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Side by Side Comparison of Redox Flow and Li-ion Batteries

PRESENTED BY

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Agenda

Introduction of Technologies

- Li-ion Batteries
- Redox Flow Batteries

Comparison of Performance Characteristics

Use Cases Comparison

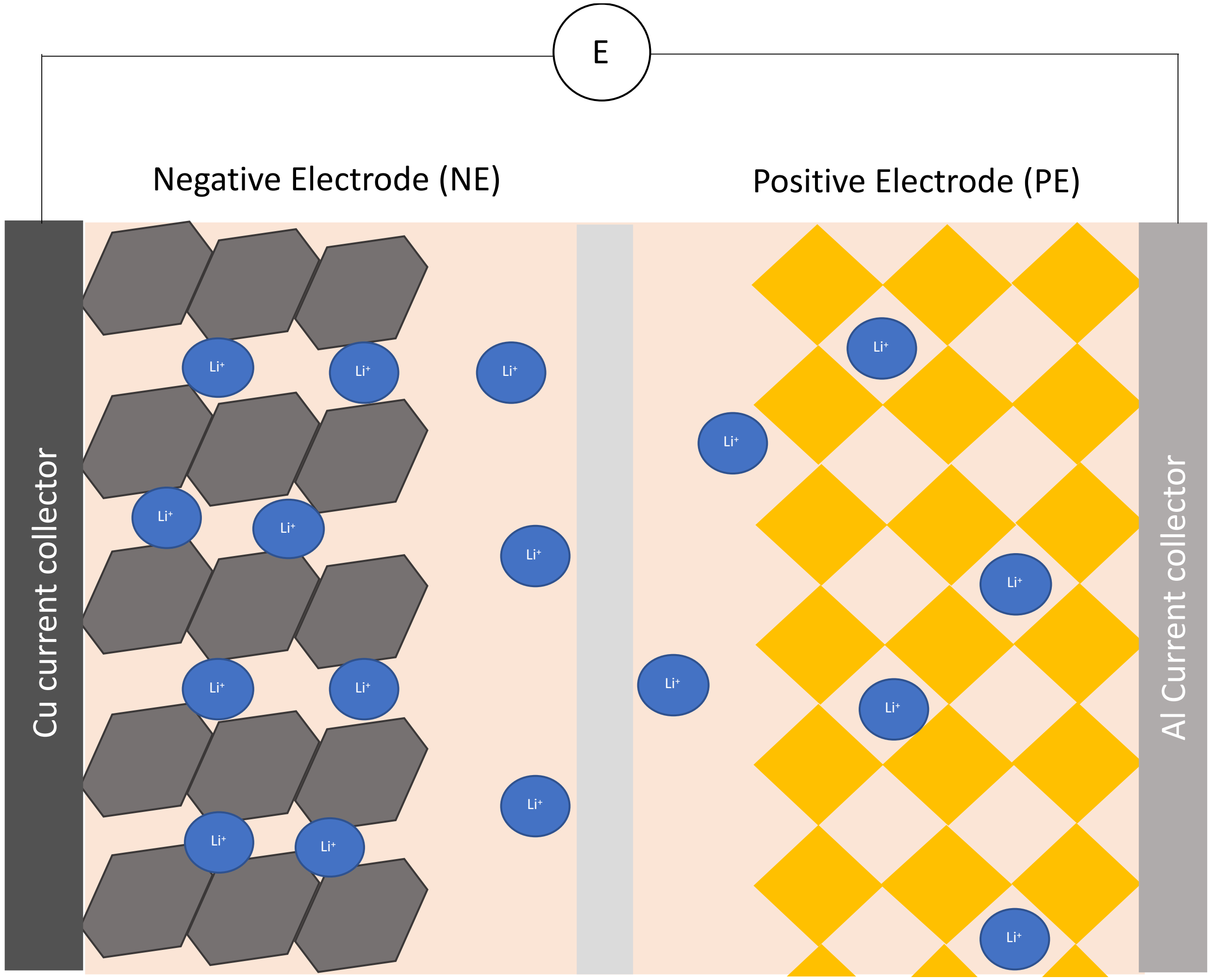
Conclusion

Introduction of Li-ion Cell Operation

Moves Li between two electrodes

When charged Li is stored in the Negative Electrode (NE)/ Anode

Li moves to Positive Electrode/ Cathode during discharge to release energy



General Characteristics of Li-ion Cells

High energy and power density

- 120-250 Wh/kg depending on chemistry

High efficiency

- 80-95% round trip efficiency

Relatively high cost

- $178-196/kWh for just the cell

Come in multiple formats

- Power and energy scale together

Long life

- 1,200 to 2,000 cycles at 80% depth of discharge (DOD)
- 10 year calendar life
- Degradation rate is dependent on cycling conditions (Temp, rate and DOD)

Fast response time

- 1-4 Sec

Thermal runaway risk needs to be managed

Numbers from: Energy Storage Cost and Performance Database
https://www.pnnl.gov/ESGC-cost-performance

Li-ion Cell Characteristic Vary with Cathode Composition

Cathode Chemistry	Pros	Cons	Active Companies
Nickel Manganese Cobalt Oxide (NMC)	• High energy density • Higher power density	• Higher thermal runaway risk • Lower cycle life	• LG Chem • Saft • Samsung • GE • BYD • CATL
Lithium Iron Phosphate (LFP)	• Long cycle lifetime • Lower thermal runaway risk • Removes cobalt and nickel • Lower installed and levelized cost	• Lower energy density • Lower power density	• A123 Systems • Samsung • Tesla • Saft • Lithium Werks • BYD • CATL

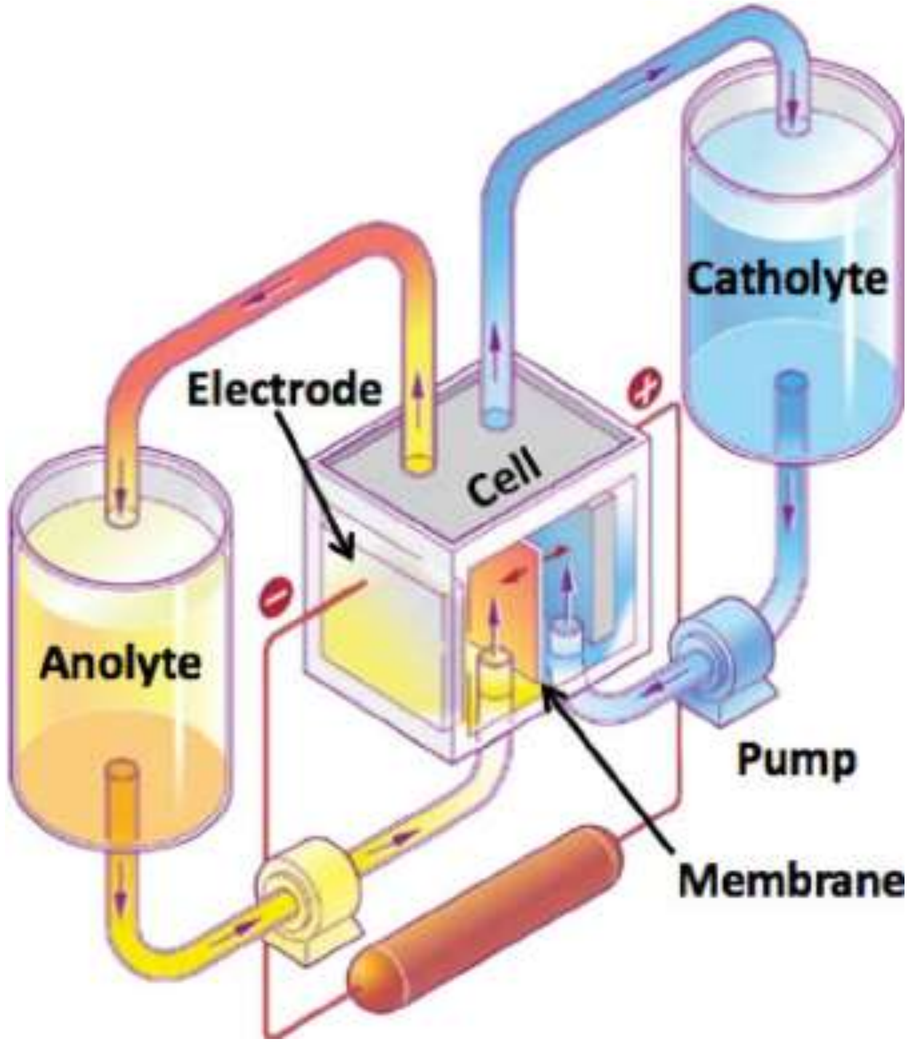
- Grid market has been dominated by NMC based cells
- Many companies are starting up lines of LFP based cells for grid storage

Introduction to Flow Batteries

Charged species is dissolved into electrolyte

Pumped from storage tanks to electrode stacks

Reaction takes place in the stack and products are pumped back to storage tanks



Travis Anderson, Sandia National Laboratories, 2013

General Characteristics of Flow Batteries

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
- Degradation not dependent on rate or DOD

Low energy density ~20-30Wh/L

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

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

Numbers from: Energy Storage Cost and Performance Database
https://www.pnnl.gov/ESGC-cost-performance

Flow Batteries Come in a Variety of Chemistries

Chemistry	System Type	Pros	Cons	Active Companies
All Vanadium	Aqueous flow All soluble	• No crossover contamination • Relatively high efficiency • Highly Scalable • Well researched and developed	• Limited energy Density • Relatively high cost • Low thermal Stability	• Sumitomo Electric Industries • Largo Clean Energy • Cell Cube • Invinity Energy • StorEn Technologies • VRB Energy • Rongke Power
Zn-Br	Aqueous hybrid Insoluble and soluble charge species	• High energy density • Low cost • High cell voltage • Well researched and developed	• Does not scale power and energy density independently • Low efficiency • Issues with long term cycling	• Redflow • Primus Energy • Gelion
Organic	Organic flow All soluble	• High power density • Low cost • Potentially high energy density	• Low long term stability • Currently low energy density • Increased flammability • Early in development	• Jolt Energy Storage Technologies • Jena Batteries • Green Energy Storage

Limitations of Flow Batteries

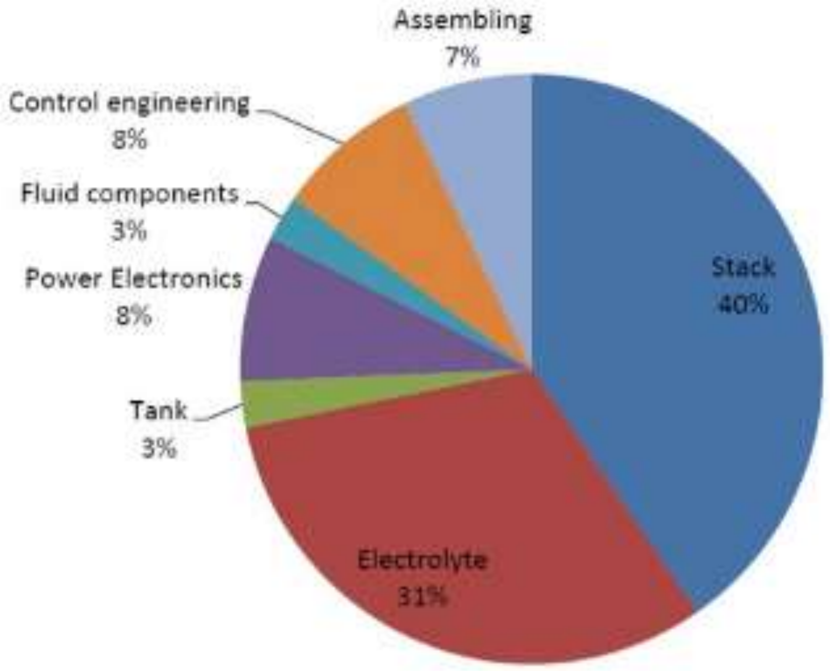
Low power and energy density
- Narrow voltage range
- Relatively low solubility of charge carriers

Low round trip efficiency
- 60-80%

Response time varies
- 0.1- 4 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
- Corrosion of membrane and electrode materials



Cost break down of a VRFB system, Energies 2016,9, 627

Data Compiled from:
Applied Energy 274 (2020) 115213, 10.1016/j.apenergy.2014.09.081
Energy Storage Cost and Performance Database https://www.pnnl.gov/ESGC-cost-performance
Largo Clean Energy, https://www.largocleanenergy.com/products

Comparison Performance and Cost Characteristics

- 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
    - VRFB costs are uncertain due to lack of fielded systems

	Li-ion (LFP and NMC)	VRFB
Energy Density (Wh/L)	150-250	16-35
Power Density (W/L)	1.5K-10K	~2
Lifetime (Years)	10	20+
Number of cycles	1,200-2,000	5,000-15,000
Round Trip Efficiency	90%	60-80%
Self Discharge	.1-5% per month	Near 0
Duration of Discharge	Min to 4hr	4+ Hours
Total Installed energy capacity cost ($/kWh)*	379 - 531	541 - 661
Total Installed power cost ($/kW)*	1,517 - 2,122	2,163 - 2,644
Levelized Cost ($/kWh)*	0.356 - 0.712	0.286 - 0.318

*Number are estimates based on PNNL projections of system costs, lifetime, energy through put and expected cycle numbers for a 1MW/4MWh system. May differ from actual install and operation costs.

Data Compiled from:
Applied Energy 274 (2020) 115213, 10.1016/j.apenergy.2014.09.081
Energy Storage Cost and Performance Database https://www.pnnl.gov/ESGC-cost-performance

Current Development Status

Flow Batteries:

Varies by chemistry and type

Few well established companies

~85 systems either announced or operational*

- 298MW total power as of Nov 2020

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 FOA out now on this topic

Li–ion Batteries:

Wide range of established types with new in development

Large number of existing vendors to purchase cells from

- Not all suitable for grid scale storage
- Competition from EV and commercial cells for resources

600+ systems announced or operational*

- 2GW total power as of Nov 2020

Developed for consumer electronics and EVs before grid applications

- Many issues resolved before systems were scaled up
- New issues introduced when scaled to grid sizes

*System and power numbers are from DOE OE Global Energy storage Database: https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/ last updated 11/17/2020

How Each System Scales: Li-ion

1 cell
11.8Wh
11.4W

35cells
422.1Wh
614 W

Tesla model S Battery Pack

~7,000cells*
85kWh
96kW

Tesla PowerPack

~11,500cells*
232kWh
130kW

Tesla/SoCal Edison Energy Storage Station

~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
Tesla Model S: https://evannex.com/blogs/news/understanding-teslas-lithium-ion-batteries
Powerpack and SoCal Edison Energy Storage Station: https://www.linkedin.com/pulse/how-many-2170-cells-tesla-80mwh-powerpack-system-frederic-rivollier/

How Each System Scales: Flow Batteries

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

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

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

From Largo Clean Energy
https://www.largocleanenergy.com/products

- 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 Each System Scales: Flow Batteries

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)

https://www.cellcube.com/the-cellcube-1

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

https://sumitomoelectric.com/products/redox

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

https://invinity.com/solutions/vanadium-flow-batteries/

- Adding additional energy does not require additional cell stacks
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- Can tailor system to exact demands of energy capacity and power
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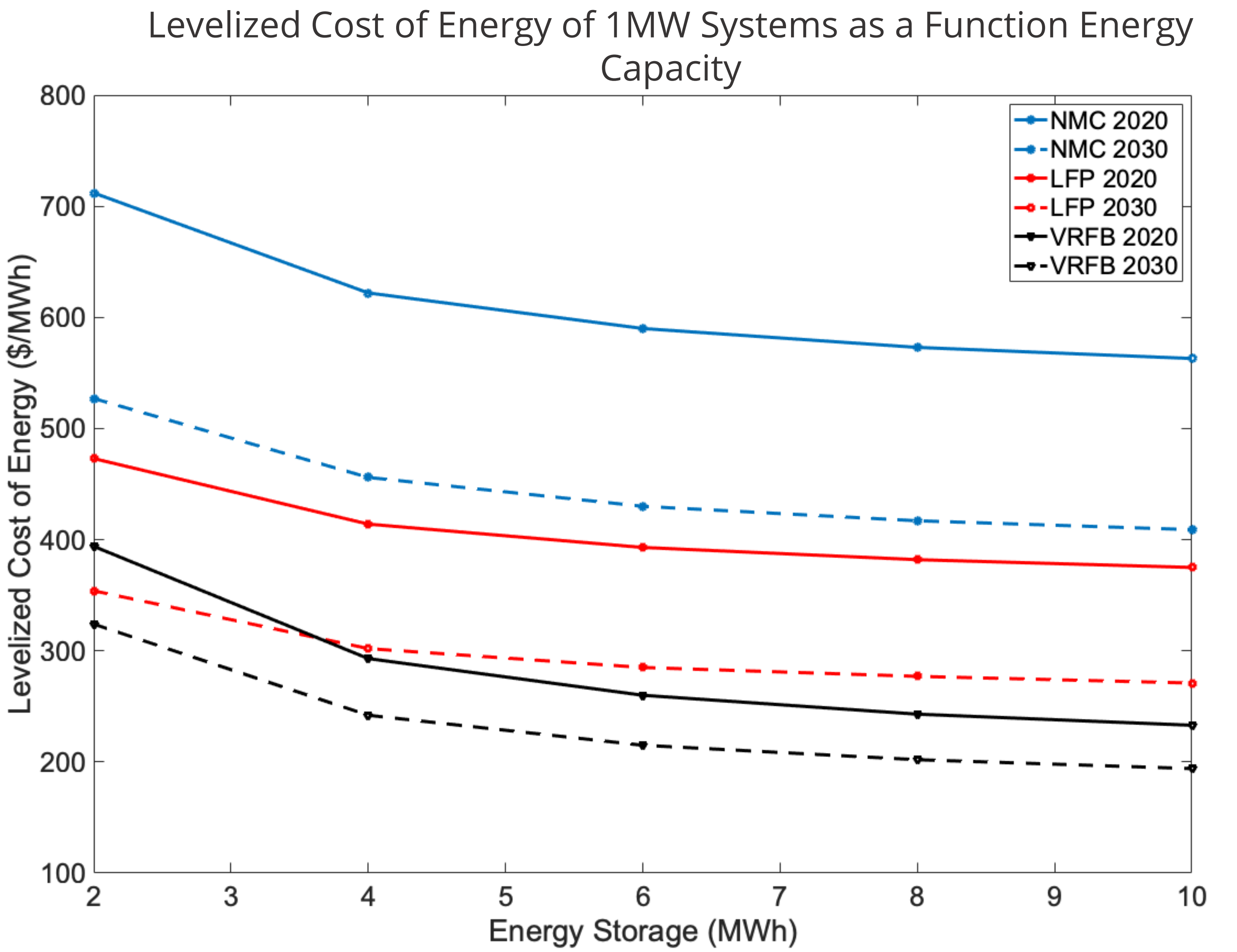
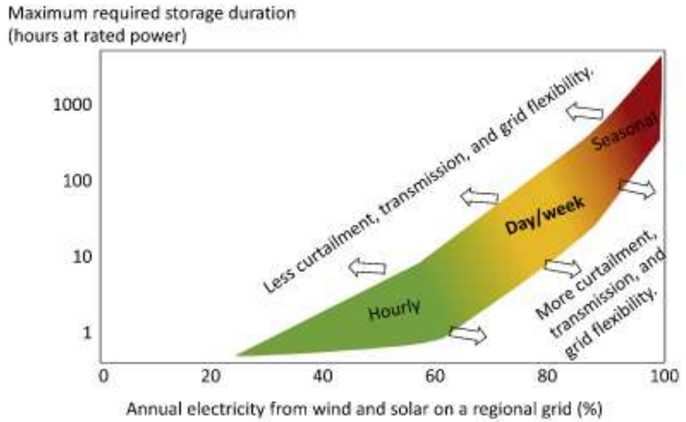
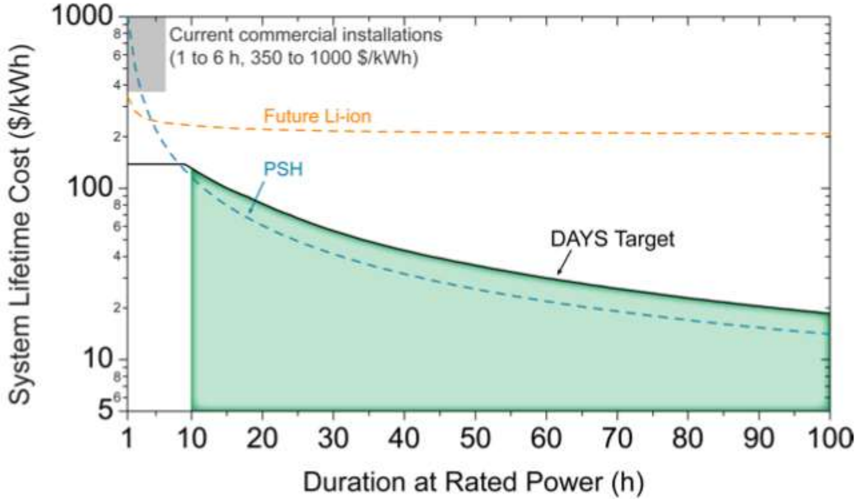
Cost of Storing Energy in VRFBs Decreases Significantly as Energy Capacity Increases



Data from PNNL Energy Storage Cost and Performance Database: https://www.pnnl.gov/ESGC-cost-performance

What is the Right Fit for Each Technology?





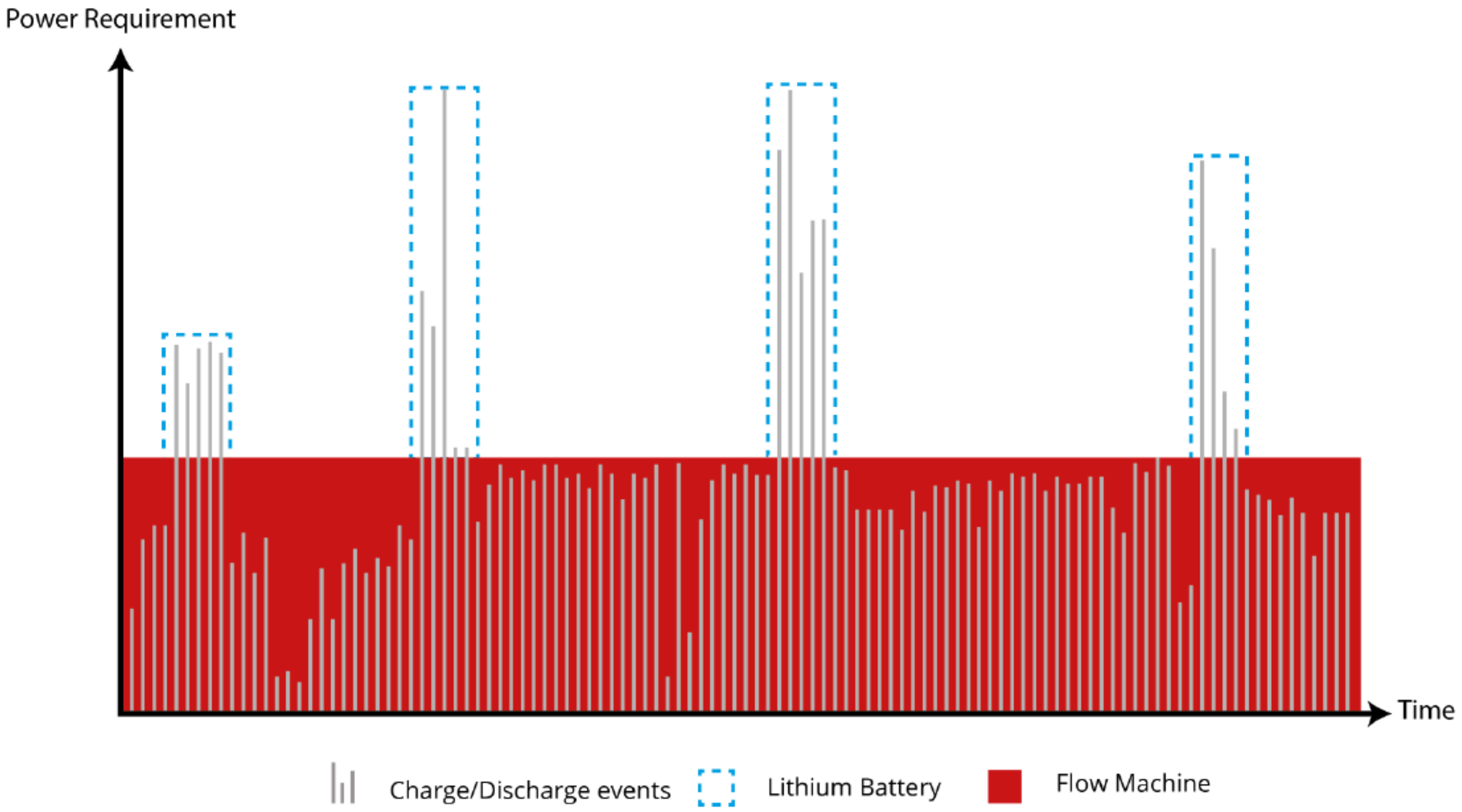
Albertus et al., Joule 4, 21-32, January 15, 2020

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 can both work together?

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



From Invinity Energy Systems: https://invinity.com/energy-superhub-oxford/

Conclusions

- Flow batteries are an emerging technology that may be able to satisfy emerging demands for energy storage on the grid
- They have lower power and energy density compared to Li-ion systems
- Flow batteries can scale energy storage capacity with ease, making them attractive for longer duration storage needs (+4 hours)
- Several challenges need to be resolved before systems are ready for broad commercial use
  - Scale up to MWh sized systems
  - High materials cost

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