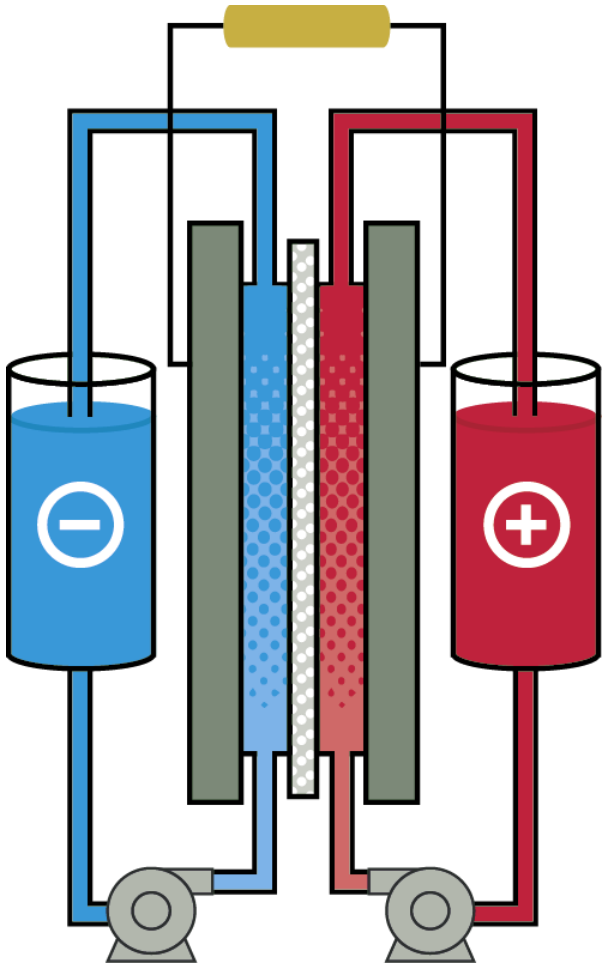
# Cost-targeted Design of Redox Flow Batteries for Grid Storage

**Jarrod D. Milshtein**

Giner, Inc.

Beyond the Hour and the Day: Long Duration Stationary Energy Storage, Chicago, IL
December 8th, 2017

# Redox Flow Batteries for Grid Storage





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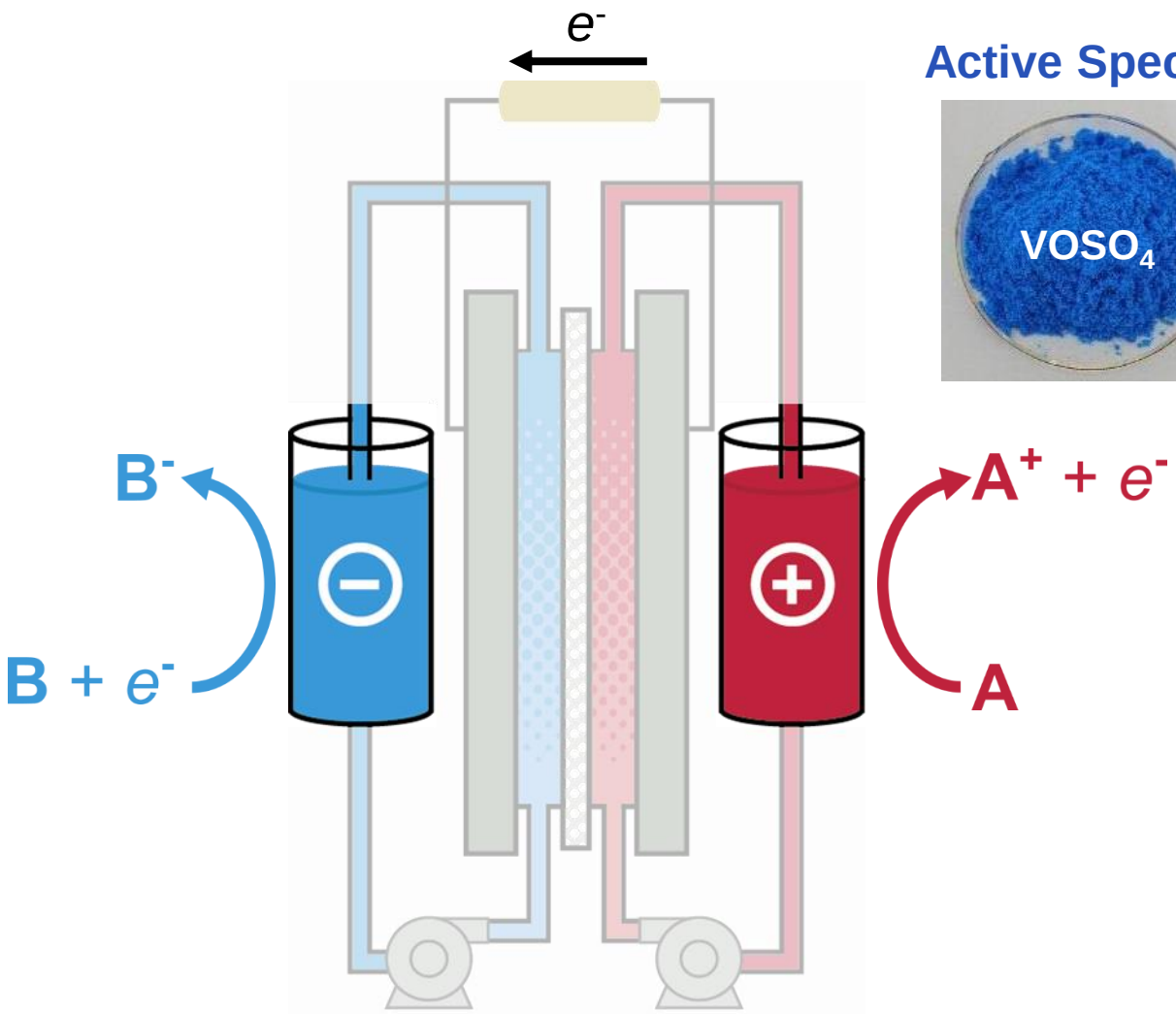


**Active Species**

**Supporting Electrolyte**

**Solvent**

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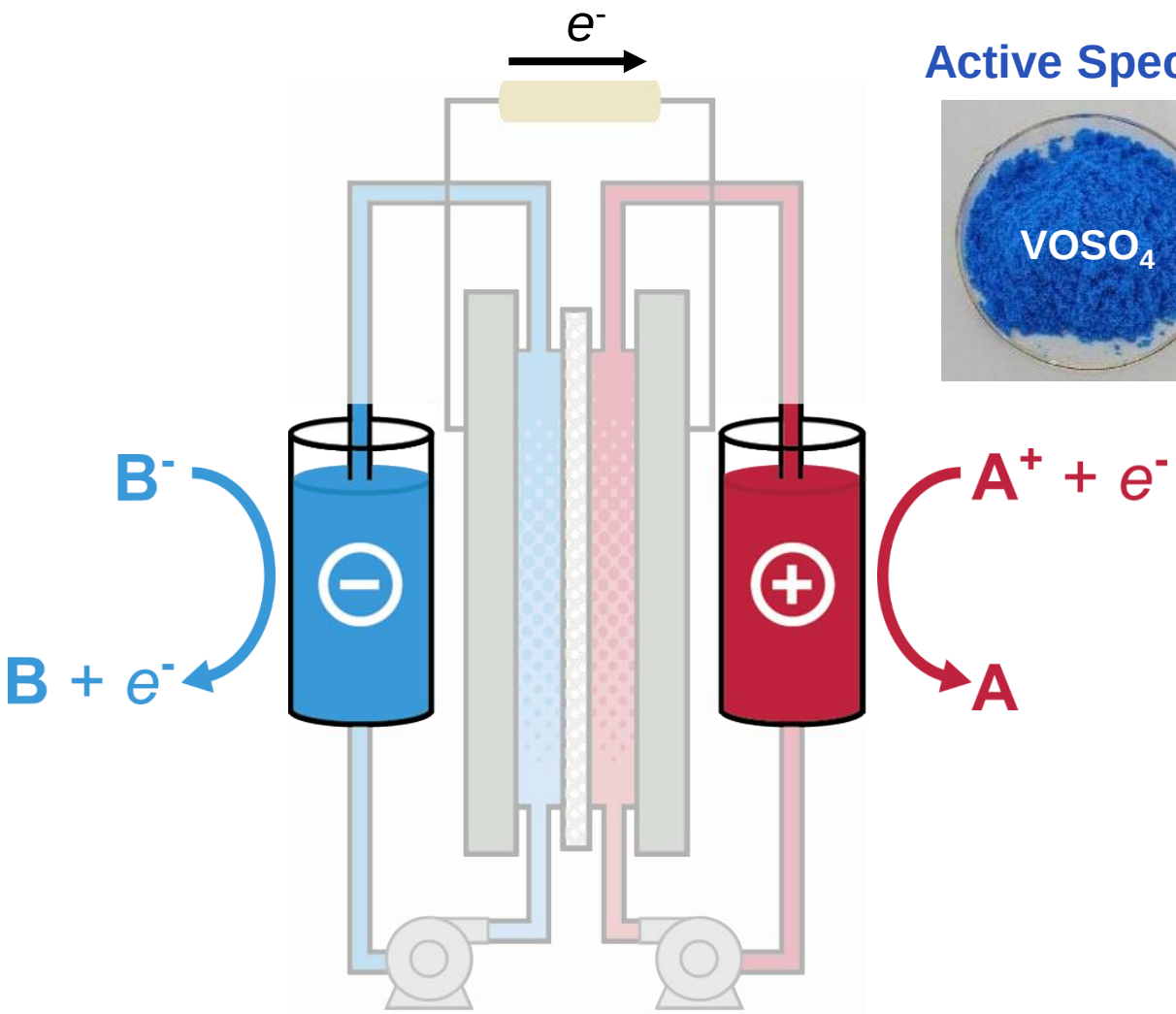


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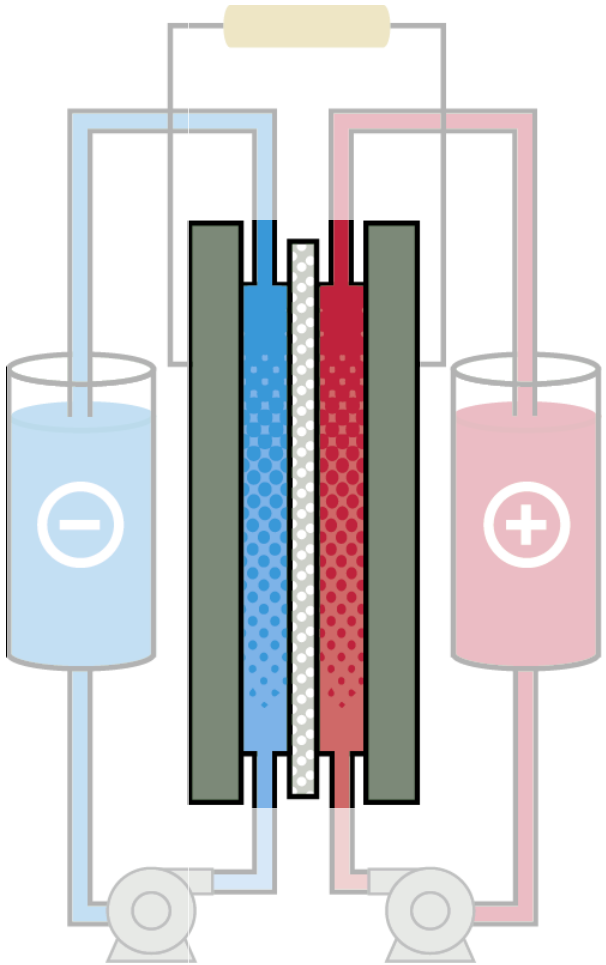

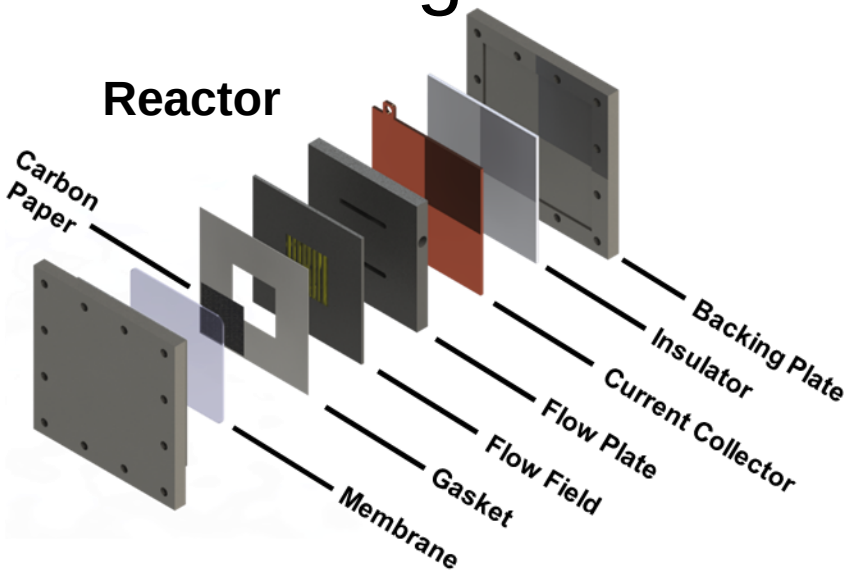




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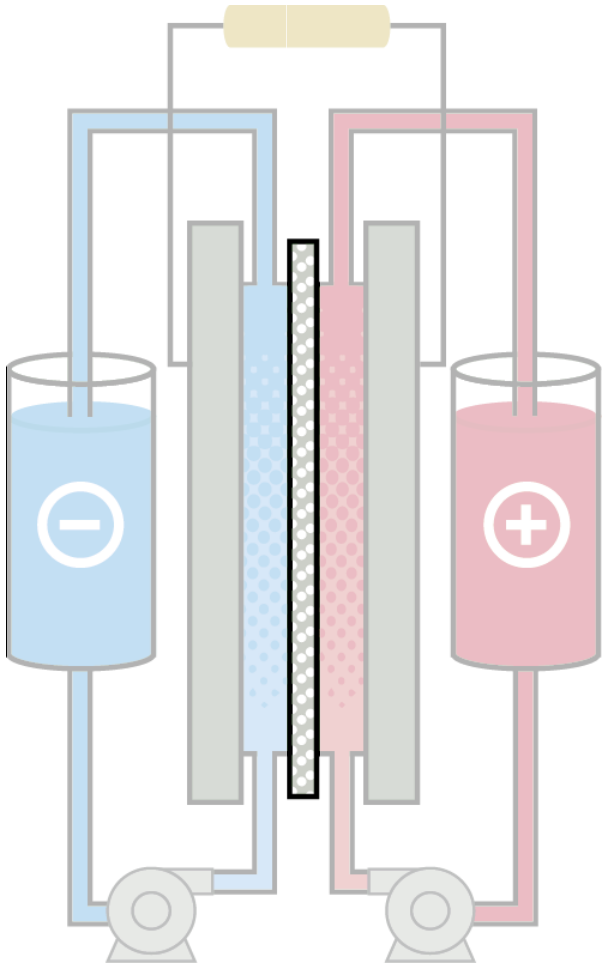

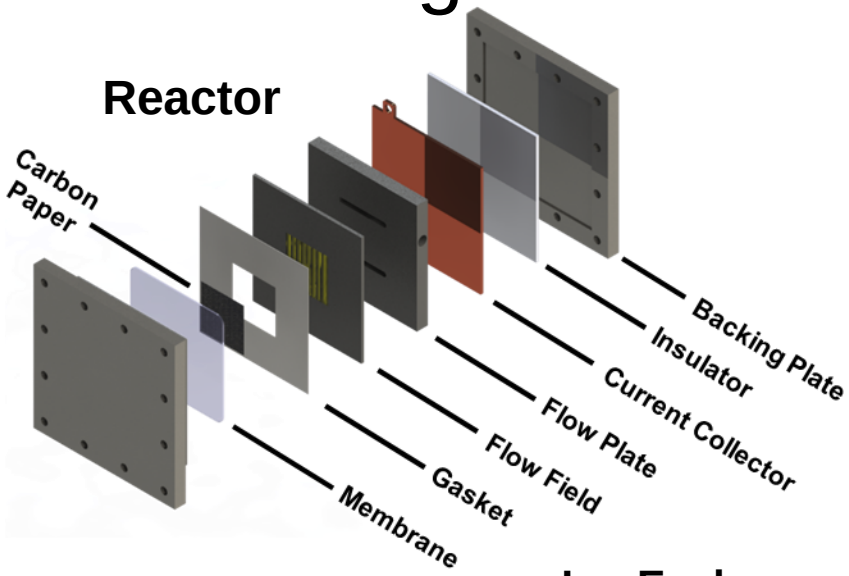


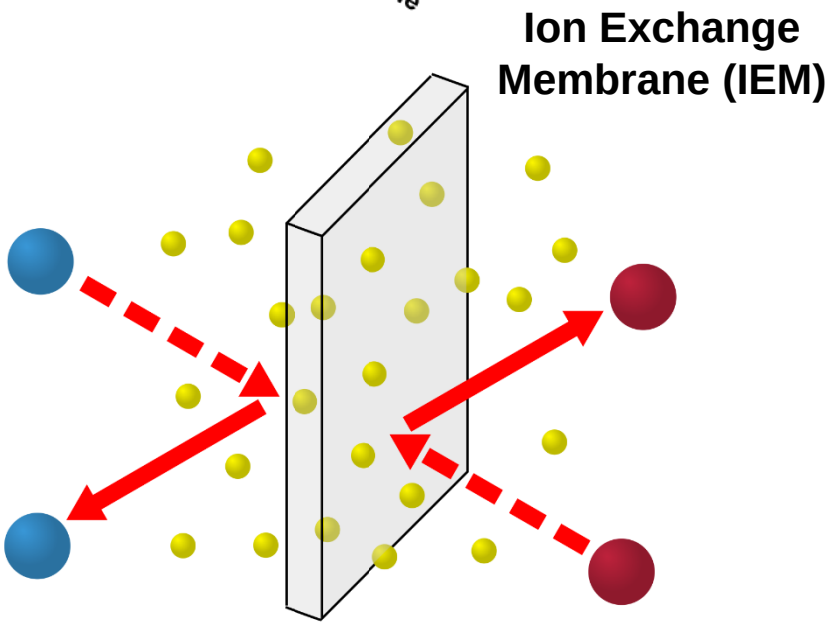




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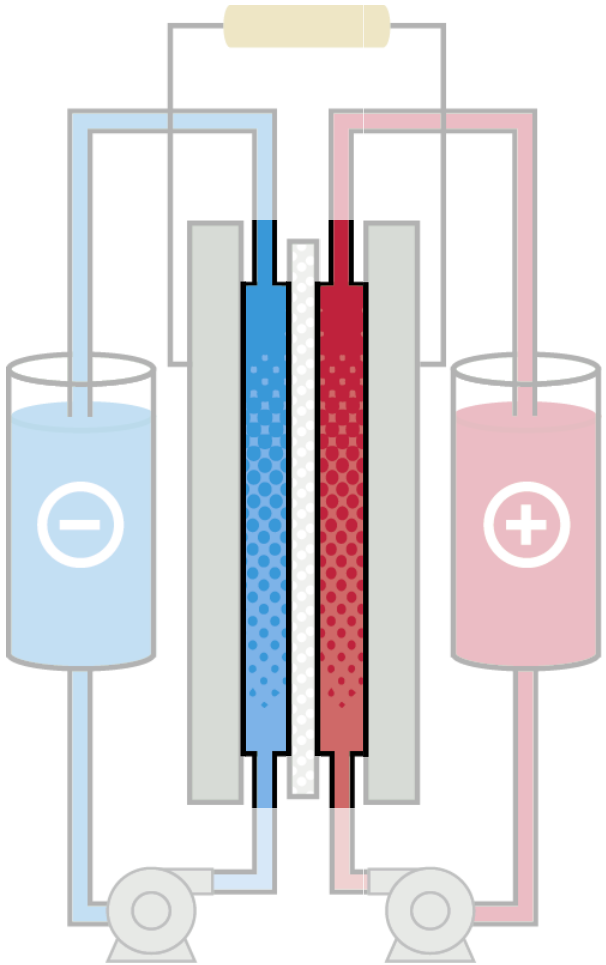
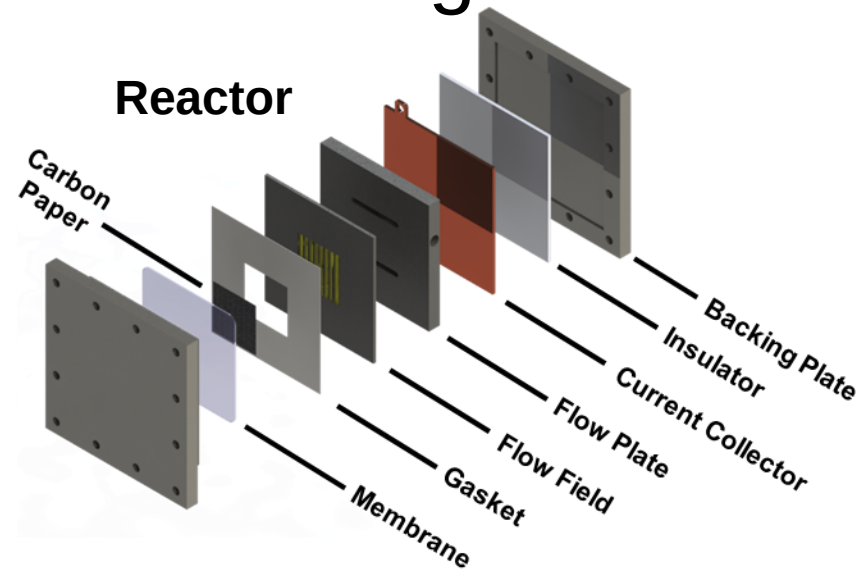
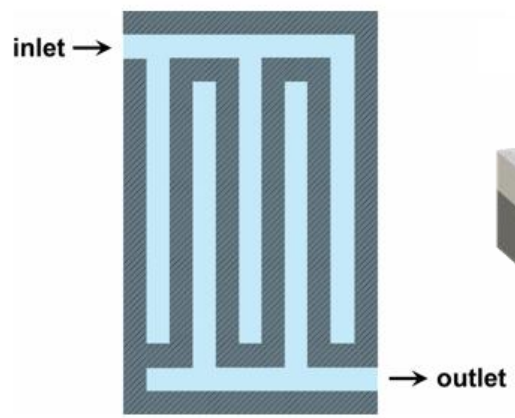
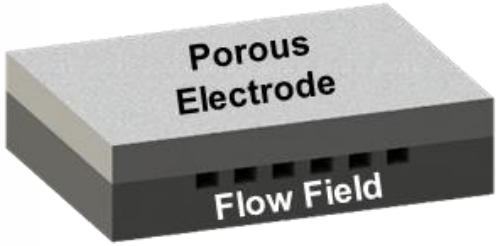





Interdigitated Flow (IDFF)



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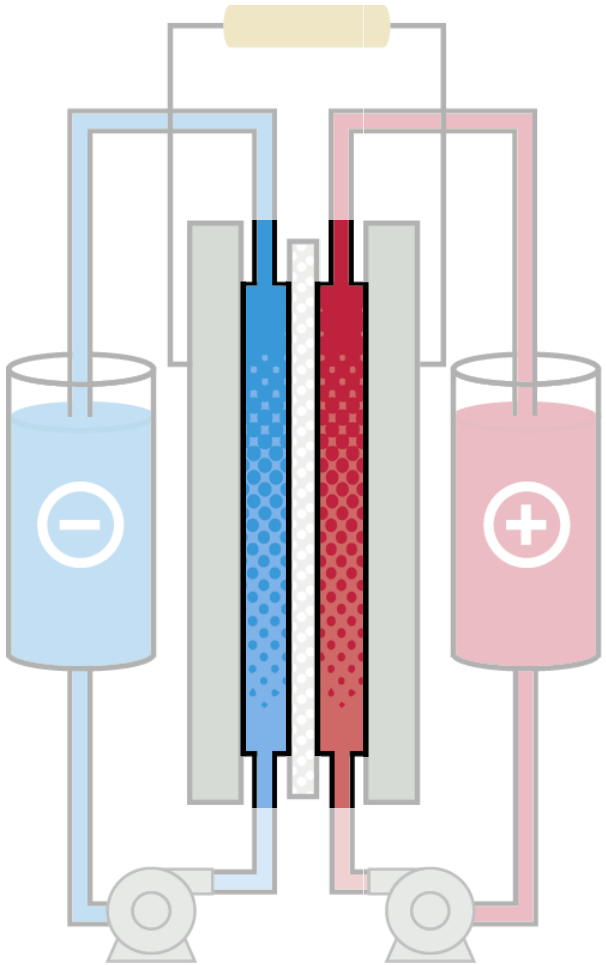

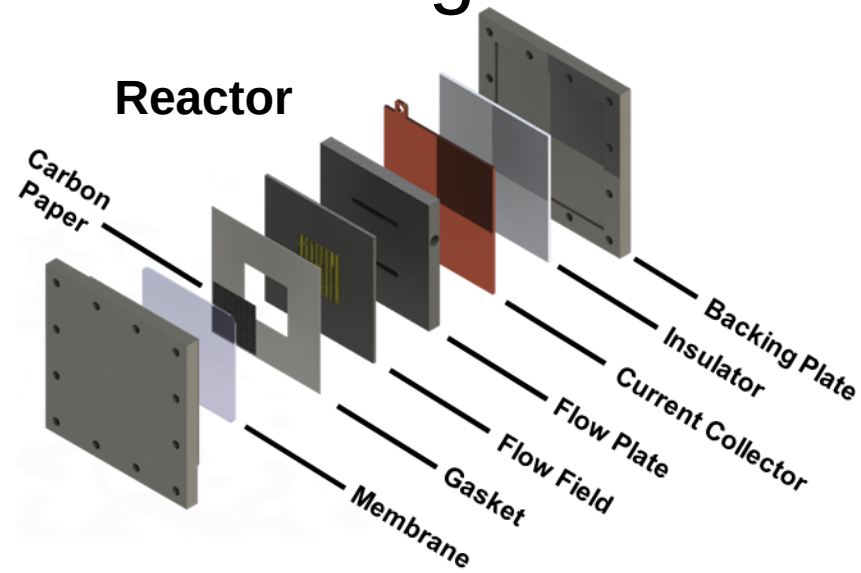


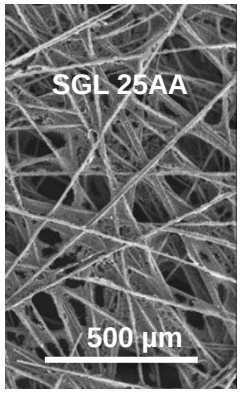


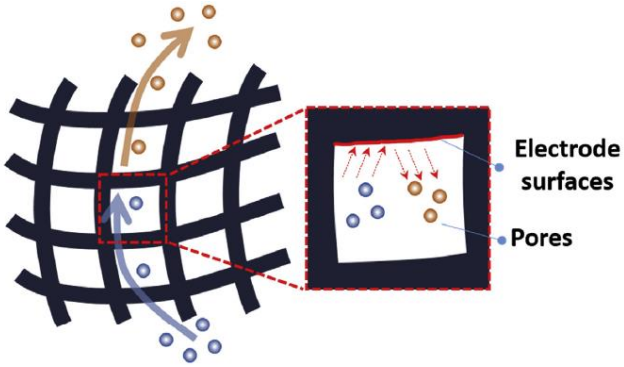




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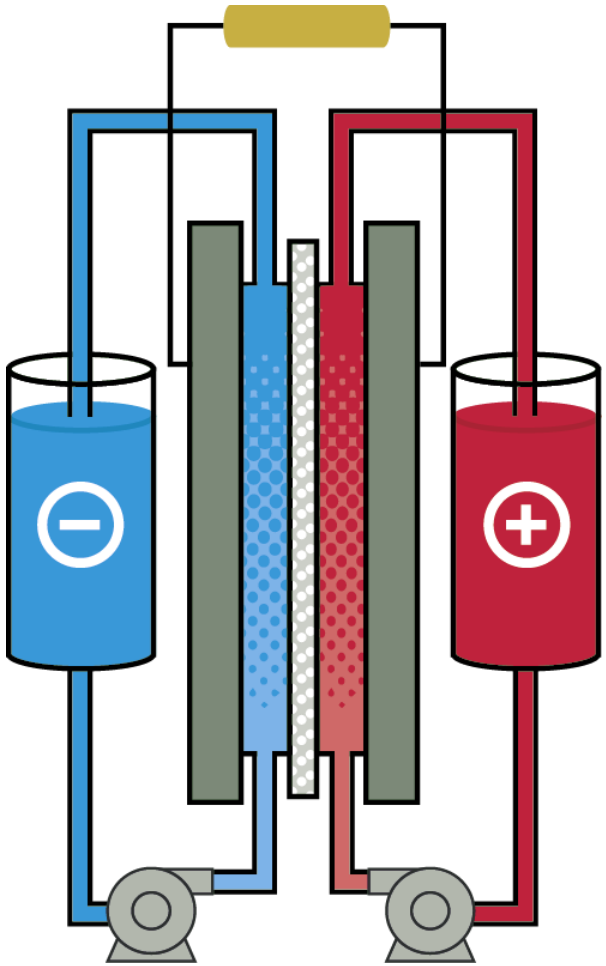

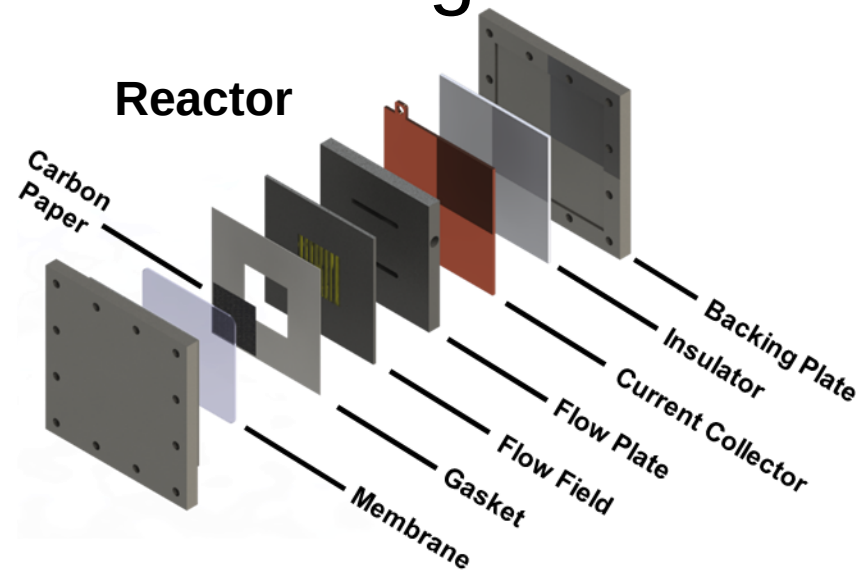


**Advantages of the RFB Architecture**

- Decoupled energy and power scaling
- Simple manufacturing
- High durability and low maintenance
- Location independence

**Present RFB costs exceed $400 kWh$^{-1}$, well beyond the $150 kWh$^{-1}$ target set forth by the DOE EERE.**



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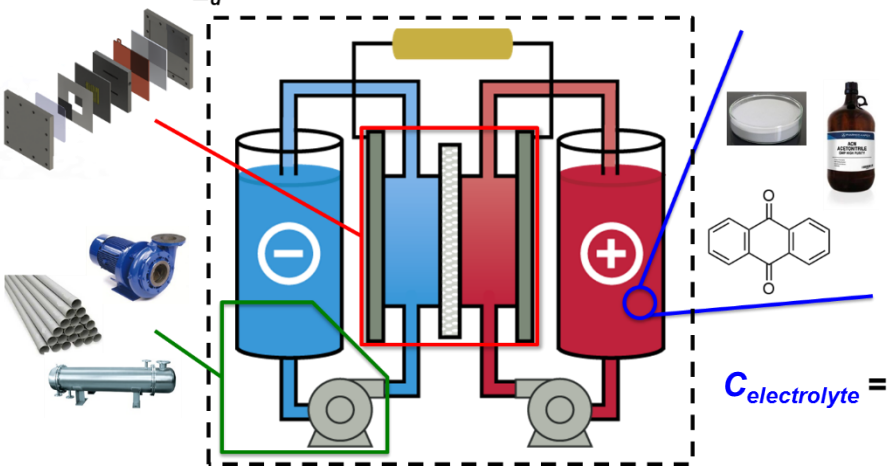
# Techno-Economic Analysis

- Materials Properties
- Cost Parameters
- Component Performance

Desired System Cost and Performance

$$\frac{P}{E_d} = C_{Reactor} + C_{Electrolyte} + C_{BOP} + C_{Additional}$$



*Consider present and future-state **battery costs**, excluding installation.*

$$C_{reactor} = \frac{c_a R}{\varepsilon_{sys} U^2 \varepsilon_v (1-\varepsilon_v) t_d}$$

Cost ($ m$^{-2}$) — ASR — Efficiency — Potential — Discharge Time

$$C_{electrolyte} = \frac{1}{\varepsilon_{sys}\varepsilon_q F \varepsilon_v U}\left(\frac{s_+ M_+}{X_+ n_{e+}} c_{m,+} + \frac{s_- M_-}{X_- n_{e-}} c_{m,-} + 2 r_{avg} M_{salt} c_{salt} + \frac{2}{m_{avg}} c_{sol}\right)$$

Discharge Energy — Active Material — Salt — Solvent

**Identify cost effective design pathways and quantify technical hurdles.**

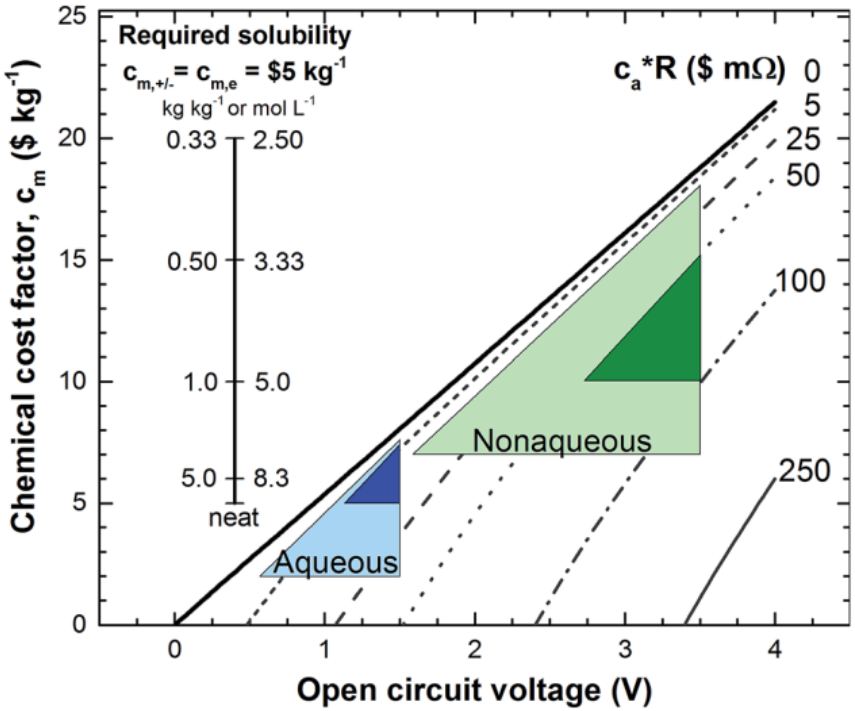
GINERLABS



Darling & Gallagher et al., Energy Environ. Sci., 7 (2014) 3459.
Dmello & **Milshtein** et al., J. Power Sources, 330 (2016) 261.

# Baseline Techno-Economic Analysis

- First JCESR analysis highlighted pathways to low-cost, multi-hour batteries
  - Tailored for 5 h discharge
- Future-state cost estimates assuming mass production
  - 2 GW annual stack output
- Identified viable, multi-dimensional design space for Aq and Naq RFBs
- Largest cost benefits from economies of scale
  - Ha & Gallagher, J. Power Sources, 296 (2015) 122.



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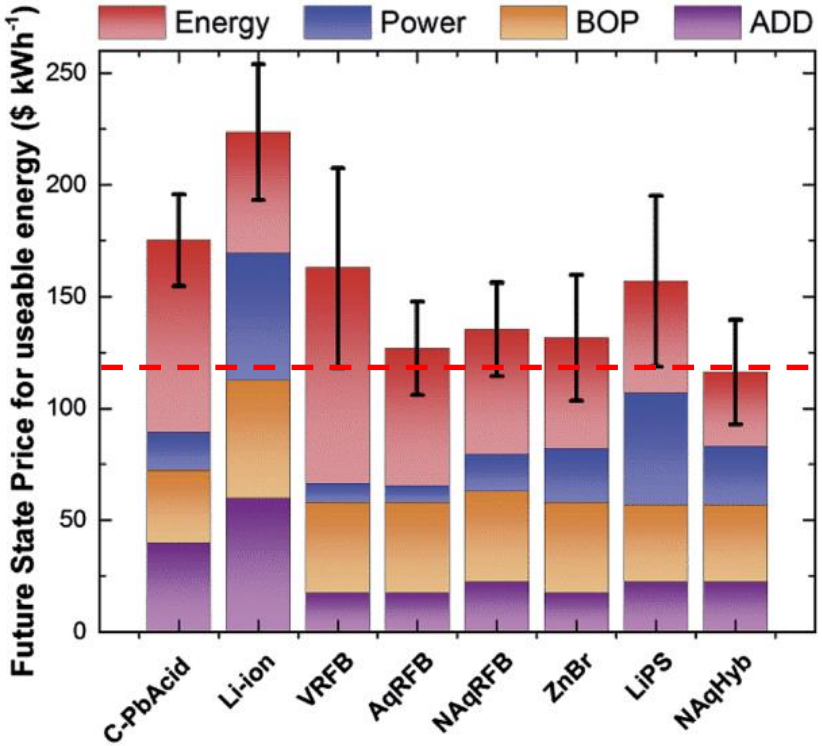
- Compared RFB capital costs to other battery architectures



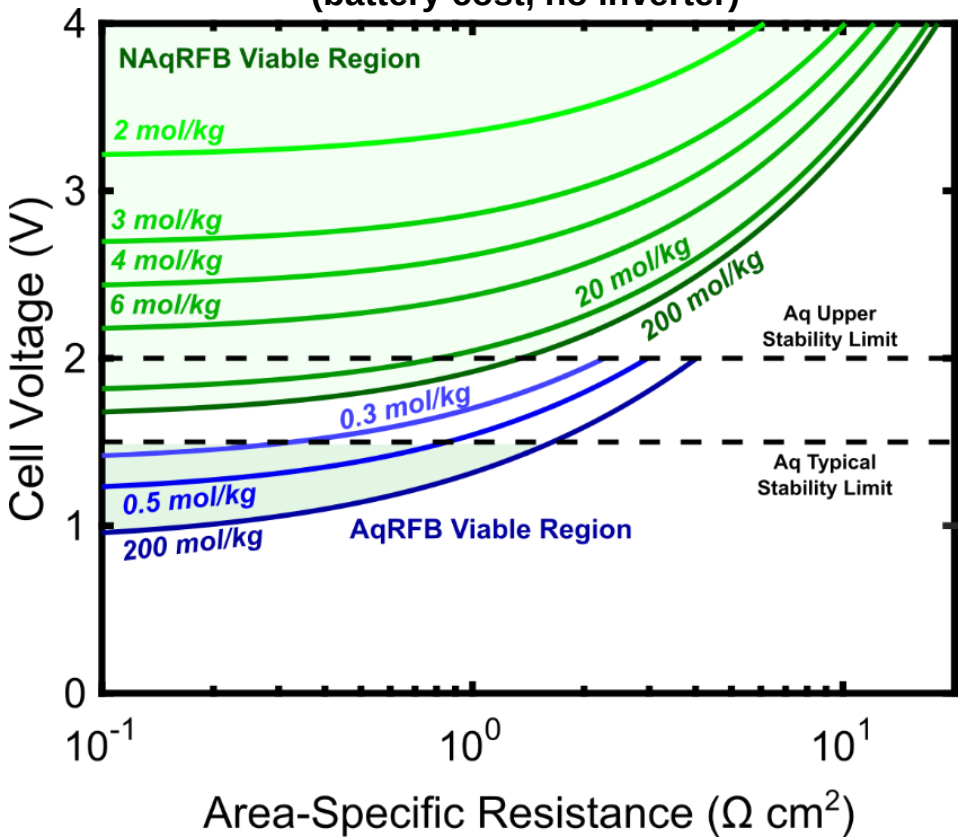

**Explicit cost analysis hides possible cost savings through design, material, or performance improvements.**



Darling & Gallagher et al., Energy Environ. Sci., 7 (2014) 3459.

# Utilizing Cost-Driven Design Maps

**$100 kWh$^{-1}$ Design Map**
**(battery cost, no inverter)**

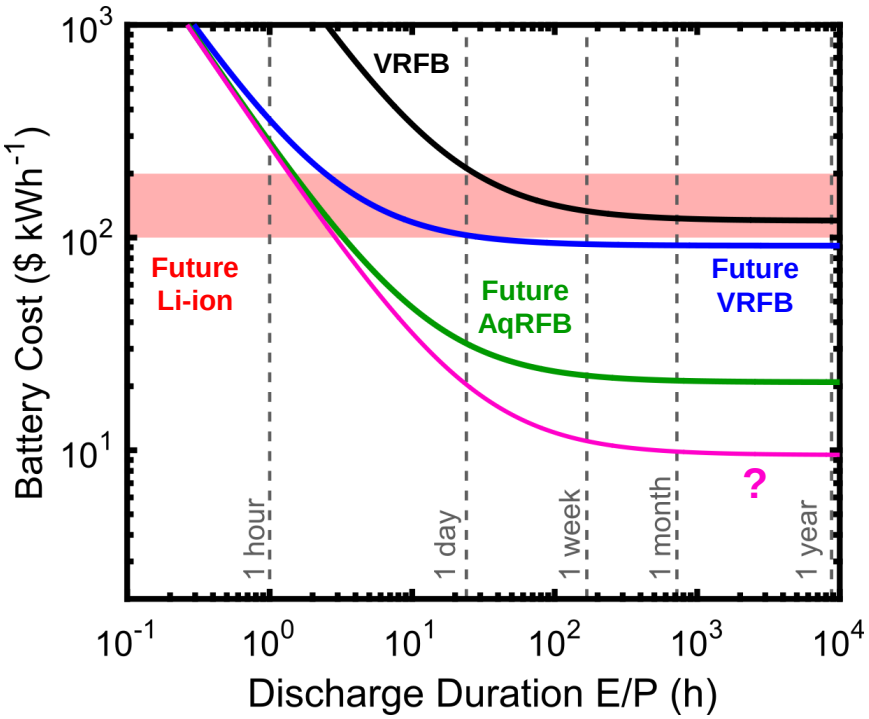



## Key challenges for 5 h Discharge

- All RFBs:
  - Active species cost < $7 kg$^{-1}$
  - Molecular weight < 200 g mol$^{-1}$
- AqRFBS:
  - Cell Voltage ≥ 1.4 V
  - ASR < 1.5 Ω cm$^2$
- NAqRFBs
  - Actives conc: 2 – 4 mol kg$^{-1}$
  - Cell Voltage ≥ 2.8 V
  - ASR < 5 Ω cm$^2$
  - Salt Cost Factor < $0.5 mol$^{-1}$

**Techno-economic analysis guides experimental research by identifying largest technical obstacles.**

# Impact of Discharge Time on RFB Cost




***Increasing discharge duration approaches electrolyte cost.***

- Present VRFB costs validated with:
  - Other literature models
  - Vionx Energy cost estimate
  - Lazard energy storage report
- Future VRFB cost reductions:
  - Economies of scale
  - Cheaper stack components
  - Lower chemical costs
- Future Li-ion: $100 - 200 kWh$^{-1}$
- Future AqRFB cost reductions:
  - Anticipate slight performance boost
  - Significantly cheaper chemicals

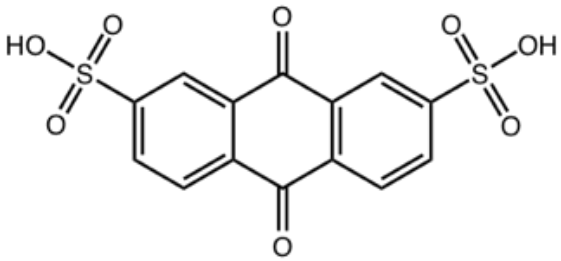
**The RFB architecture could enable extremely low capital costs for long duration discharge applications.**



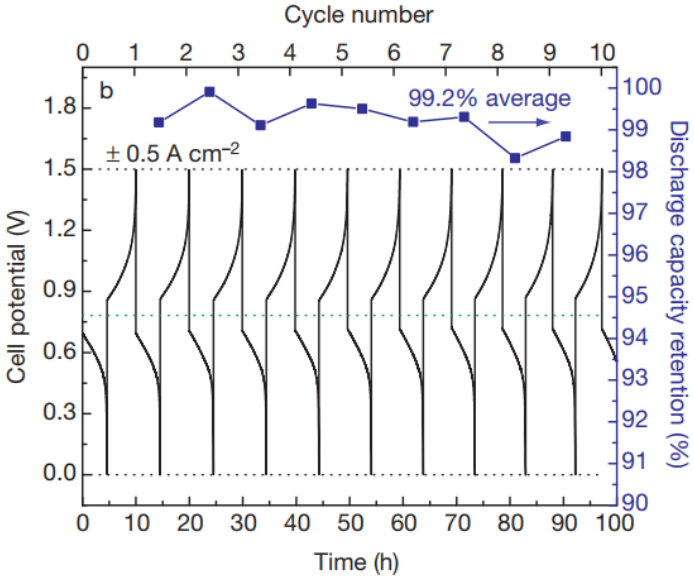
Darling & Gallagher et al., Energy Environ. Sci., 7 (2014) 3459. Dmello & **Milshtein** et al., J. Power Sources, 330 (2016) 261.
B. Gellerman, "A novel liquid battery could hold potential for unlimited energy 942 storage," BostonomiX Ser, (2017).

# Defining Inexpensive Chemistries

- RFBs require low chemical costs to compete in long-duration storage
- Certain inorganics are inexpensive commodities
  - *e.g.*, Sulfur ($0.20 kg$^{-1}$), Bromine ($1.41 kg$^{-1}$)
- Organic active species show promise due to rational design
  - Ding *et al*., Chem. Soc. Rev., 2017, doi: 10.1039/C7CS00569E.
  - Are organic battery materials inexpensive (≤ $5 kg$^{-1}$)?
- **Process cost modeling** case study: **A**nthra**q**uinone **D**i**s**ulfonic Acid




***AQDS is an industrially-relevant material with a large amount of process information known.***






Dietrich et al., *Estimating the Cost of Organic Battery Active Materials: A Case Study on Anthraquinone Disulfonic Acid*. in preparation.
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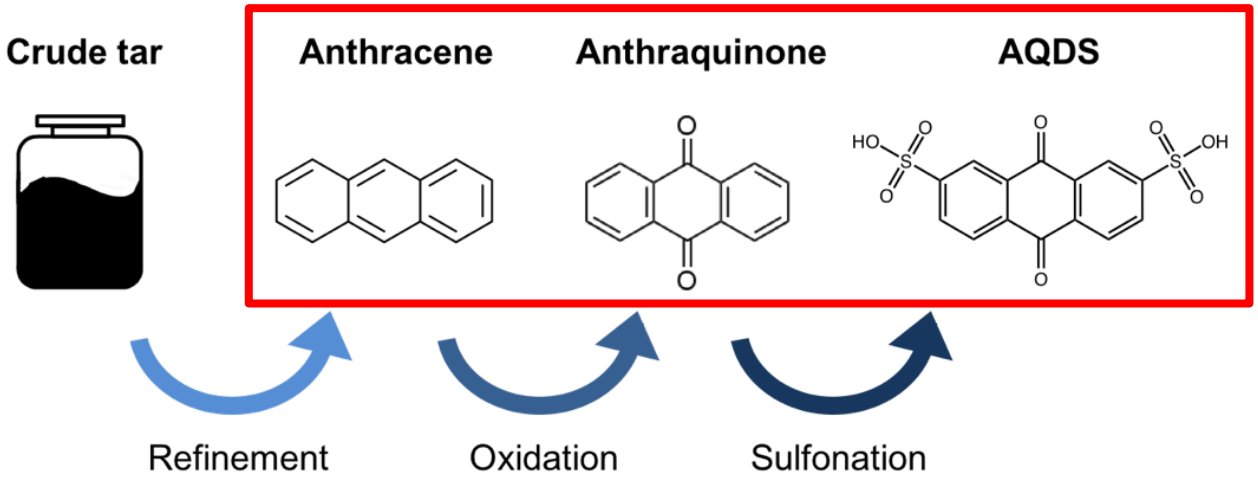


**Estimate cost per unit mass of AQDS as a function of production quantity.**



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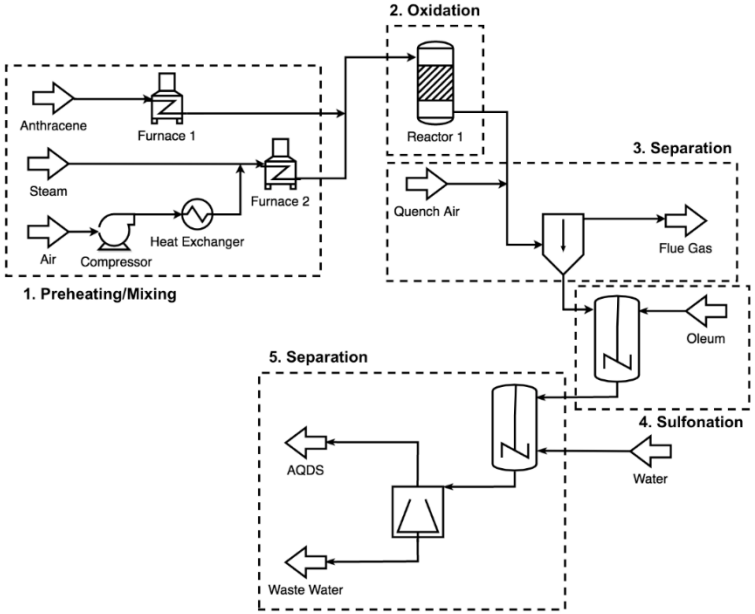
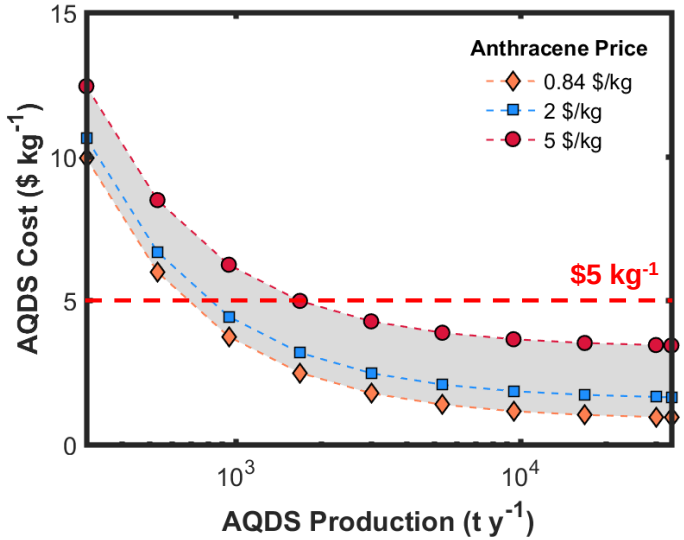
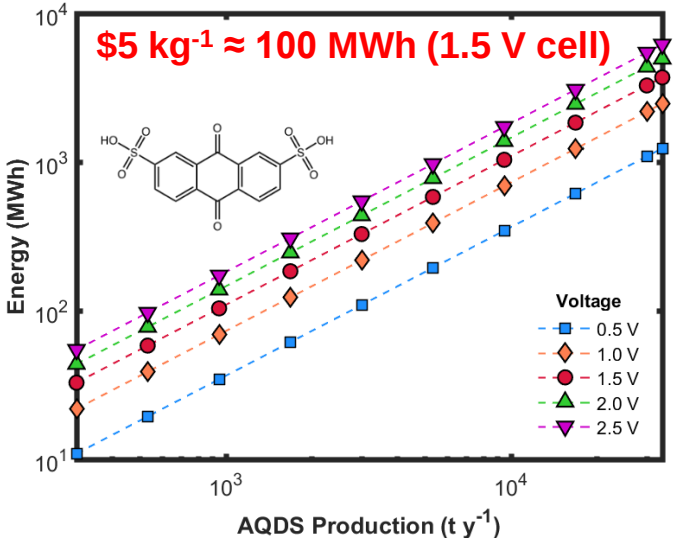
# Estimating AQDS Cost per Unit Mass




**Aspen Economic Analyzer**

- CAPEX consists of:
  - ISBL, OSBL, Engineering costs, Contingency
- OPEX contributions:
  - Labor, Maintenance, Overhead, Raw Materials, Utilities, Waste Disposal



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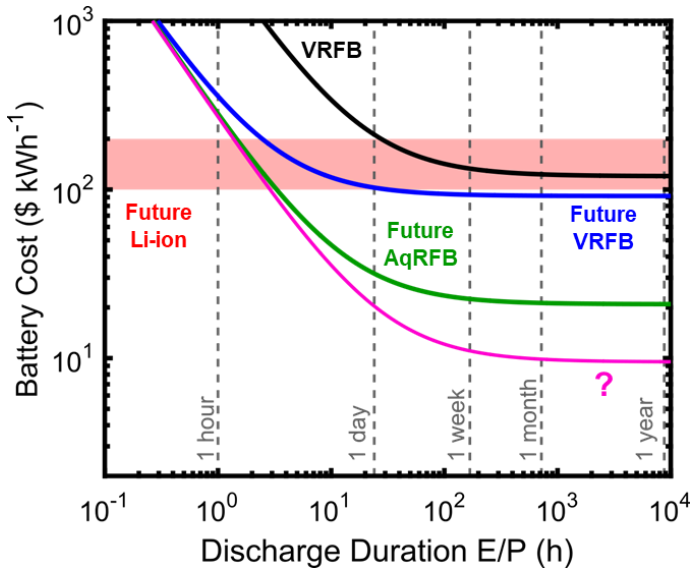
# Conclusions

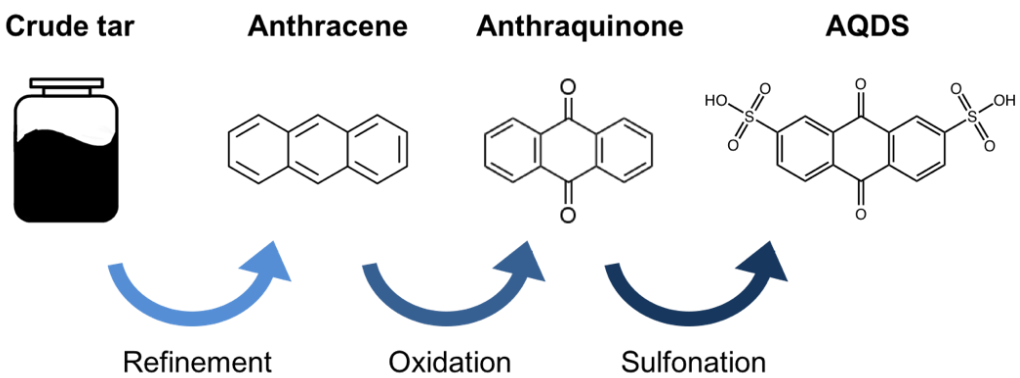
$$\frac{P}{E_d} = C_{Reactor} + C_{Electrolyte} + C_{BOP} + C_{Additional}$$

Early-stage **techno-economic modeling** can inform research directions and highlight technical bottlenecks.



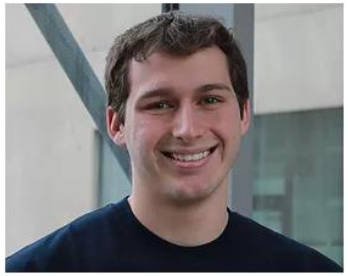

**RFBs show promise for long-duration energy storage**, IF inexpensive electrolyte chemicals and balance-of-plant designs can be identified.

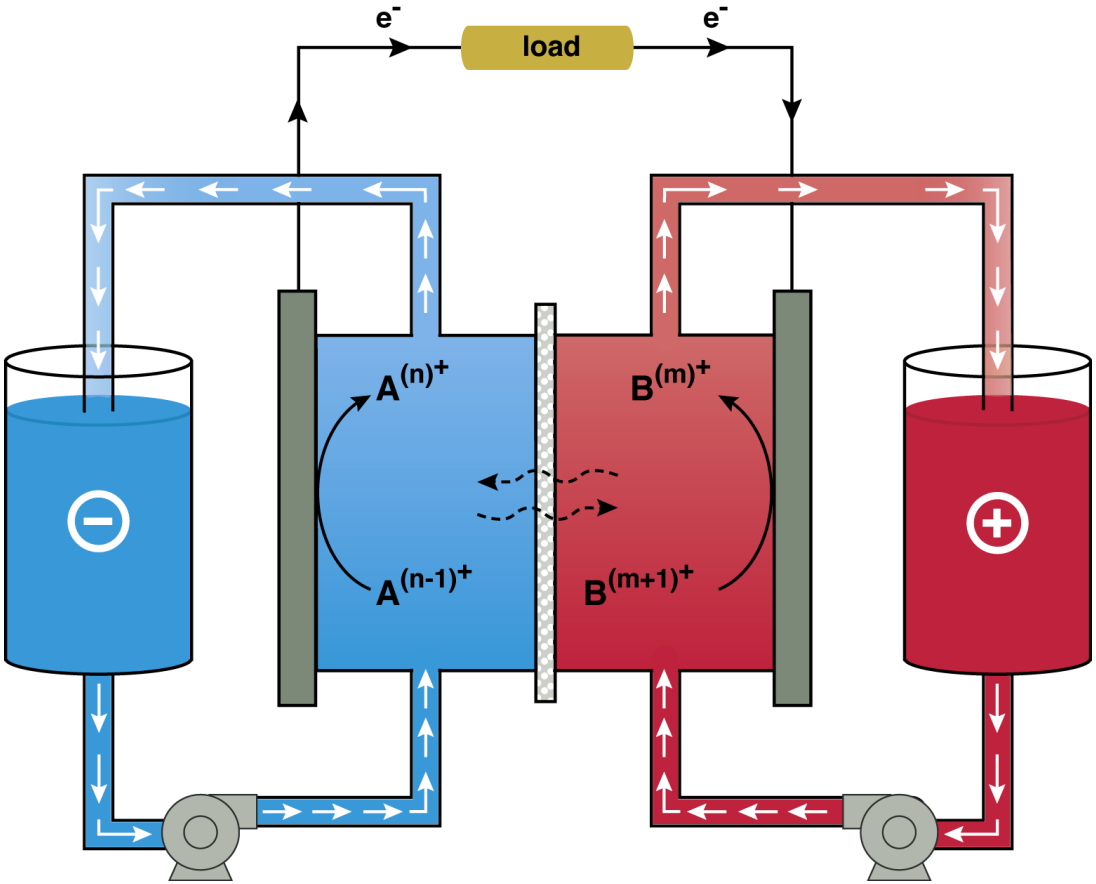
Process-based cost modeling can **illuminate the cost-effectiveness of new materials.**



# Acknowledgements

JCESR | Joint Center for Energy Storage Research



United Technologies Research Center

# Questions?