# Next Generation Redox Flow Battery Development at PNNL

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**Pacific Northwest National Laboratory**

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

EESAT
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# Project Overview

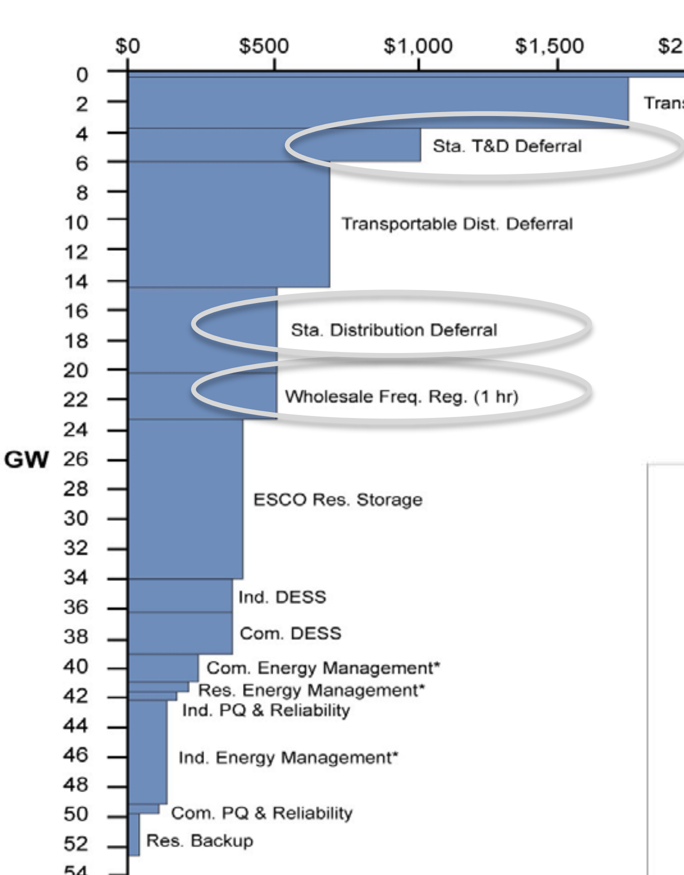
## Project Objective

- Develop lower-cost, multi-functional redox flow battery for stationary energy storage.

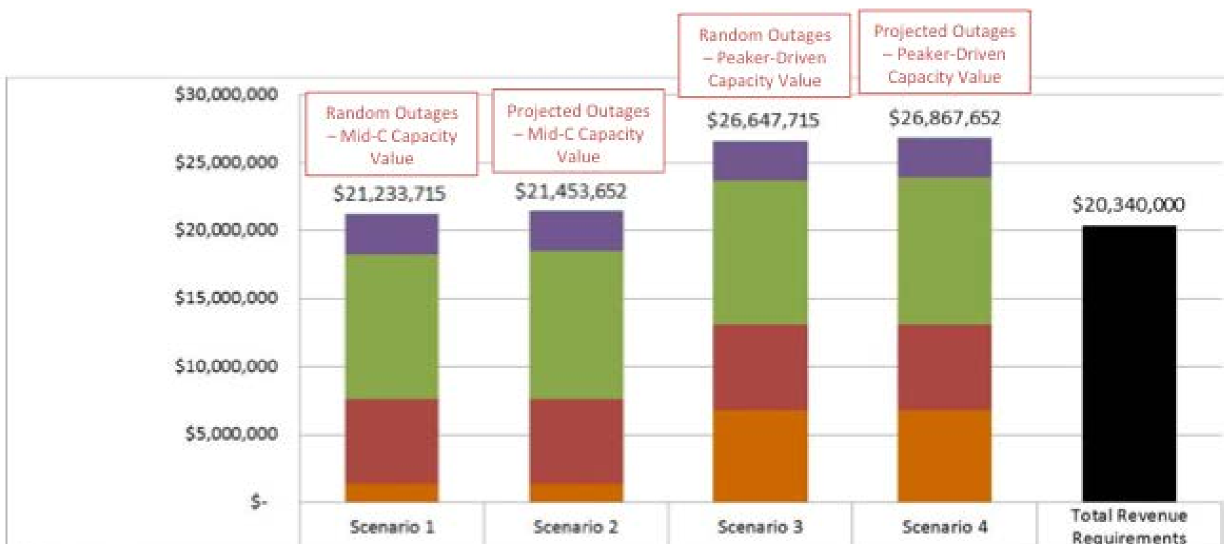
## Outline

- Enhanced value for energy storage technologies that can enable bundled services.
- V/V Redox Flow battery development at PNNL
- Cost projections curves for Redox Flow and Li-ion technologies.
- Next generation redox flow batteries.

# Grid Energy Storage Diverse Markets Encourage Bundling and Cost Reduction



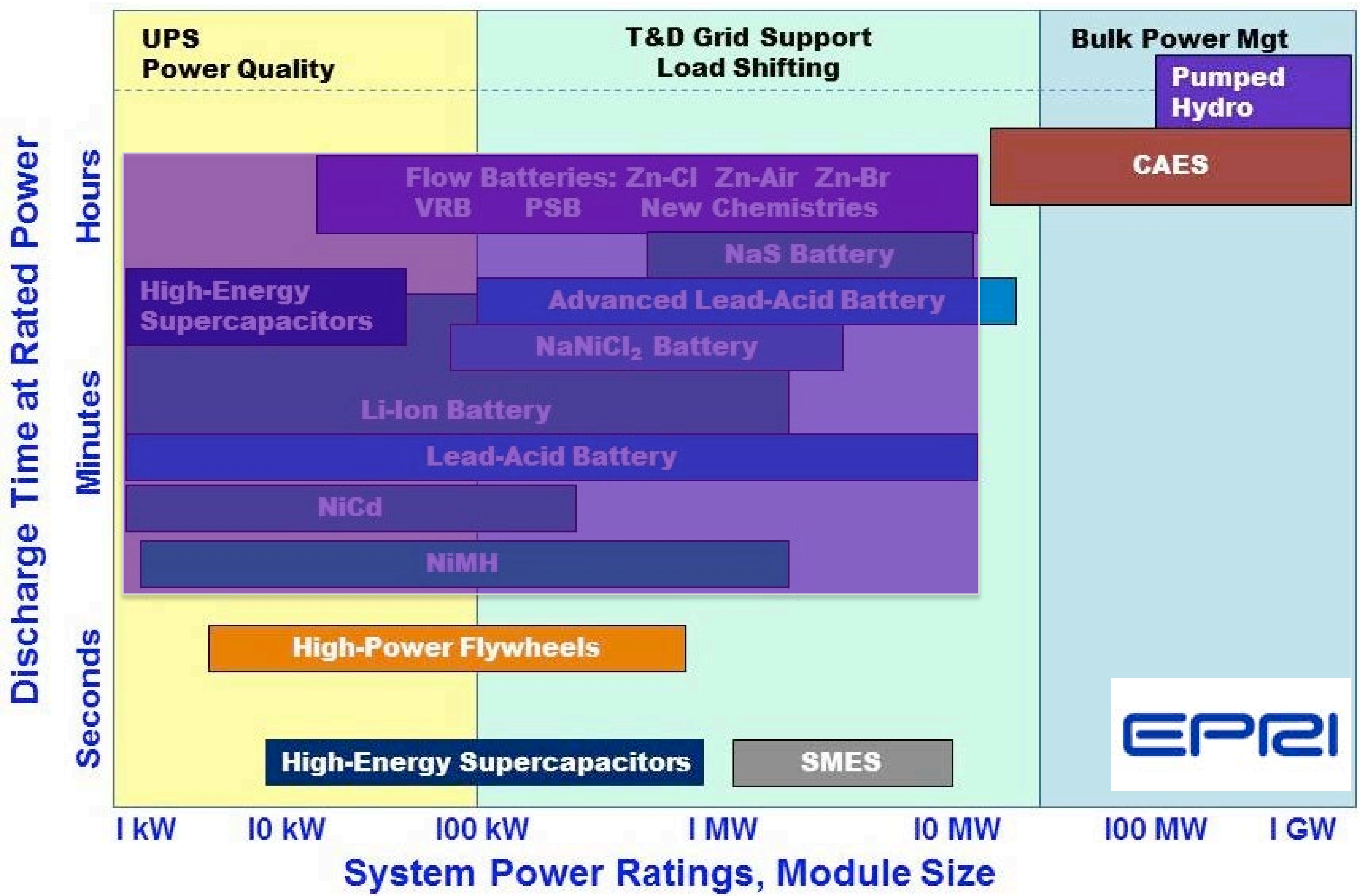

*EPRI – Electric Energy Storage Technology Options: A Primer on Applications, Costs & Benefits (2010)*




| | 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 | |

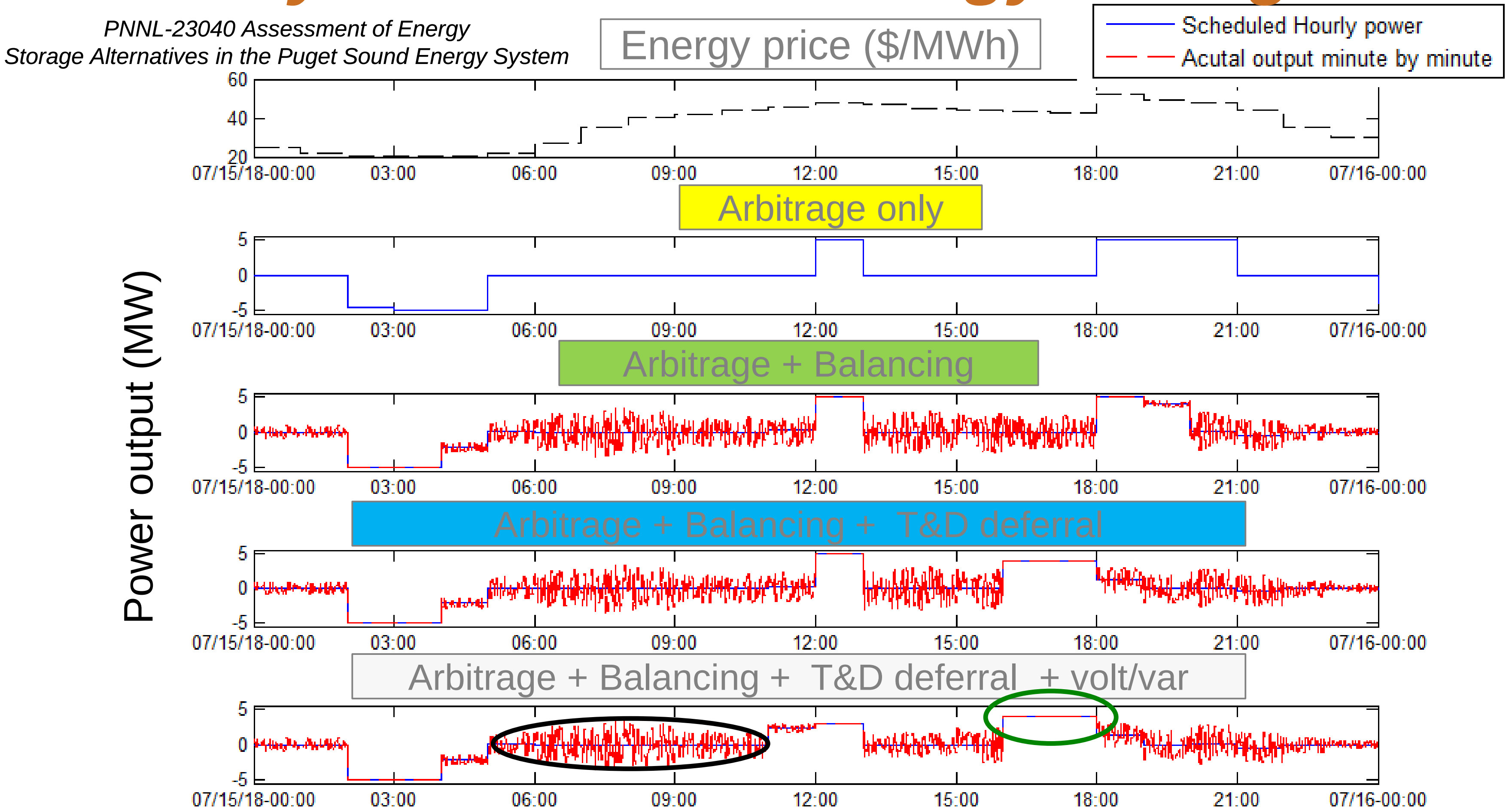
*PNNL-23040 Assessment of Energy Storage Alternatives in the Puget Sound Energy System*

# Electrical energy storage (EES) Options




*EPRI - Electricity Energy Storage Technology Options* 1020676

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




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

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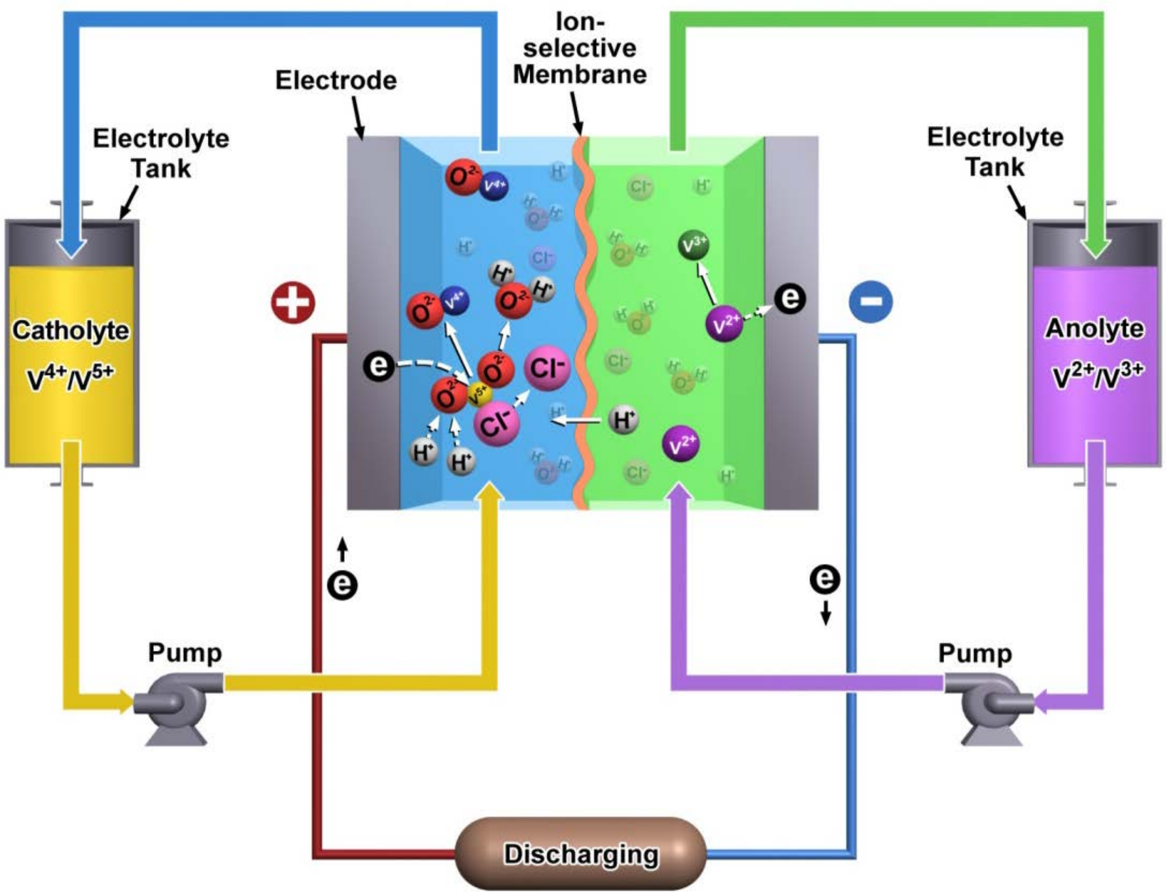
# Mixed Acid Vanadium Redox Flow Battery




Catholyte: $VO^{2+} + Cl^{-} + H_2O - e \xrightleftharpoons[\text{Discharge}]{\text{Charge}} VO_2Cl + 2H^{+}$ $\varepsilon_{co}=1.0$ V

Anolyte: $V^{3+} + e \xrightleftharpoons[\text{Discharge}]{\text{Charge}} V^{2+}$ $\varepsilon_{ao}=-0.25$

*Overall:* $VO^{2+} + Cl^{-} + H_2O + V^{3+} \xrightleftharpoons[\text{Discharge}]{\text{Charge}} VO_2Cl + 2H^{+} + V^{2+}$ $E_o=1.25$ V

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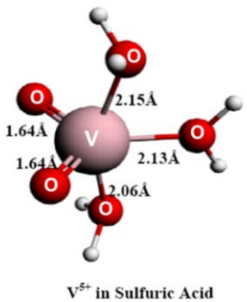
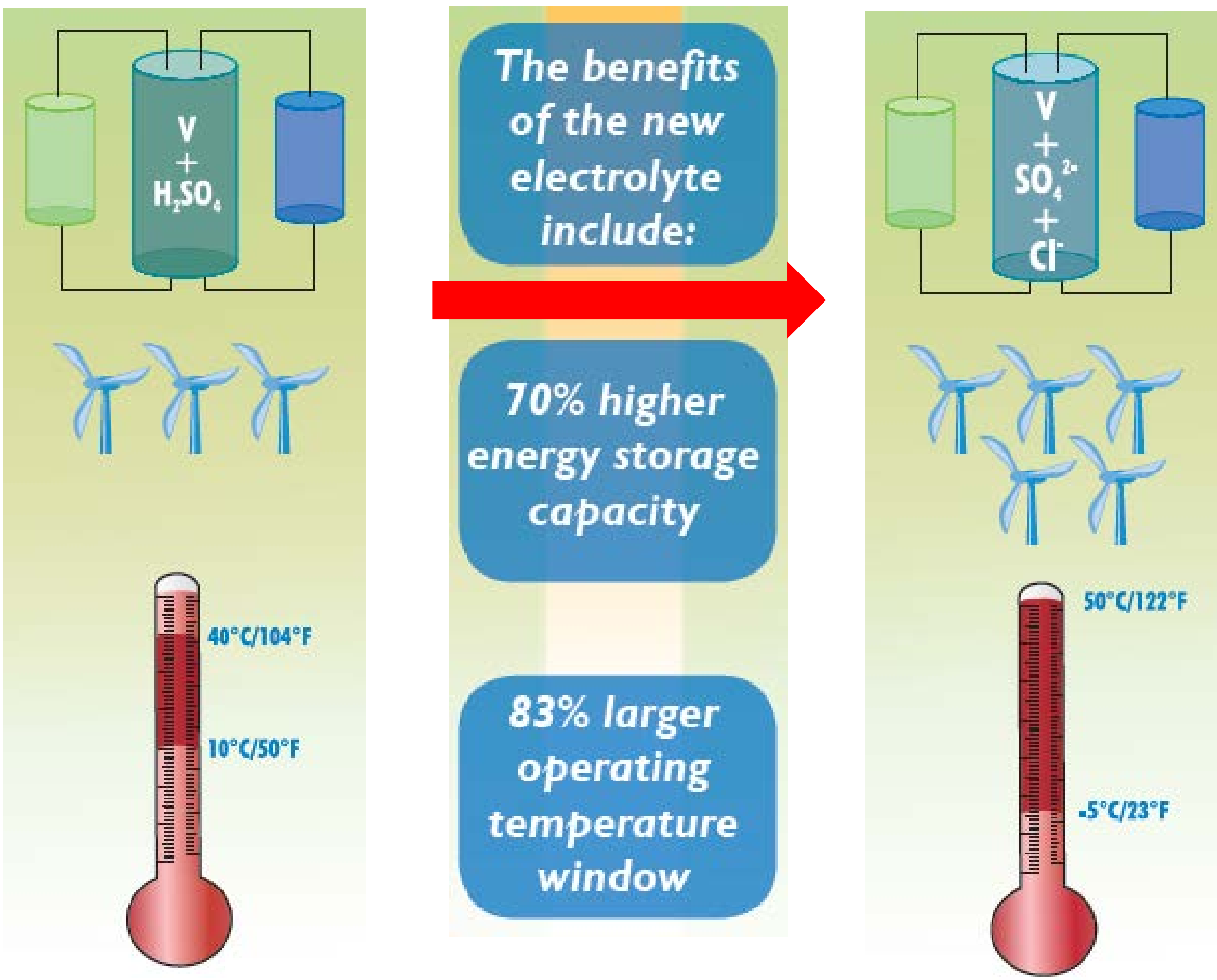
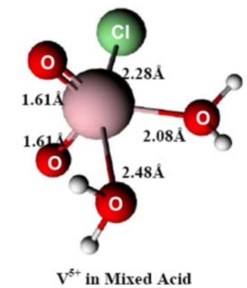
# A new vanadium redox chemistry based on $SO^{2-}$/$Cl^-$ supporting electrolytes

*Conventional Sulfate VRB*

Mixed Acid VRB

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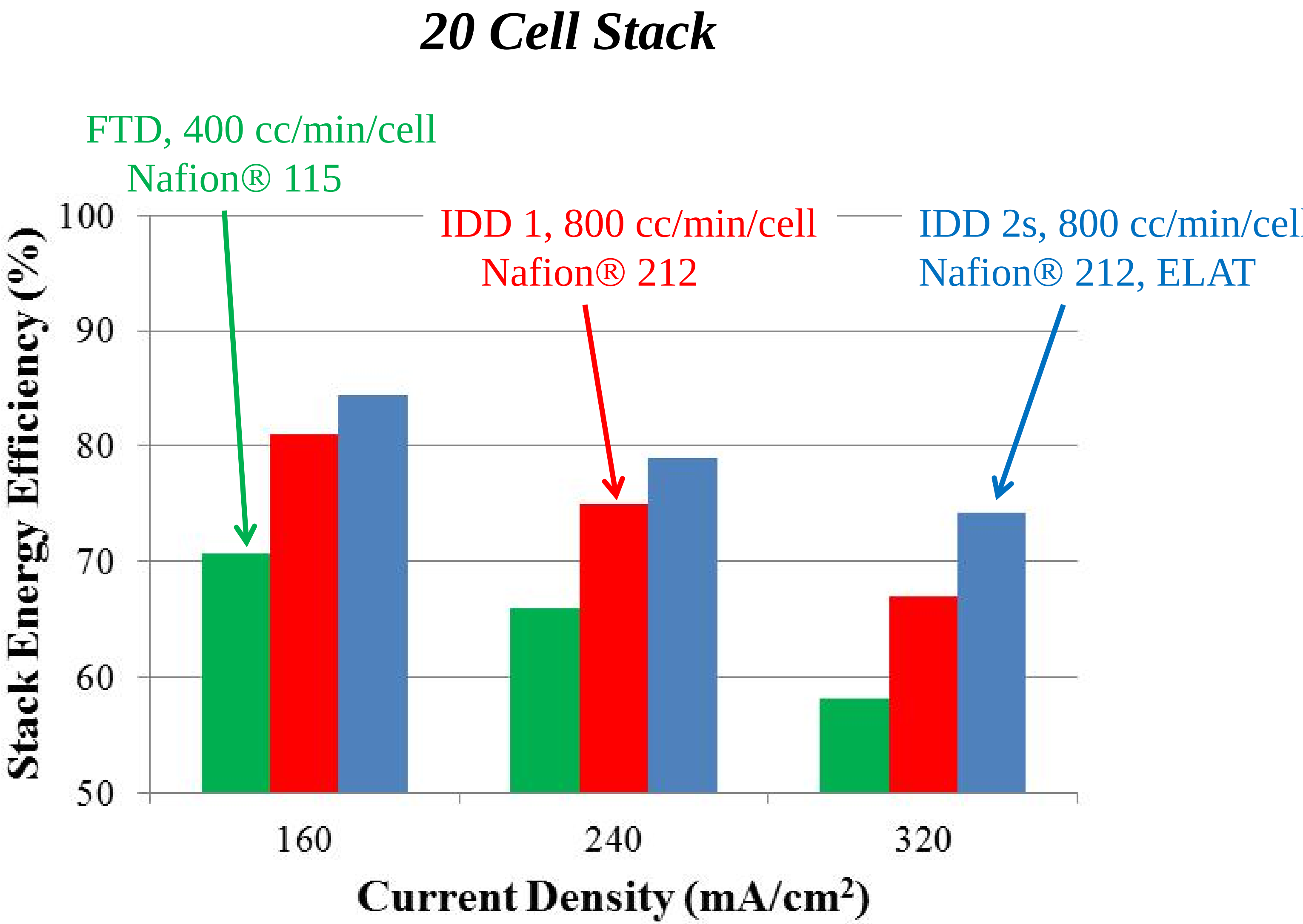
**Mixed-acids All Vanadium Redox Flow Battery (VRB)**

# FY15 Stack Performance

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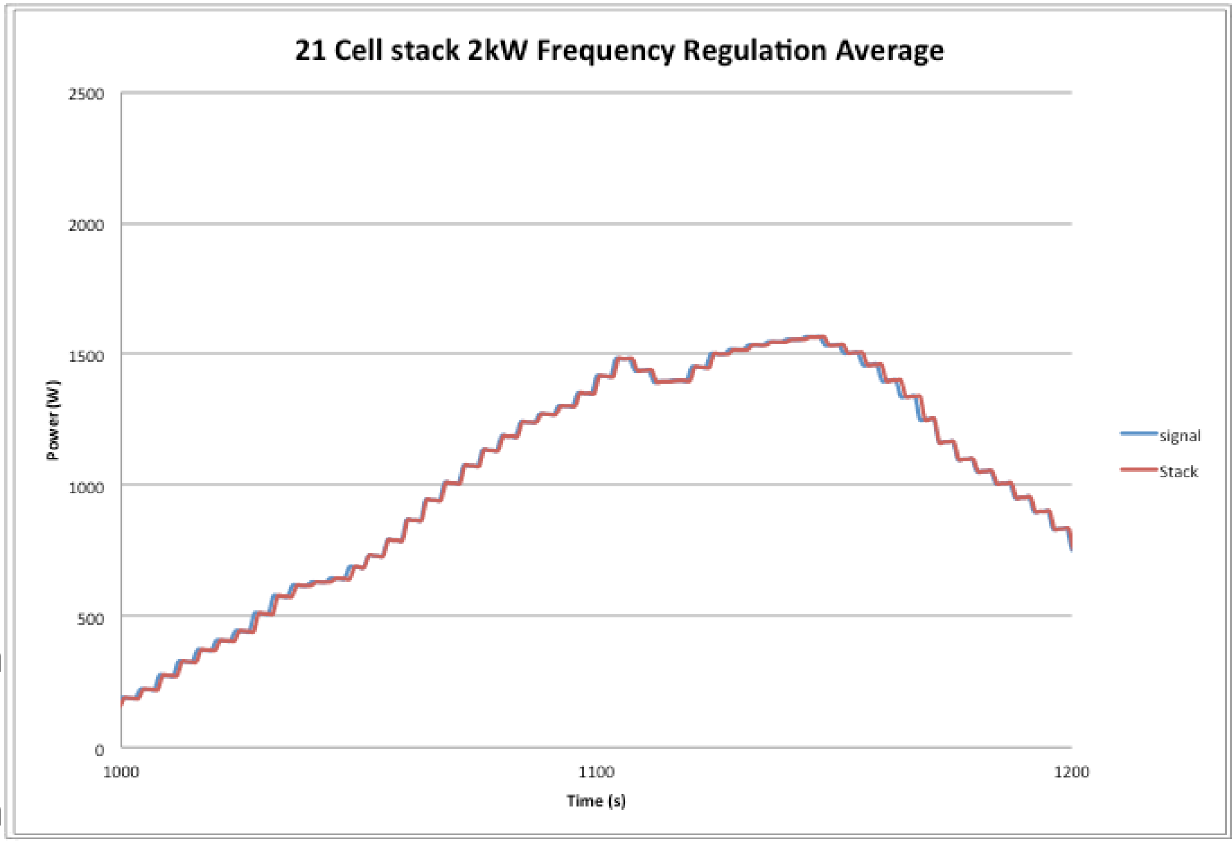
# 21 cell VRFB stack under Frequency Regulation protocol

- 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

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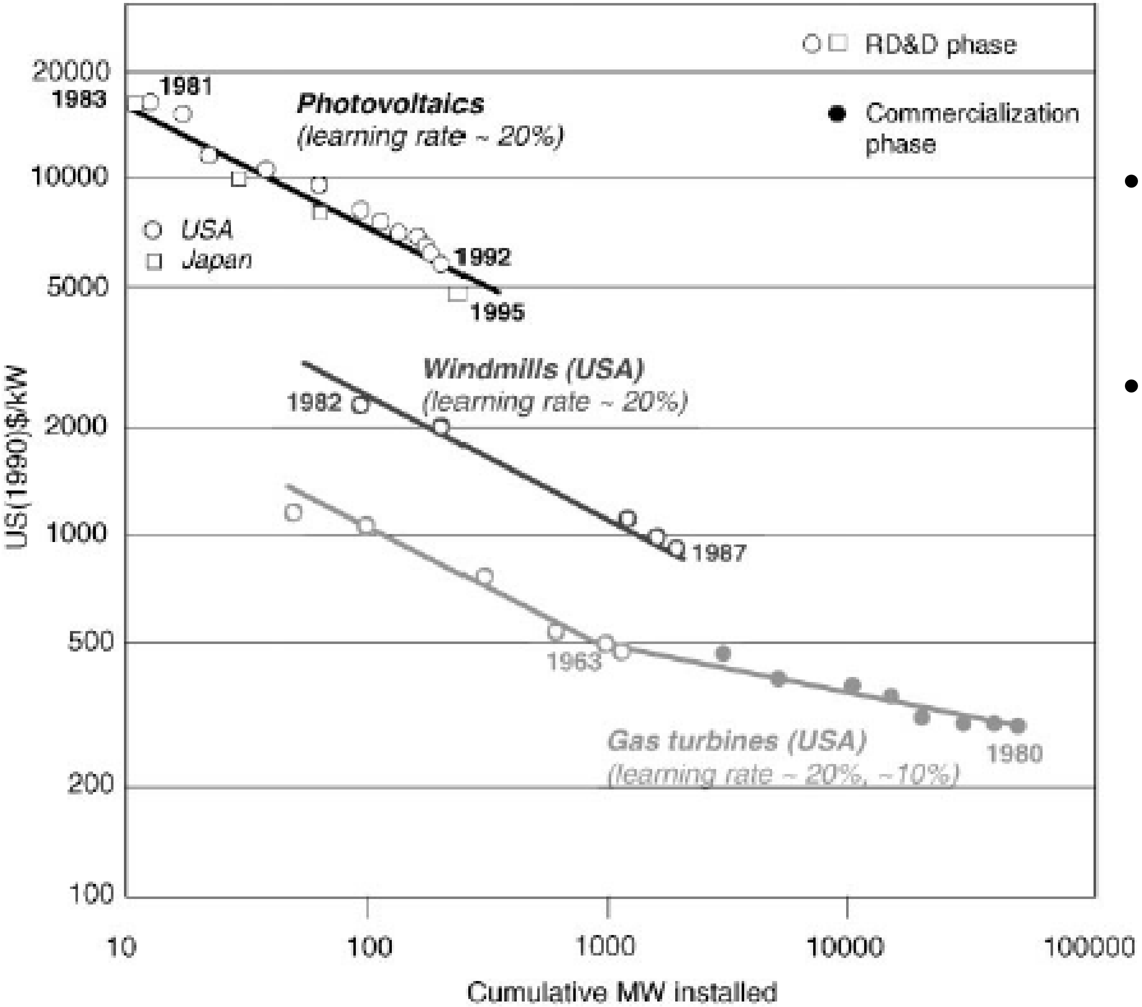
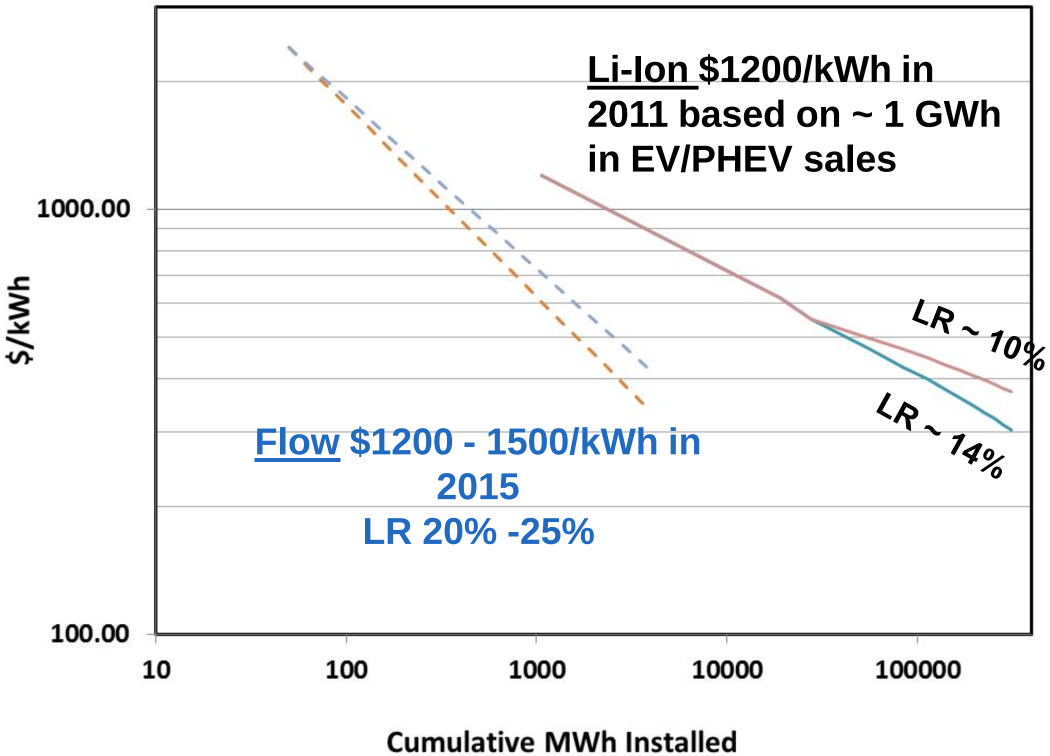
# Technology Learning rates




- Learning rate (LR) is defined as the % drop in cost as production volume doubles.
- Based on previous development of PV, windmills and gas turbines
  - Learning rate of -20% during early stage development/commercialization.
  - - 10% LR for full scale manufacturing.

*Gritsevski and Nakicenovic, Energy Policy 28 (2000) 907-921*

# Redox Flow and Li-ion Battery Price Projections (Preliminary)




## Redox

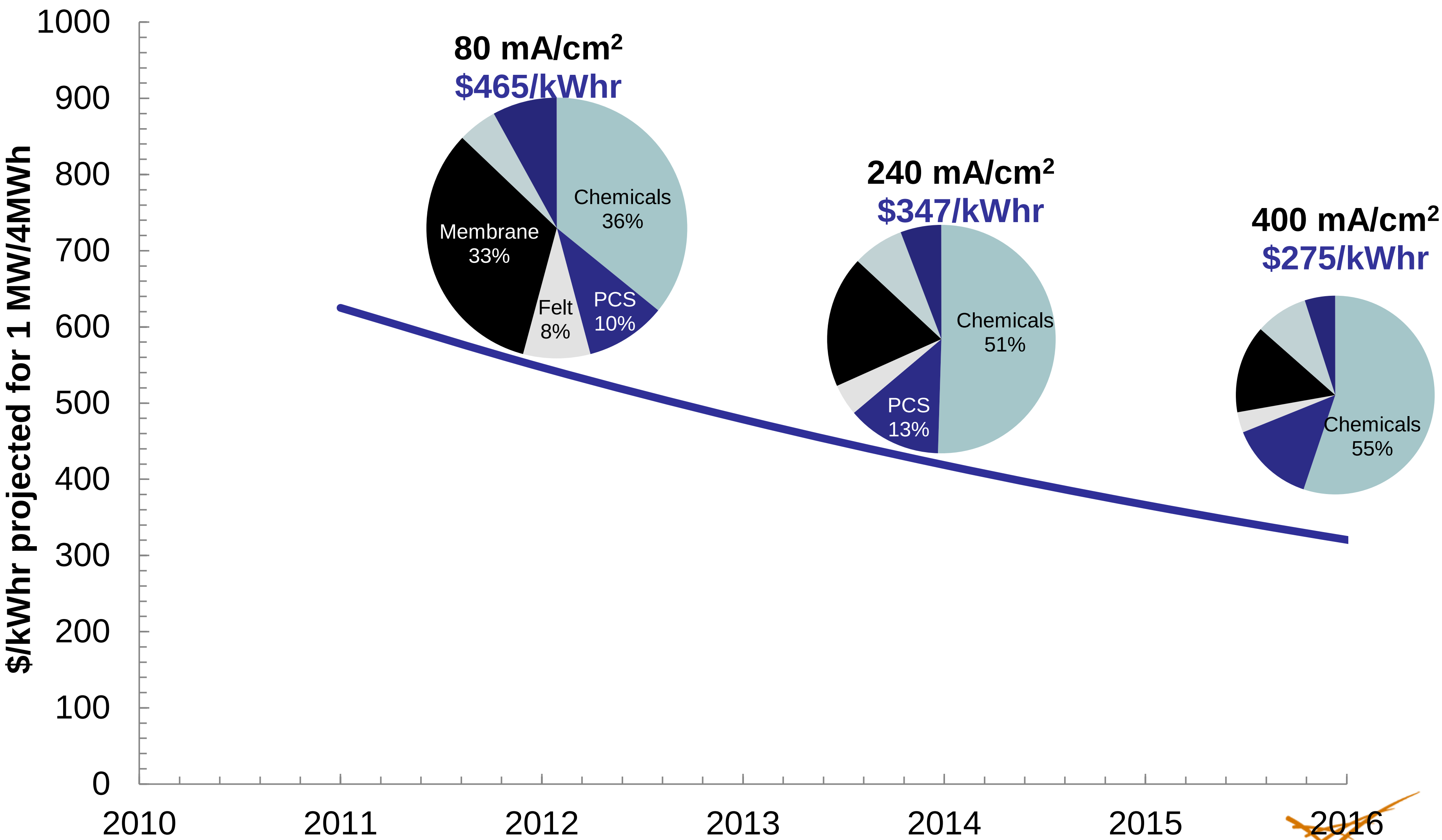
- @ 20 - 25% LR for redox, can achieve ~ $500 kWh with ***4 GWh*** of installed capacity.

## Li-ion

- First commercialized 1991
- ~ 15% LR 2011-2015 all EV/PHEV
  - $1200/kWh in 2011 – 1.06 GWh[1]
  - 2014 – projected 7.5 GWh[1,2]
    - ~15% LR
  - 2014 – Actual ~ 9 GWh[4]
- To maintain 15% LR requires 27.6 GWh in 2015
- Projected cost range of $300-375/kWh in 2025 for ***310 GWh*** cumulative production
- Stationary storage market:
  - 6.6 GWh by 2025[3]

1. Technology Roadmap, Electric and plug-in electric vehicles, IEA, Updated June 2011
2. Electric and plug-in hybrid vehicle roadmap, IEA, 2010
3. Source for stationary storage projected production rates: http://cleantechnica.com/2014/08/26/energy-storage-market-rises-50-billion-2020-according-lux-research/
4. http://evobsession.com/ev-battery-manufacturer-sales-market-share-march-2015/

# *Redox Flow System Component Cost Analysis*

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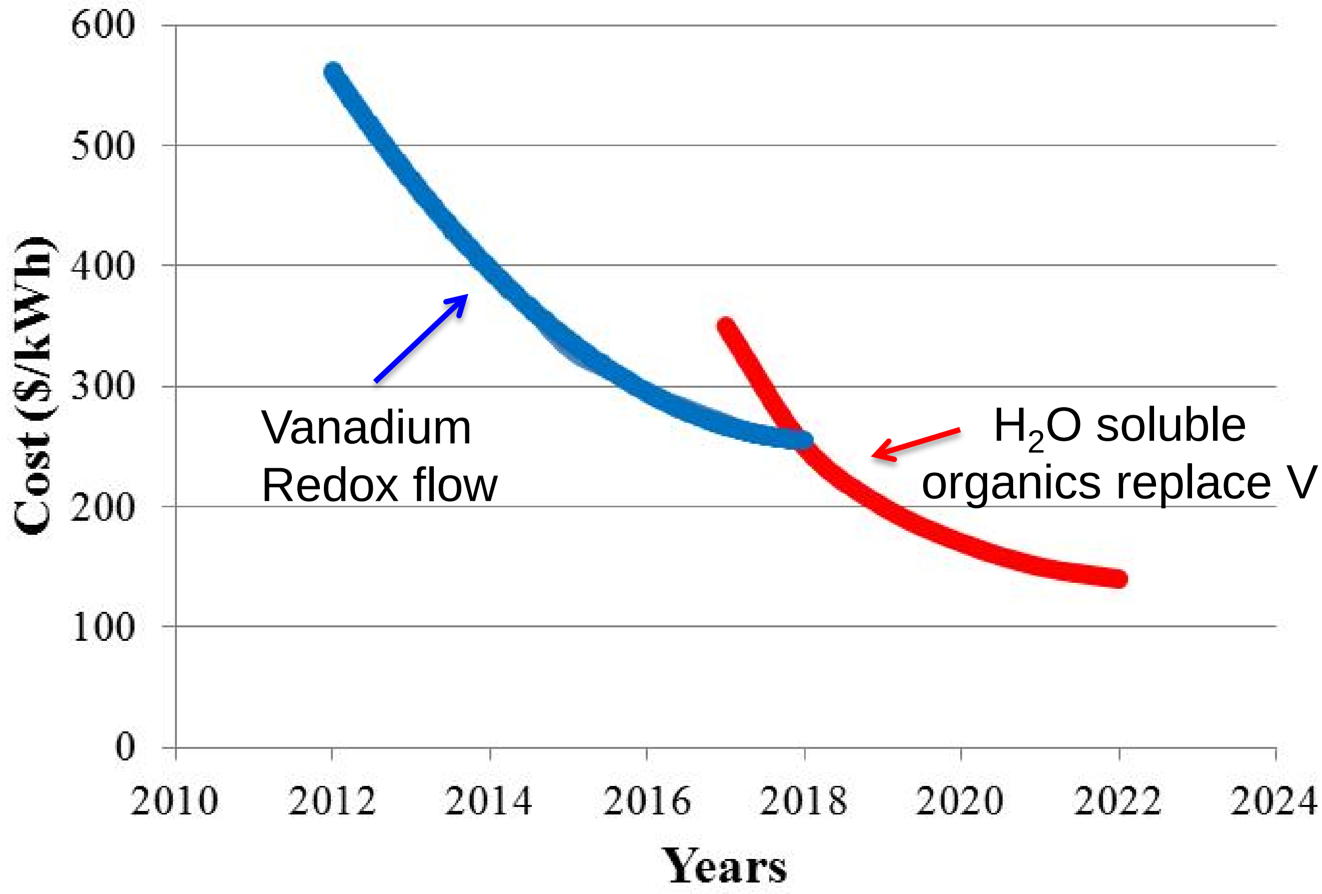
# Future Redox Battery Development

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# *Conclusions*

- The flexibility of redox flow battery technology offers the potential to capture multiple value streams from a single storage device.
- Current research has demonstrated high power conditions can be achieved with minimal impact in stack efficiency.
- Next generation RFB technology based on Aqueous Soluble Organics (ASO) being developed to replace vanadium species.
- Continued cost reductions in Li-ion technology will be driven by EV/PHEV deployments.  RFB maybe able to achieve similar cost targets at ~ 100X lower production volume.

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