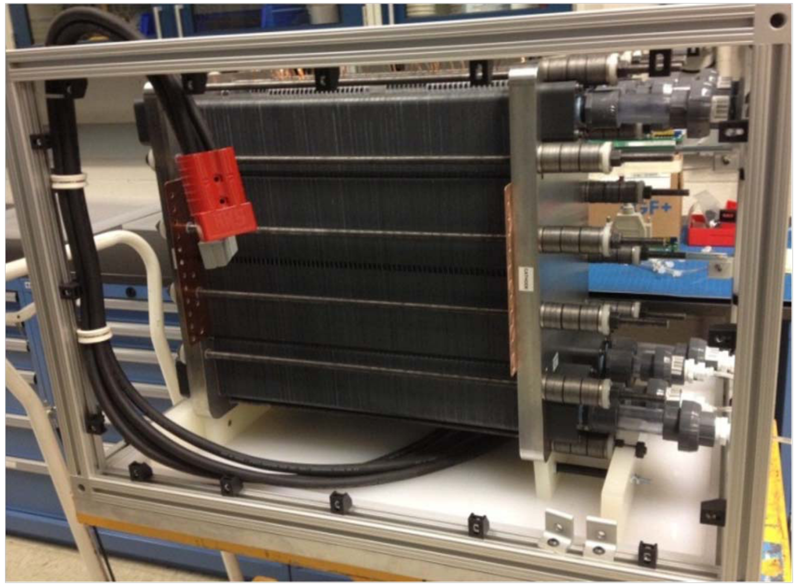
Nafion Ion exchange membrane

Flow Battery Component: Stack

- Stack is a set of cells connected in series
- Electrolyte is pumped to each cell in the stack
- Stacks can vary between10 and 150 cells in size
- Power rating will be a function of cell current and the number of cells in a stack



Arenas et al, J. Energy Storage, 2017



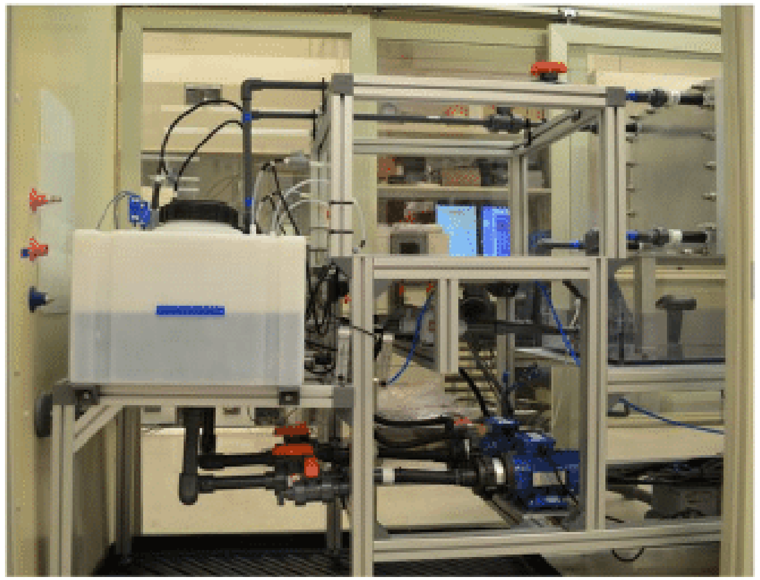
Chalamala et al., Proceedings of the IEEE, 2014

Ke et al., Chem. Soc. Rev, 2018

Flow Battery Components: Electrolyte Flow System

- Storage tanks for electrolyte
  - 1MWh can require up to 20,000 Gallons of electrolyte
- Tubing to move electrolyte to and from tanks
  - Needs to be tolerant of the electrolyte used
  - Needs to be sized correctly to achieve desired flow rates
- Pumps required to move the electrolyte
  - Needs to be tolerant of the electrolyte used

Emura, EESAT, 2003



Kim et al, JPS, 2013

Flow Batteries Come in a Variety of Types

General Types	System Type	Pros	Cons
Aqueous	All soluble Metal cations and anions dissolved in acid or bases	• No crossover contamination • Relatively high efficiency • Highly Scalable • Well researched and developed	• Limited energy Density • Relatively high cost • Low thermal Stability • Low operating voltage (1-1.5V)
Organic	All soluble Organic cations and anions dissolved in organic solution	• High power density • Low cost • Potentially high energy density	• Low long term stability • Currently low energy density • Increased flammability • Early in development
Hybrid	Insoluble and soluble charge species Generally metal deposited on negative electrode Usually aqueous systems	• High energy density • Low cost • High operating voltage (+2V) • Well researched and developed	• Does not scale power and energy density independently • Low efficiency • Issues with long term cycling

General Characteristics of Aqueous Flow Batteries

Most common is Vanadium Redox in sulfuric acid electrolyte

Power and Energy scale separately

- More power => add more electrode stacks
- More energy => add more electrolyte

System can be easily scaled to meet needs

- Systems can be self contained modules or specifically designed for a given site

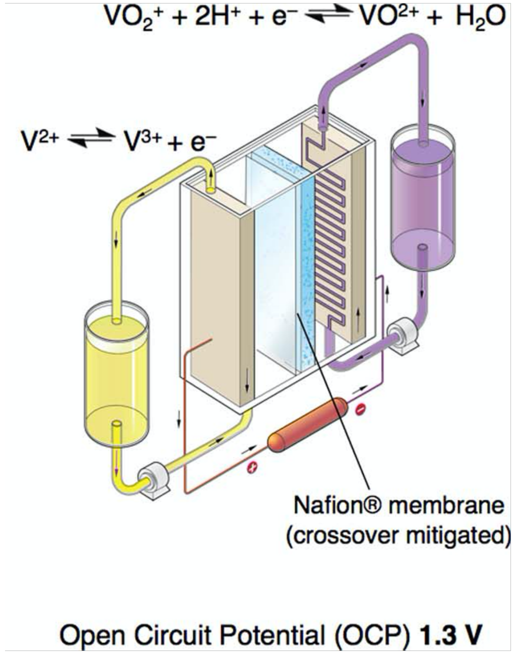
Relatively safe systems

- Thermal runaway generally not an issue
- Gas evolution needs to be monitored

Rated for long life +20 years

- Target +10,000 cycles without significant fade

Low energy density ~20-30Wh/L



Sumitomo 2MW/8MWhr Vanadium Redox Flow Battery system in San Diego, CA

General Characteristics of Organic Flow batteries

Similar to aqueous system however uses organic electrolyte and charge carrying species

Power and Energy scale separately
- More power => add more electrode stacks
- More energy => add more electrolyte

System can be easily scaled to meet needs
- Systems can be self contained modules or specifically designed for a given site

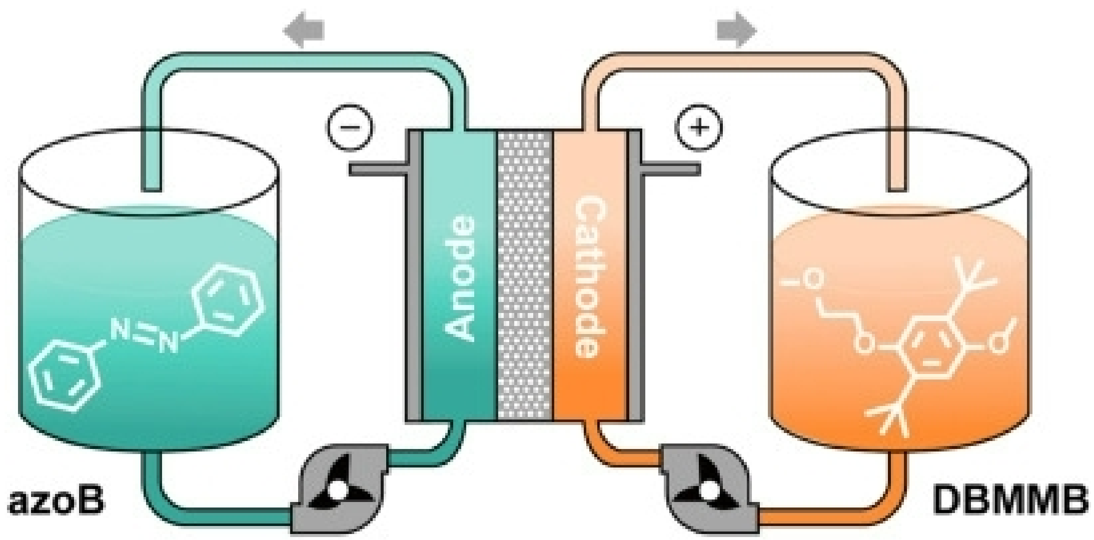
Safety has yet to be defined
- Thermal runaway and fire are possibilities

Life span has yet to be proven
- Products have rapid decay rate

Increased pumping losses

Higher energy and power density

Reduced active material cost



General Characteristics of Hybrid Systems

Zinc-Bromine system is the most common type currently

Half the system store charge in solution other half stores charge as a deposited metal

Power and Energy scale do **not** separately

Safety has yet to be defined

- Thermal runaway and fire are possibilities

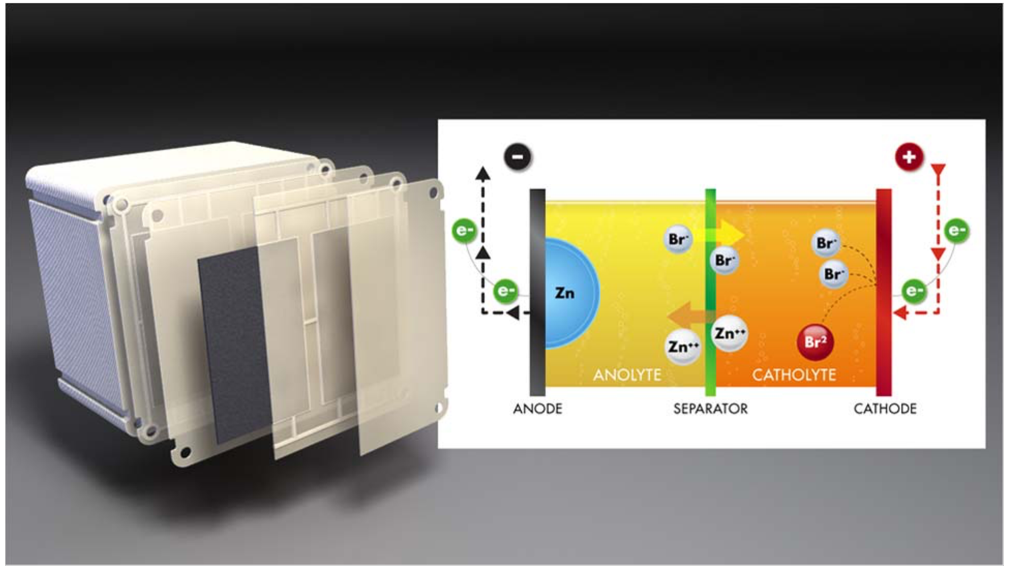
Life span varies by chemistry

- Low depth of discharge can make dendrites
- Hygiene cycles are required periodically

Higher energy and power density

Relatively low cost

Higher efficiency



ZBB Energy Corporation

10kWh Zn-Br System from Redflow

Primus Power modular Zn-Br, each unit is 25kW/125kWh

Limitations of Flow Batteries

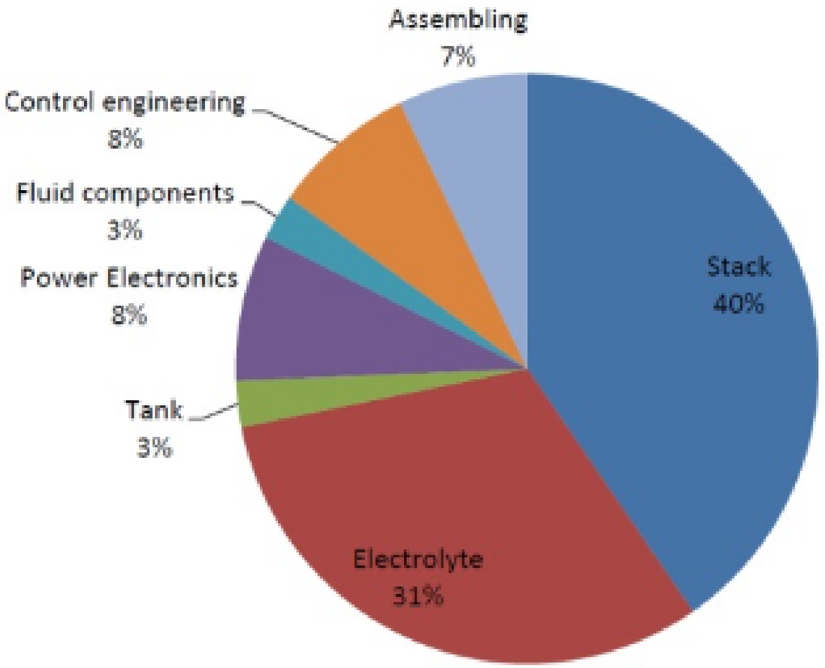
Low power and energy density
- Narrow voltage range
- Relatively low solubility of charge carriers

Low round trip efficiency
- 60-80%

Response time varies
- 0.1 sec if pumps operating
- 1 min if pumps are not operating

Relatively high material cost
- Membrane
- Redox species

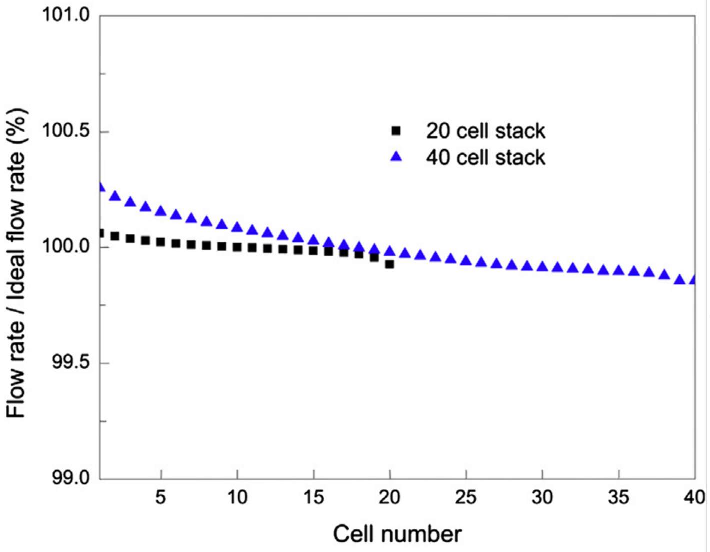
Long term stability of electrolyte and component materials
- Narrow operating temperature window
- Degradation of membrane and electrode materials
- Corrosion of auxiliary equipment by electrolyte

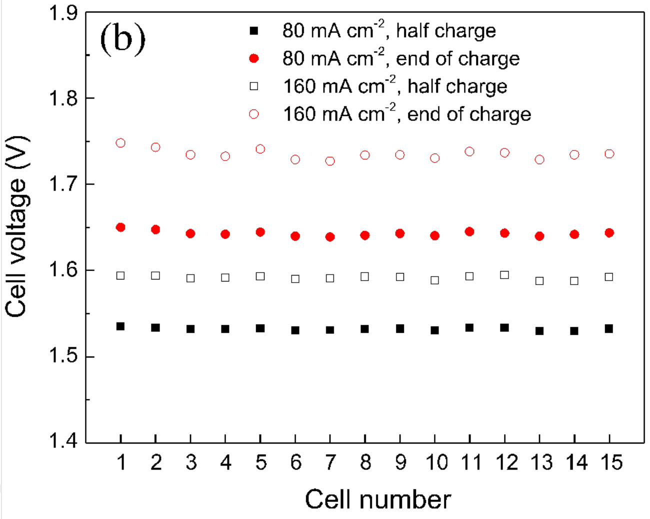


Cost break down of a VRFB system, Energies2016,9, 627

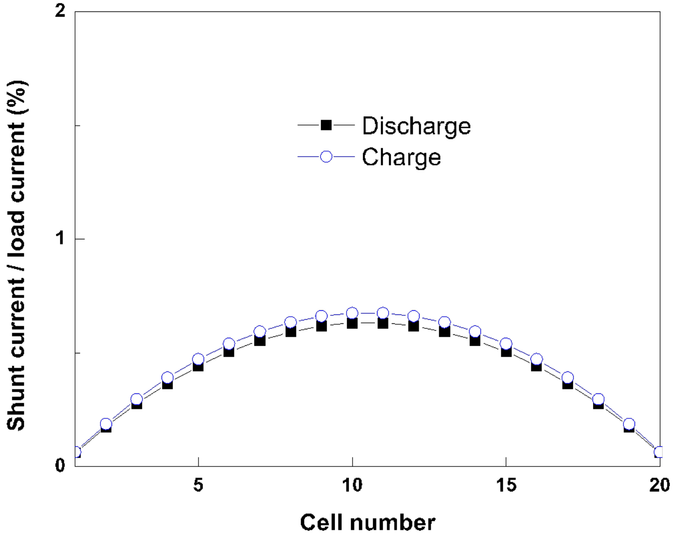
Integration considerations: Stack Operation

- Equivalent to a traditional battery cell module
- Stacks generally are electrically in series but chemically in parallel
- Flow rate and reactant distribution can vary through stacks
- Significant imbalance between desired current and flow will cause side reactions and degradation of system
- Shunt currents also need to be managed
  - Where chemical reactions take place out of cell active area
  - Result of high electrolyte conductivity creating current gradients outside the cells



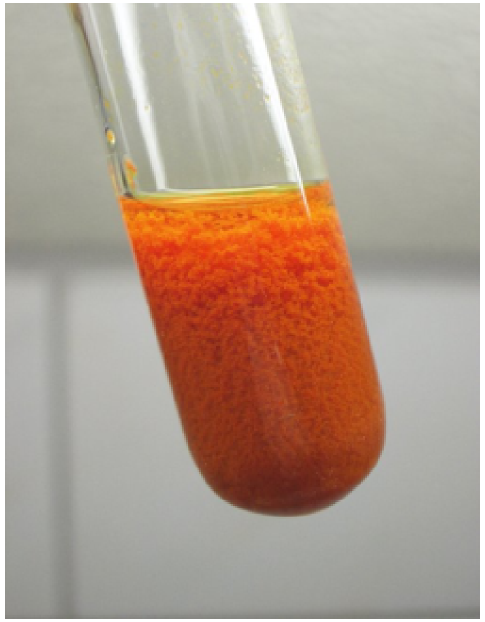


Kim et al, JPS, 2013

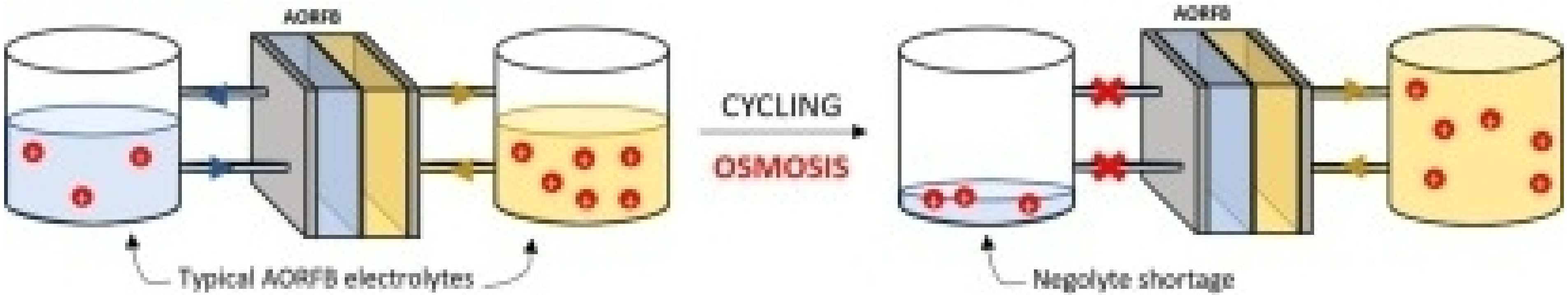


Integration considerations: Electrolyte management

- Electrolyte will crossover the membrane requiring rebalancing
- In aqueous systems active species can precipitate out of solution
  - Vanadium systems in particularly are sensitive to temperature
- Organic systems experience rapid degradation during cycling



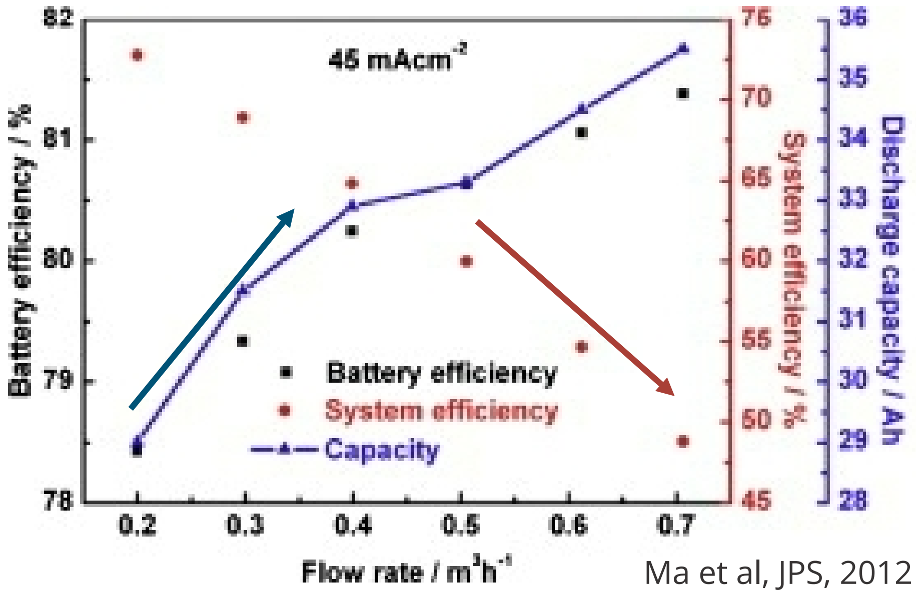
M.B. Lim et al., Materials Science & Engineering, 2021



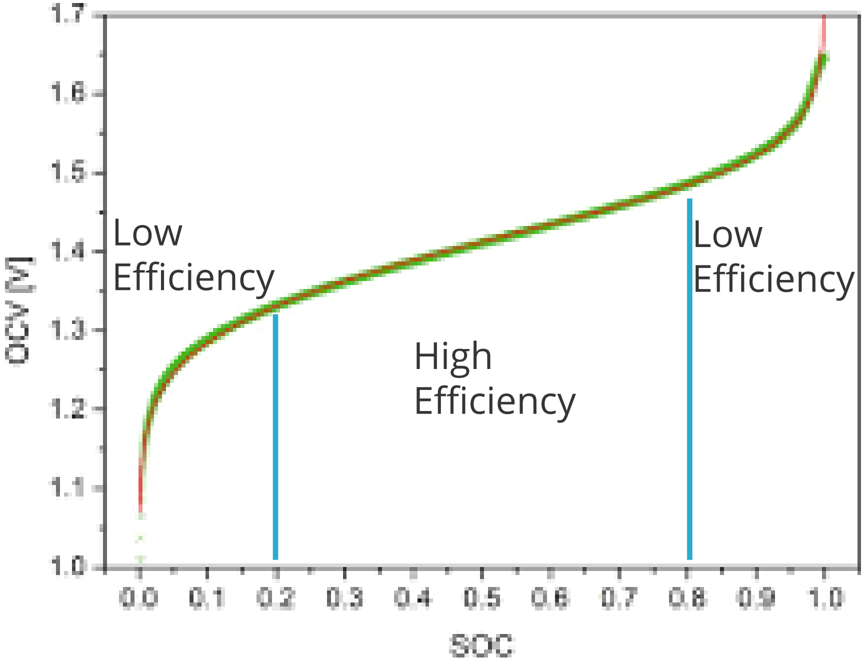
Fontmorin, Electrochem. Comm., 2021

Integration Considerations: Balance Flow Rate Required with Pumping Losses

- Flow rate dictates how much reactant is delivered to the stack/cells which dictates efficiency
  - Higher rates of charge/discharge will required higher flow rates to maintain efficiency
  - As flow rate increases losses from the pumps increase and may reduce overall efficiency
- Electrolyte viscosity will vary between systems and will influence pumping looses
- Need to consider high and low SOC efficiencies



Ma et al, JPS, 2012



Integration considerations: Size/scale

- Sizing considerations will vary by system type, desired use and power/energy rating
- Non-hybrid systems generally are designed to provide 4+ hrs of storage to grid
  - Require thousands to hundreds of thousands of gallons of electrolyte
  - Will take up more physical space than a traditional system
  - Energy and power scale independently
- Hybrid systems are often used to provide UPS to critical infrastructure or individual buildings
  - Come as modules with a set power and energy rating
  - Power and energy are tied to each other
  - Take up less space than non-hybrid system

Integration considerations: Size/scale

10kWh Hybrid Zn-Br System from Redflow
Footprint: ~4ft^2

Primus Power modular hybrid Zn-Br, each unit is 25kW/125kWh
Footprint: ~36ft^2

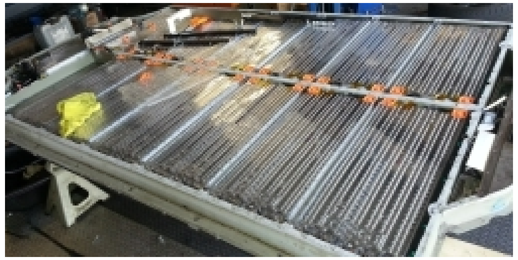
Sumitomo 2MW/8MWhr vanadium Redox Flow Battery system in San Diego, CA

200MW/800MWh Mixed-Acid Vanadium Redox Flow Battery system under construction in Dalian China

How Traditional Batteries Scale

1 cell
11.8Wh
11.4W

35cells
422.1Wh
614 W



~7,000cells*
85kWh
96kW

~11,500cells*
232kWh
130kW

~5.3 Million Cells*
80MWh
20MW

- Adding additional energy or power requires more cells and modules
- Increases battery management costs and system complexity
- Cannot add additional capacity without increasing power and vice versa
- Makes it hard to tailor systems to specific needs particularly long term storage +4hrs

*estimate made based off of Tesla cells

How Non-Hybrid Flow Batteries Scale

From Largo Clean Energy

2 stack containers
144,000 Gallons of electrolyte
6MWh
1.2MW

2 stack containers
192,000 Gallons of electrolyte
8MWh
1.2MW

2 stack containers
240,000 Gallons of electrolyte
10MWh
1.2MW

- Adding additional energy does not require additional cell stacks
- Battery management costs remain nominally the same
- Can add additional stacks to increase power output without need to add more electrolyte
- Can tailor system to exact demands of energy capacity and power
    - Ideal for longer term storage applications +4 hours

How Non-Hybrid Flow Batteries Scale

Cell Cube product spec sheet

Product	Nominal / Max Power	Usable Energy Capacity (kWh)
FB 250	250 kW / 500 kW	1000 (4 hours)
		1500 (6 hours)
		2000 (8 hours)
FB 500	500 kW / 1000 kW	1000 (2 hours)
		2000 (4 hours)
		3000 (6 hours)

Sumitomo product spec sheet

Output	Capacity	Installation Area
1MW	3MWh	15m×17m
1MW	4.5MWh	21m×17m
1MW	6MWh	27m×17m
10MW	30MWk	85m×27m
10MW	45MWh	103m×27m
10MW	60MWh	131m×27m

Invinity product configuration range

Available Configurations

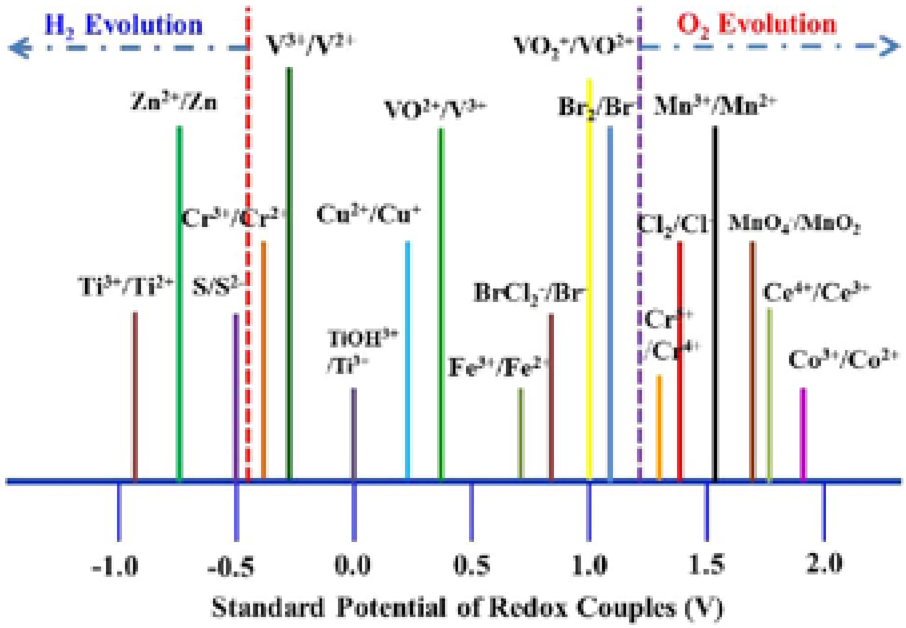
Invinity VS3-022 Six Pack™ Vanadium Flow Battery

Rated Power, Continuous:	78 kW – 10 MW
Energy Storage, Nominal:	220 kWh – 40 MWh
Energy Storage, Discharge Duration:	2 – 12 hours

- Adding additional energy does not require additional cell stacks
- Battery management costs remain nominally the same
- Can add additional stacks to increase power output without need to add more electrolyte
- Can tailor system to exact demands of energy capacity and power
  - Ideal for longer term storage applications +4 hours

Integration considerations: Safety Varies by Type and Chemistry

- Aqueous non and hybrid flow have low thermal runaway risk
- Gas evolution primary concern for aqueous systems
  - Hydrogen for all chemistries
  - Other gases depending on electrolyte used (Cl_2 from mixed-acid vanadium, Br_2 from Zn-Br)
- Organic systems have unknown safety concerns
- Leaks possible for all systems and need to be monitored
- Scale and size make safety concerns more significant



Chalamala, B. et al. Proceedings of the IEEE, 2014.

Integration considerations: Day to Day Operation and Maintenance

Operational

- Stack efficiency vs total system efficiency
- Electrolyte temperature
- Min and max SOC range
- Min and max currents
- Flow rate
- Electrolyte rebalancing
- Start up time before system is ready to provide power
- Hybrid systems require reset cycling periodically
- Gas buildup in Electrolyte tanks

Equipment

- Pumps
- Pipes/checking for leaks
- Stack care
  - Electrode
  - Membrane
  - Electrical contacts
  - Bi-polar plates
- Component corrosion from interactions with electrolyte or evolved gases
- Component corrosion from side reactions during operation

Current Development Status

Flow Batteries:

Varies by chemistry and type

Few well established companies

~85 systems either announced or operational*

- 800MW total power

Systems are being scaled to MW size

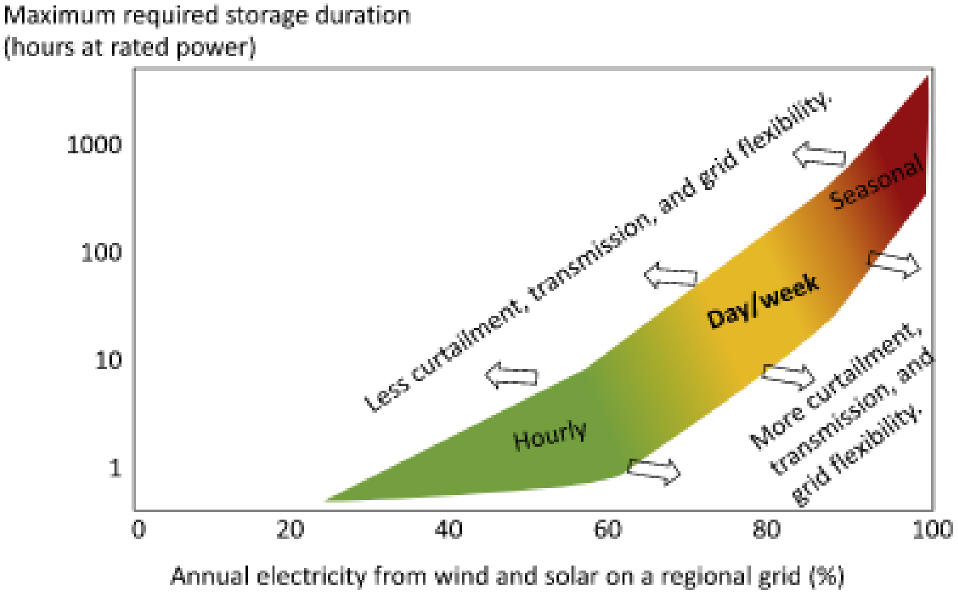
- Jumping straight from smaller systems to grid scale
- Leading to growing pains with BESS and system scale up
- AMO just funded projects on this last fall

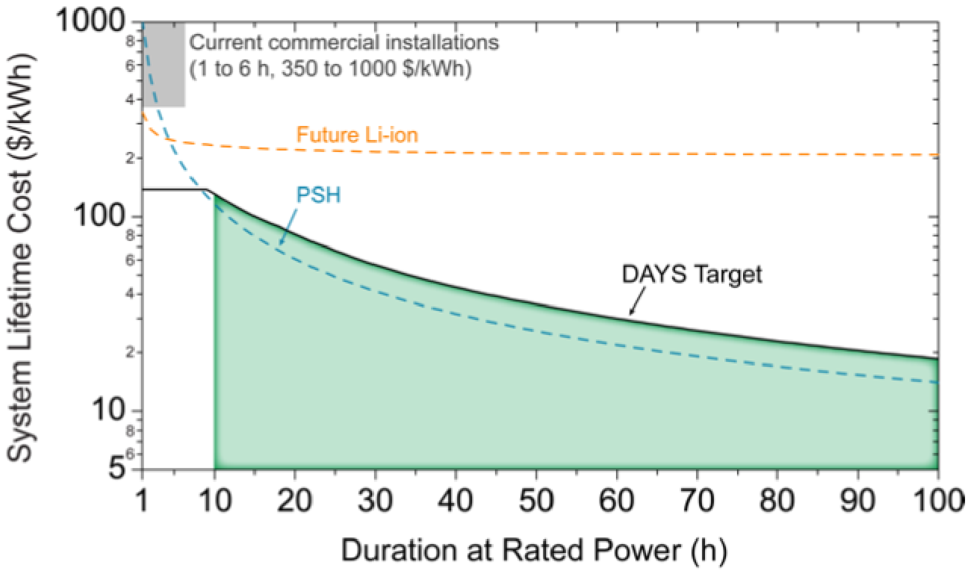
Li–ion Batteries:

- Wide range of established types with new in development
- Large number of existing vendors to purchase cells from
- 600+ systems announced or operation*
  - 2GW total power
- Developed for consumer electronics before grid applications
  - Many issues resolved before systems were scaled up.

*System and power numbers are from DOE OE Global Energy storage Database: https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/

What is the Right Fit for Each Technology?





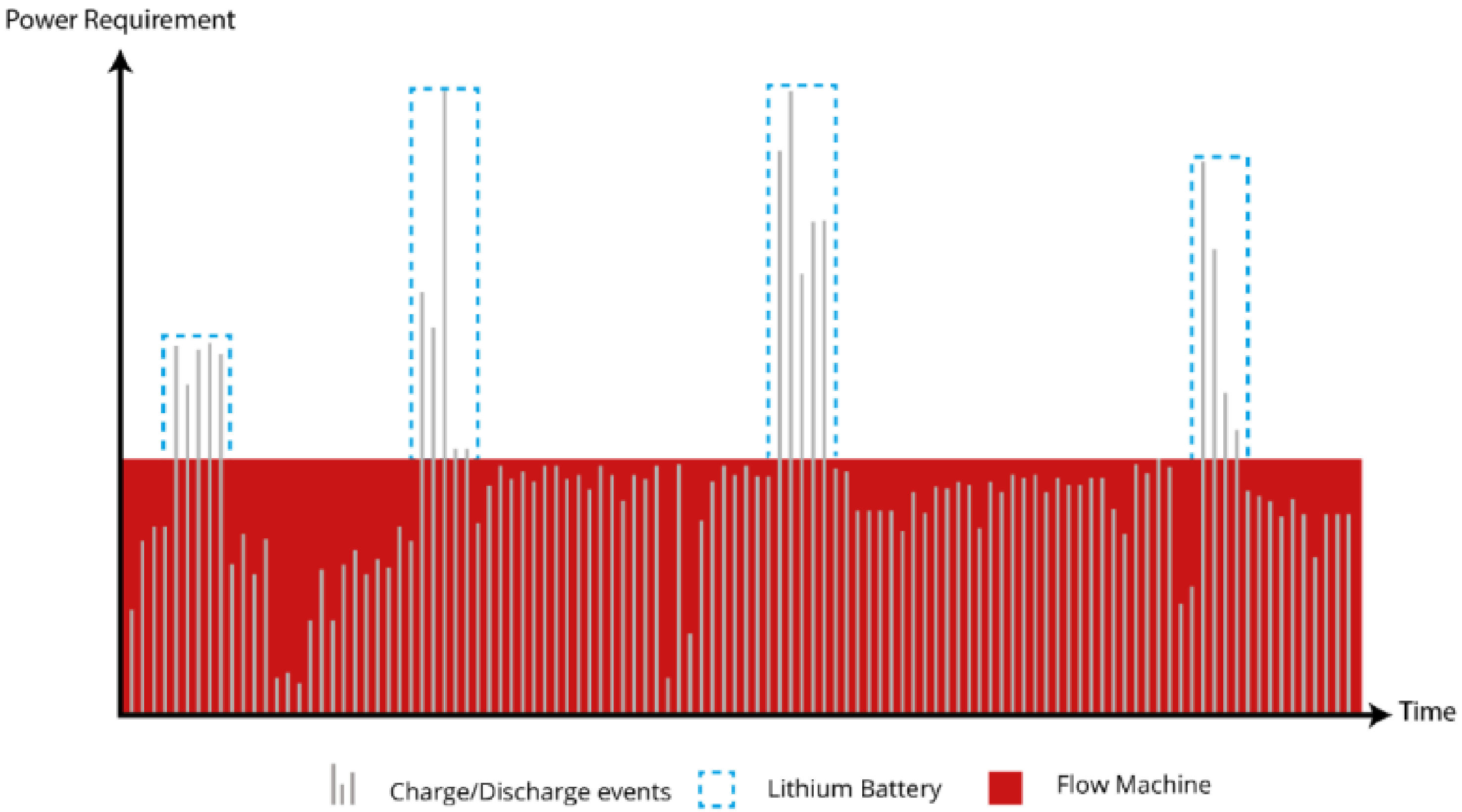
Albertus et al., Joule 4, 21-32, January 15, 2020

Applications	Storage system size	Target discharge duration	Minimum cycles/year
Energy arbitrage	1 – 500 MW	Up to 8 hours	250+
Renewable energy time-shift	1 kW – 500 MW	3 – 5 hours	
Electric supply capacity	1 – 500 MW	2 – 6 hours	5 – 100
Load following	1 – 500 MW	2 – 4 hours	
Area regulation	10 – 40 MW	15 minutes – 1 hour	250 – 10,000
Operating reserve (spinning, non-spinning, and supplementary)	10 – 100 MW	15 minutes – 1 hour	20 – 50
Voltage support	1 – 10 MVAR	15 minutes – 1 hour	N/A
Black start	5 – 50 MW	15 minutes – 1 hour	10 – 20
Load following, ramping support for renewables	1 – 100 MW	15 minutes – 1 hour	N/A
Transmission upgrade deferral	10 – 100 MW	2 – 8 hours	10 – 50
Transmission congestion relief	1 – 100 MW	1 – 4 hours	50 – 100
Transmission stability damping control	10 – 100 MW	5 seconds – 2 hours	20 – 100
Distribution upgrade deferral and voltage support	500 kW – 10 MW	1 – 4 hours	50 – 100
Reliability and resilience	0.2 kW – 10 MW	5 minutes – 1 hour	
Power quality	100 kW – 10 MW	10 seconds – 15 minutes	10 – 200
Time-of-use energy cost management	1 kW – 1 MW	1 – 6 hours	50 – 250
Demand charge management	50 kW – 10 MW	1 – 4 hours	50 – 500

Alvaro Bastos, https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/

How Might Flow Batteries Work on the Grid?

Use case for hybrid VRFB and Li-ion system planned for Energy Superhub Oxford



From Invinity Energy Systems

Conclusions

- Flow batteries are unique energy storage technologies that require new considerations for operation
- They have lower power and energy density compared to other systems
- Flow batteries can scale energy storage capacity with ease making them attractive for longer duration storage needs +4 hours
- Integration of flow batteries to the grid need to consider a number of things traditional batteries do not have
  - Flow system (Pumps, and piping)
  - Electrolyte health
  - Integrated stack of cells
  - Balance pumping losses with flow rate
  - Scaling of system to desired application
- IEEE standard P1679.3 has more information, currently being revised

If you have any questions please reach out at: rwittm@sandia.gov

Comparison Performance and Cost Characteristics

	Energy Density (Wh/L)	Lifetime (Years)	Number of cycles	Round trip Efficiency	Self Discharge	Duration of discharge	$/KWh	$/kW
VRFB	16-35	20+	15,000+	60-80%	Near 0	4+ Hours	121-810	486-1,215
Li-ion	150-250	10	5,000	90%	.1-5% per month	Min to 4hr	486-3,078	729-3,240
Lead-Acid	80-90	12	1,300	77%	~5% per month	30sec to 2hr	521-643	1,042 – 1,286

- VRFBs are relatively low power and energy density storage devices
- Setup for long duration charge and discharge cycles
- Long cycle and calendar life help make total life time cost relatively low