Ambient Temperature Aqueous Sulfur Batteries for Ultralow Cost Grid Storage

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Chicago, Illinois

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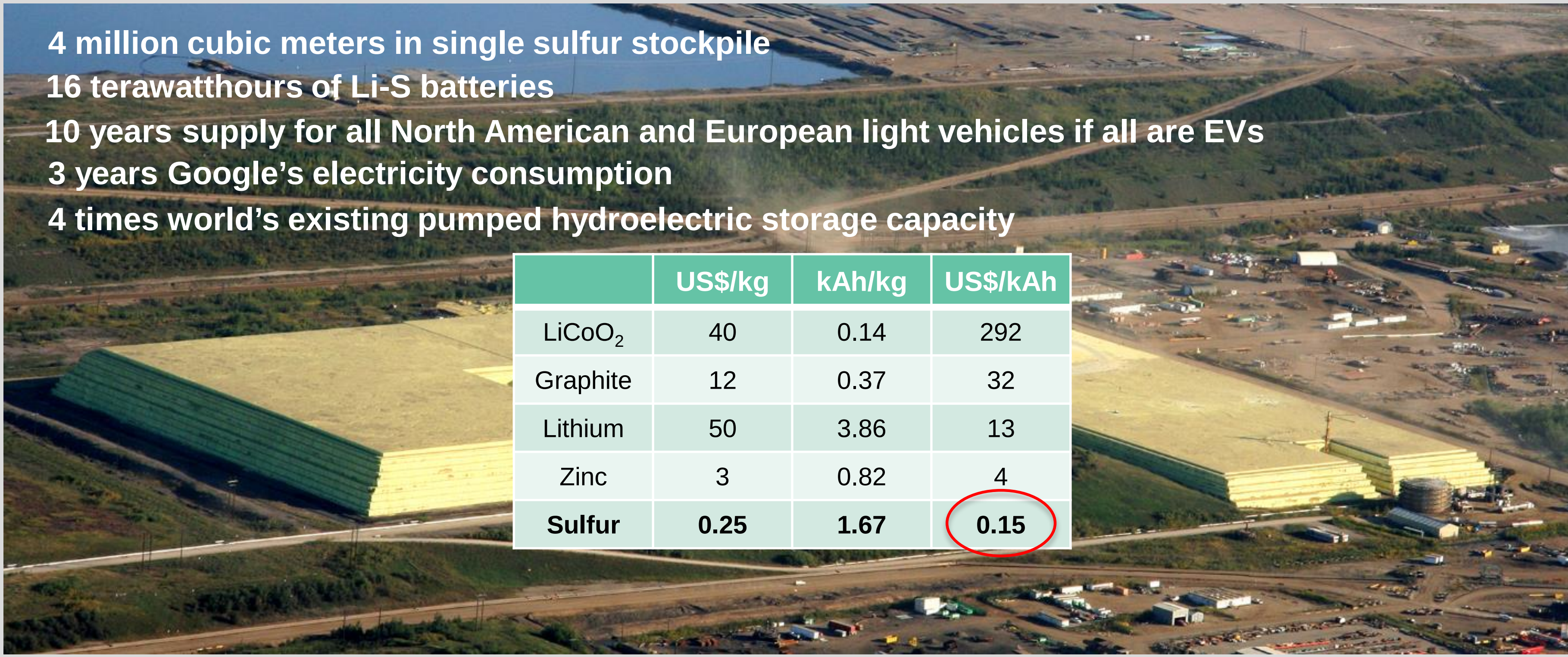
Sulfur



4 million cubic meters in single sulfur stockpile

16 terawatthours of Li-S batteries

10 years supply for all North American and European light vehicles if all are EVs

3 years Google's electricity consumption

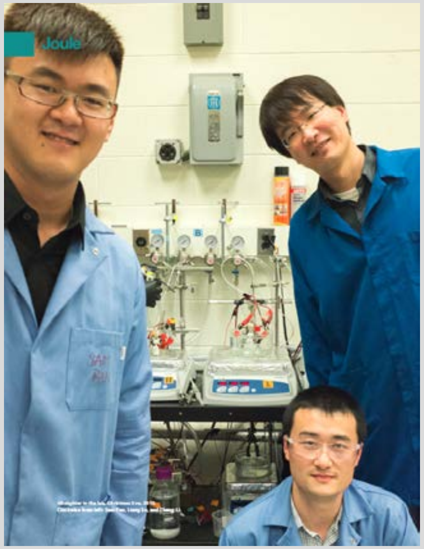
4 times world's existing pumped hydroelectric storage capacity

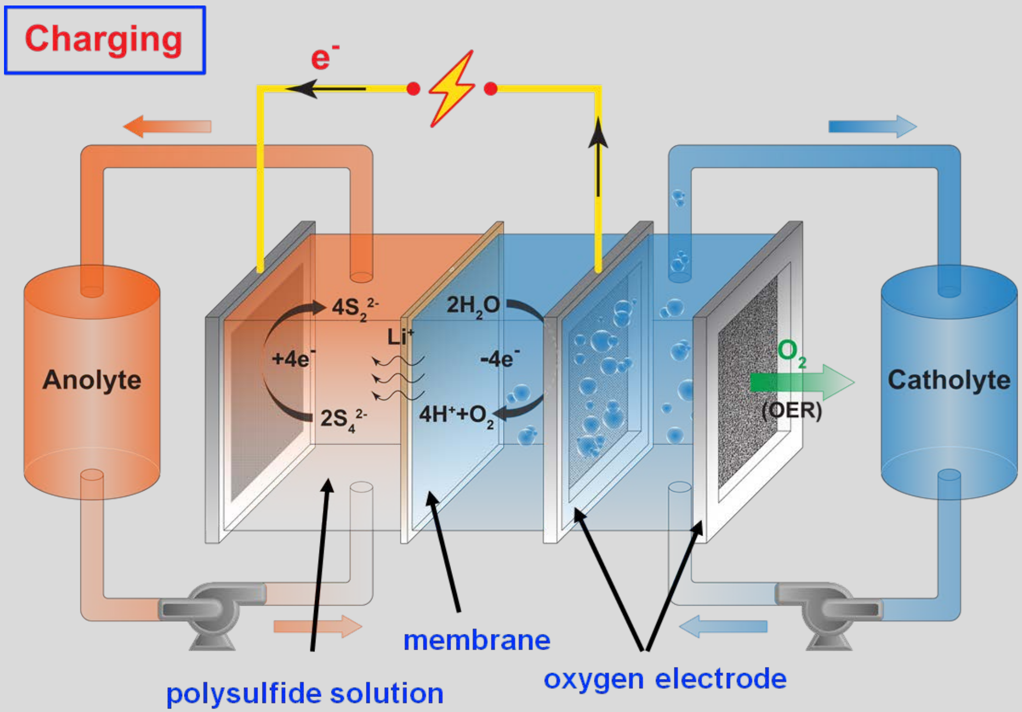
	US$/kg	kAh/kg	US$/kAh
$LiCoO_2$	40	0.14	292
Graphite	12	0.37	32
Lithium	50	3.86	13
Zinc	3	0.82	4
Sulfur	**0.25**	**1.67**	**0.15**

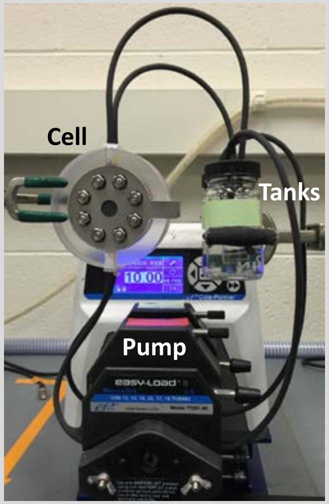
Fort McMurray, Alberta, Canada
Photo credit: GlobalForestWatch.ca

Air-breathing aqueous sulfur battery

using water, air, and sulfur, and operating at ambient temperature







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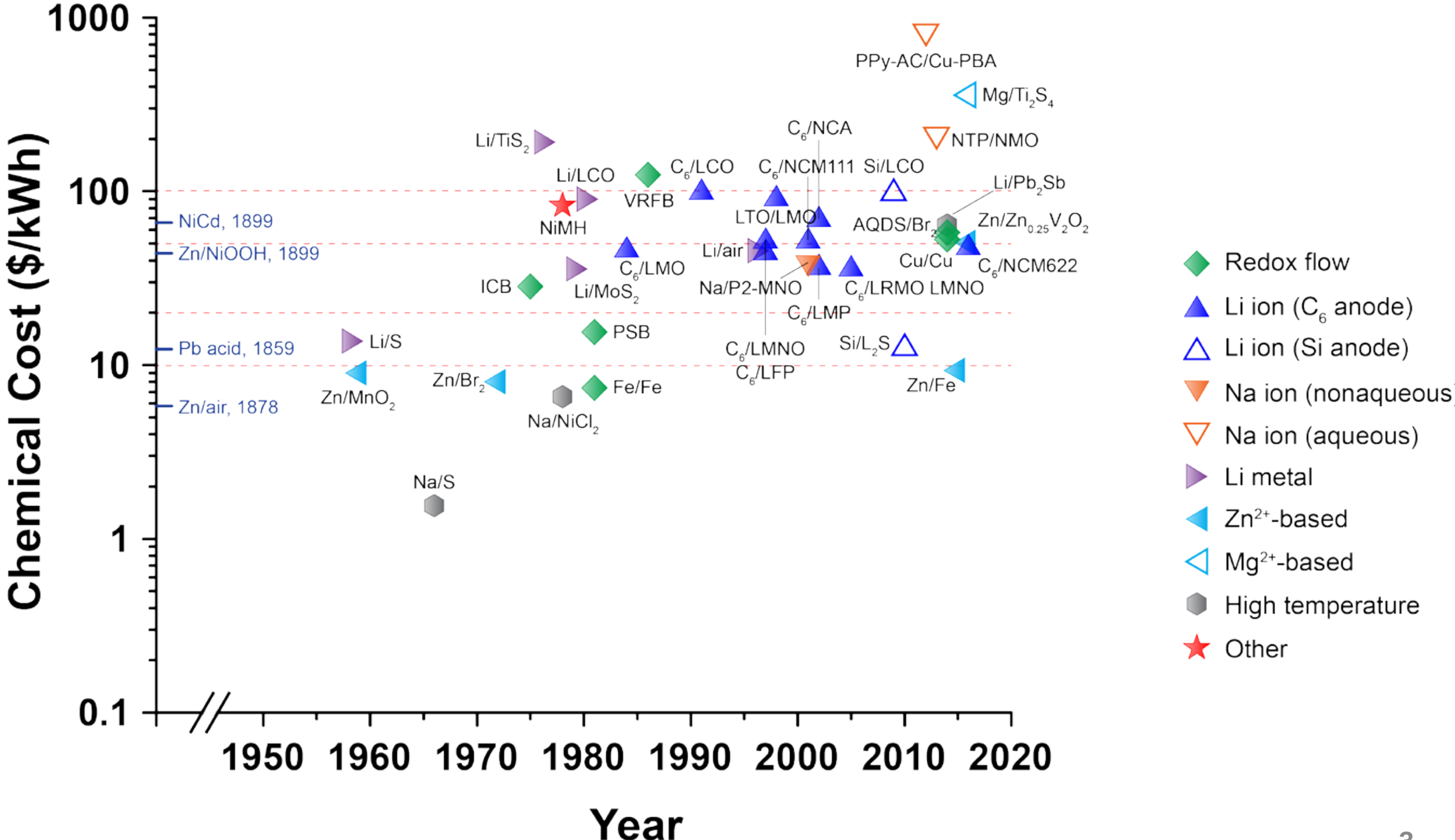
Chemical cost of new battery chemistries over 60 years of battery development

Chemical cost = cathode + anode + electrolyte



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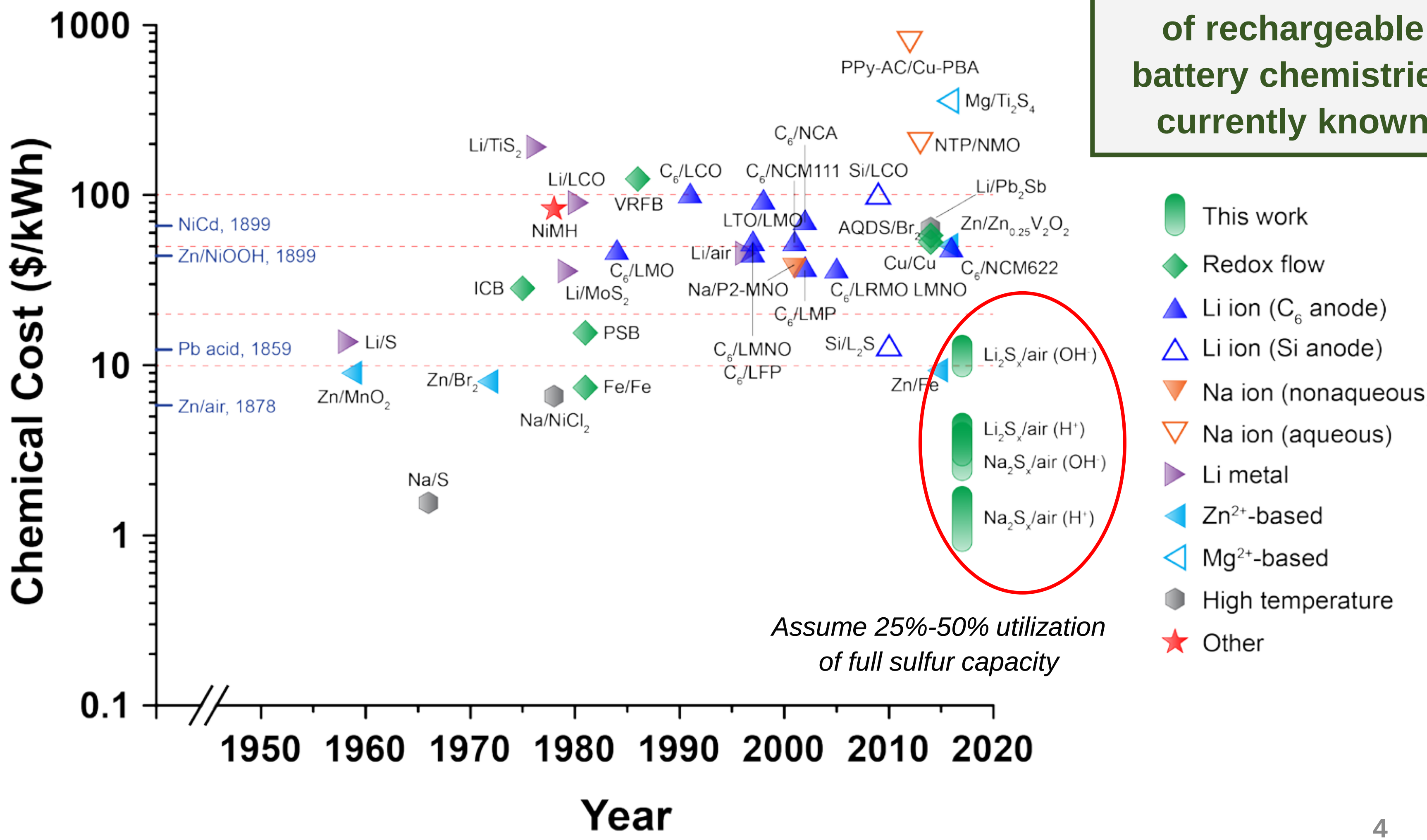
Chemical cost of new battery chemistries over 60 years of battery development

Chemical cost = cathode + anode + electrolyte

Lowest chemical cost of rechargeable battery chemistries currently known



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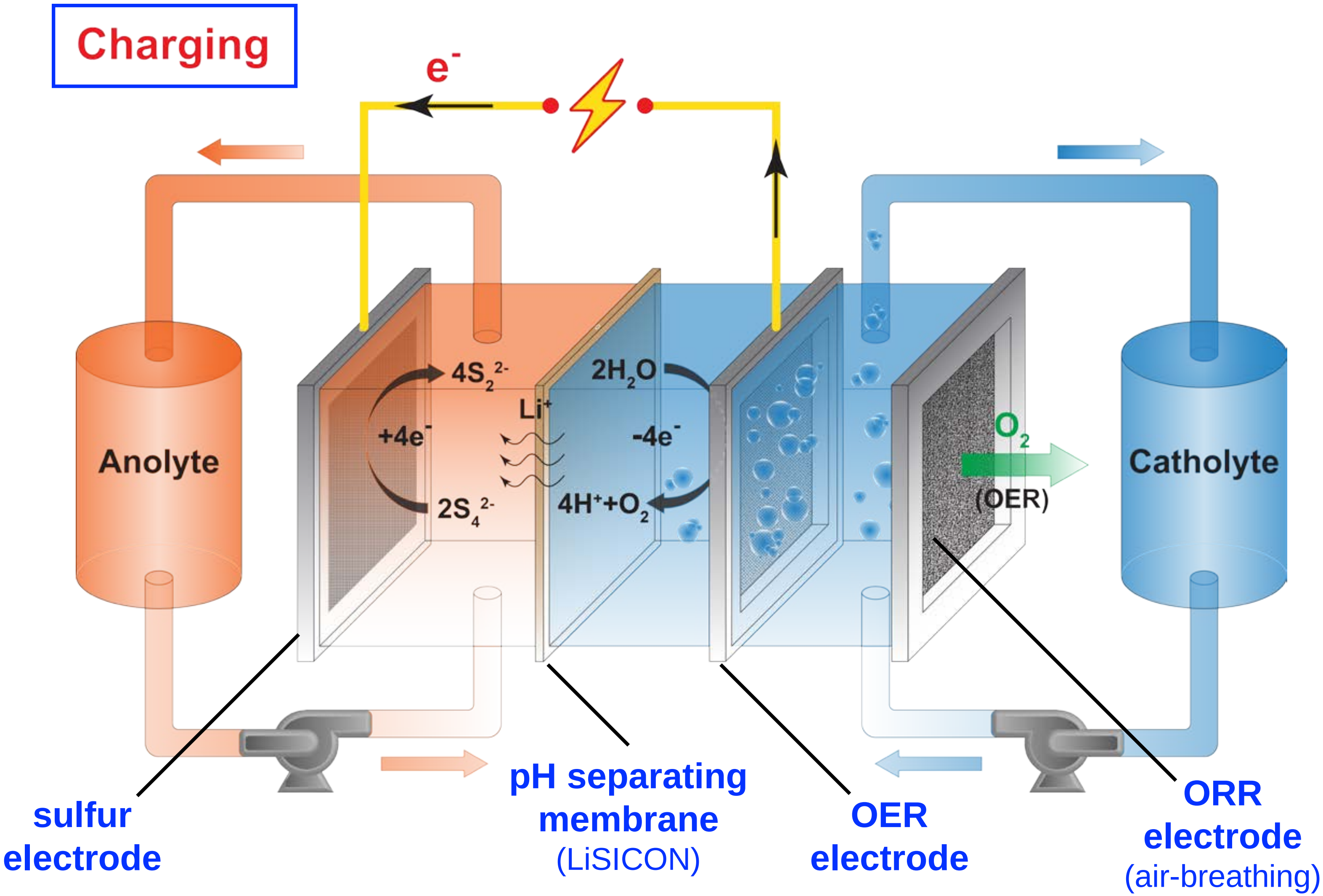
Air-breathing aqueous sulfur battery using water, air, and sulfur operated at ambient temperature



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Air-breathing aqueous sulfur battery

Cathode (oxygen) electrochemistry

E^0 = 1.23 V

vs. SHE

Discharge (reduction)

ORR

Decrease in $[H^+]$ drives A^+ to move to the cathode side

$$2H_2O \rightleftharpoons O_2 + 4H^+ + 4e^-$$

Increase in $[H^+]$ drives A^+ to move to the anode side

OER

Charge (oxidation)

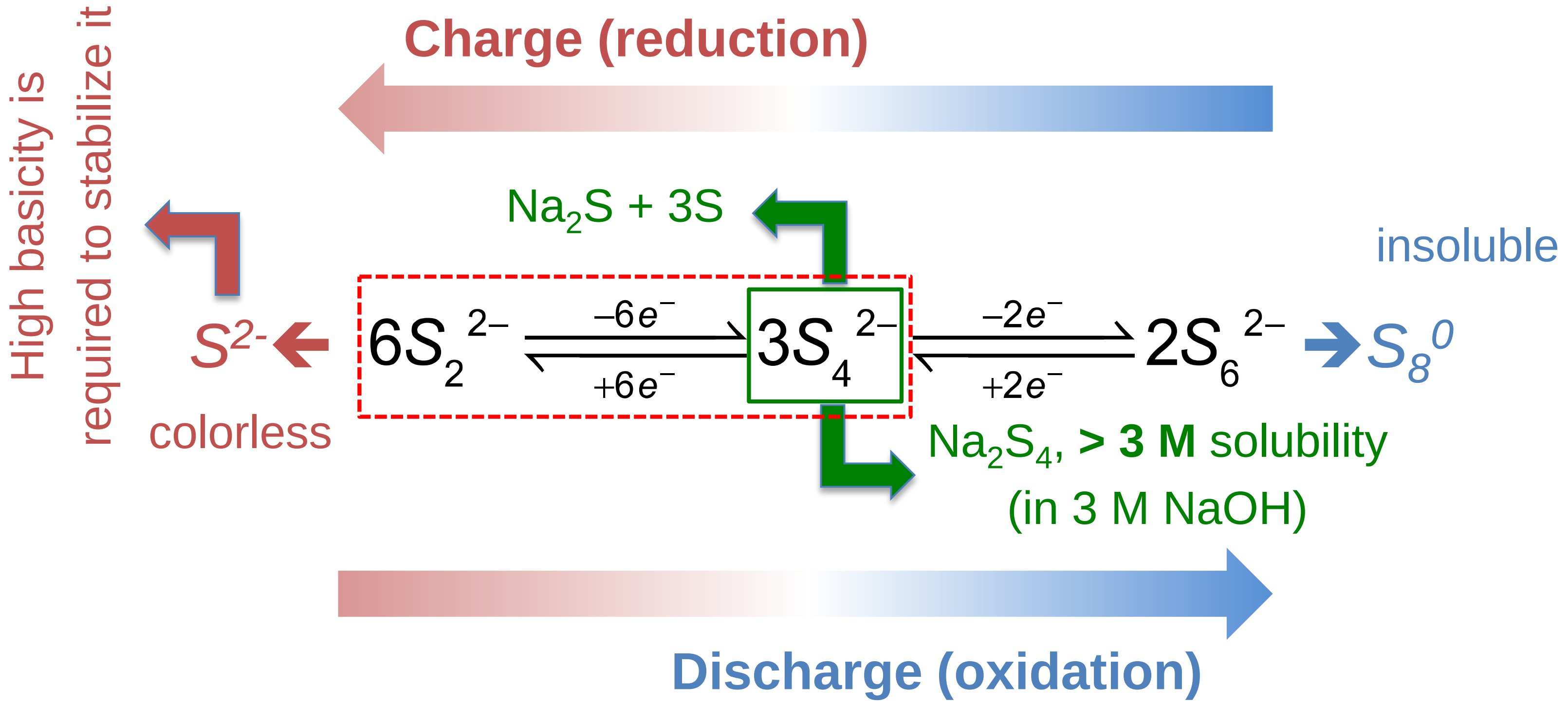
Alkaline working ion (A^+) can be either Li^+ or Na^+

Air-breathing aqueous sulfur battery

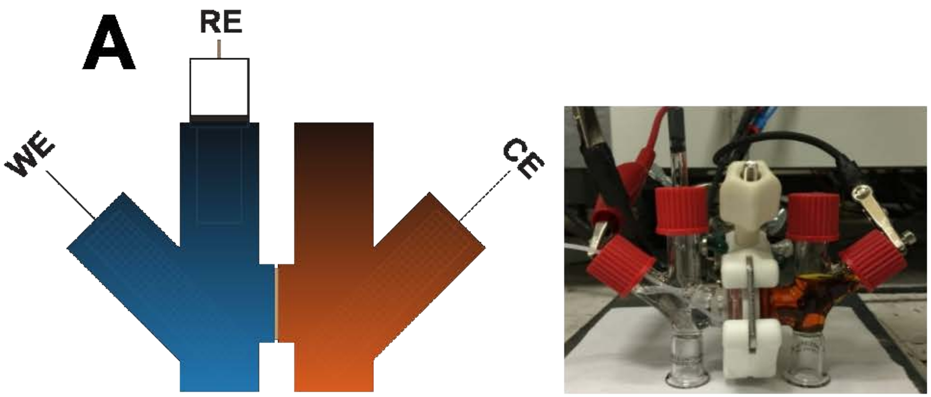
Anode (sulfur) electrochemistry

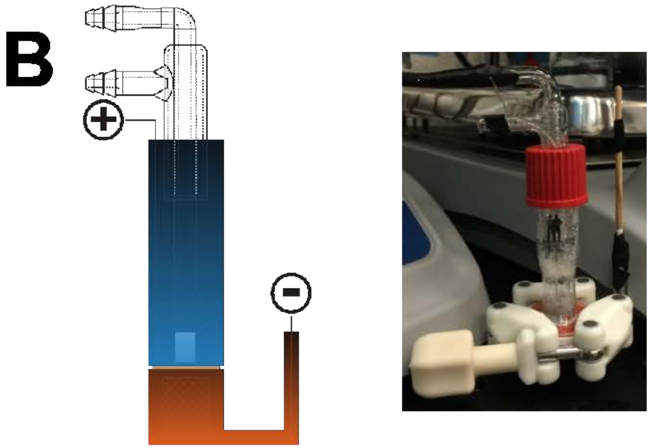
E^0 = -0.45 V

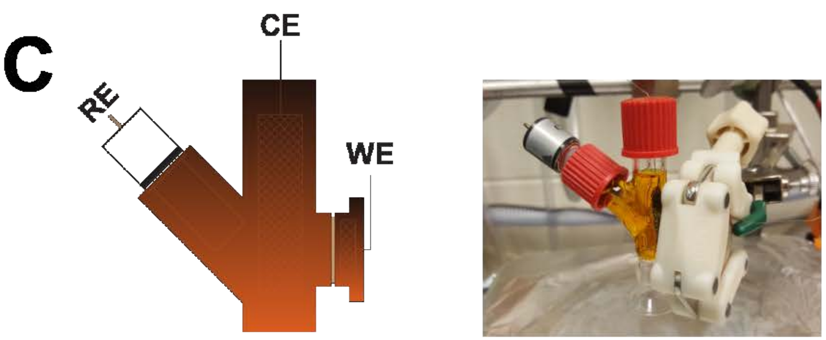
vs. SHE

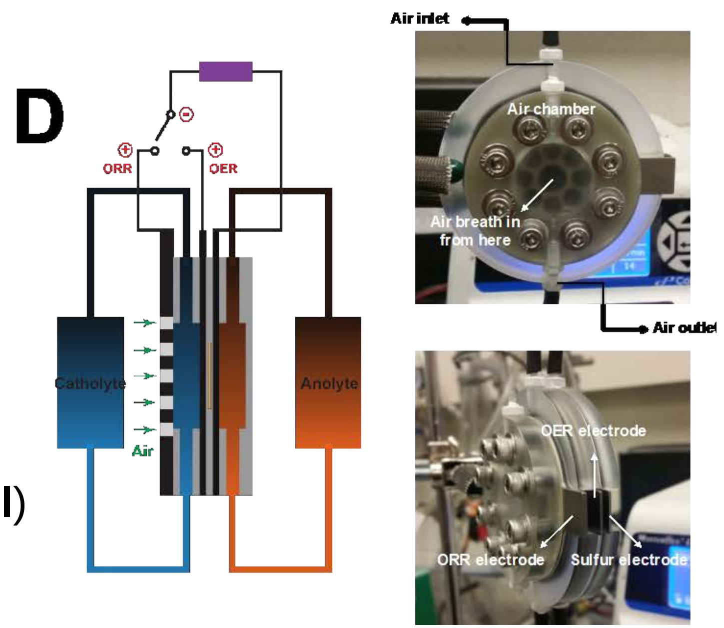


Four lab-scale cell designs for various experiments









Purpose:

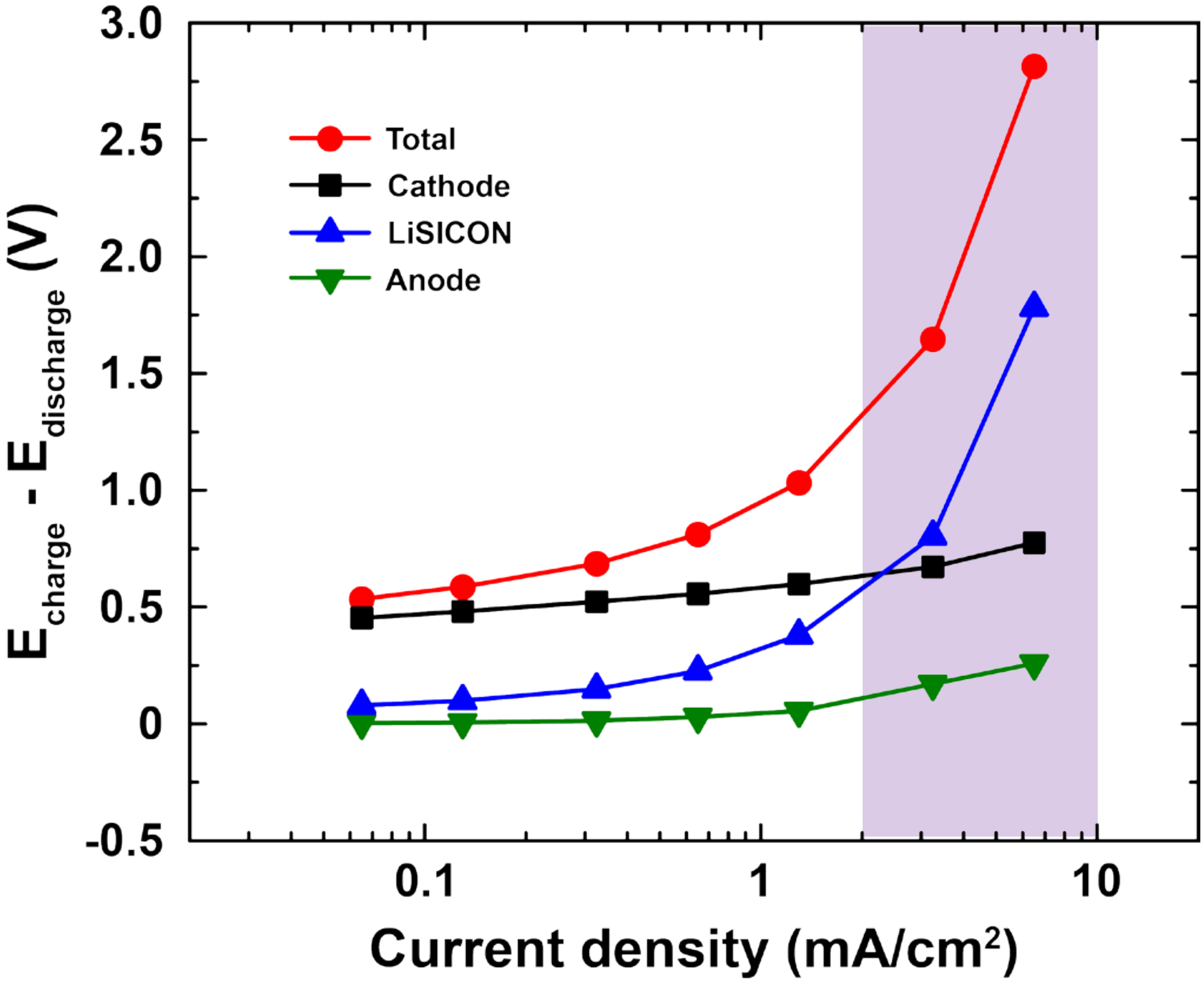
A. Polarization and efficiency tests (**H-cell**)

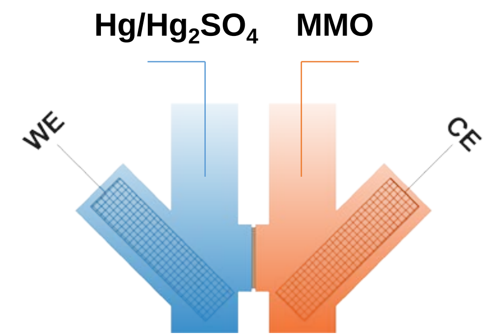
B. Catholyte limited cycling (**L-cell**)

C. Anolyte limited cycling (**low-vol. cell**)

D. Air-breathing **flow cell**

Membrane resistance dominates the overall cell resistance at > 2 mA/cm^2





Catholyte:
0.5 M Li_2SO_4 + 0.1 M H_2SO_4
Anolyte:
1 M Li_2S_4 + 1 M LiOH

55 °C

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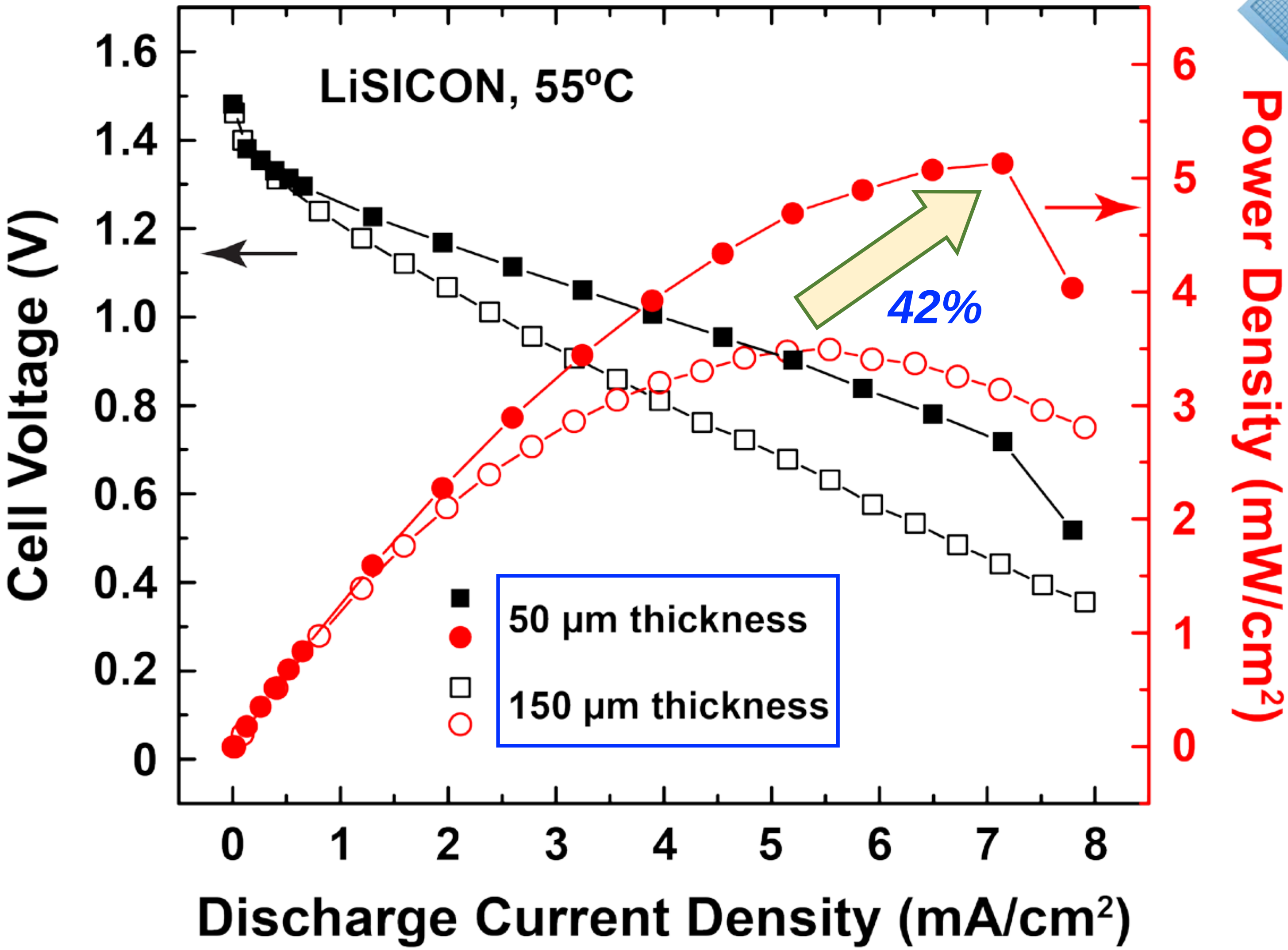
Lower membrane resistance, higher power density



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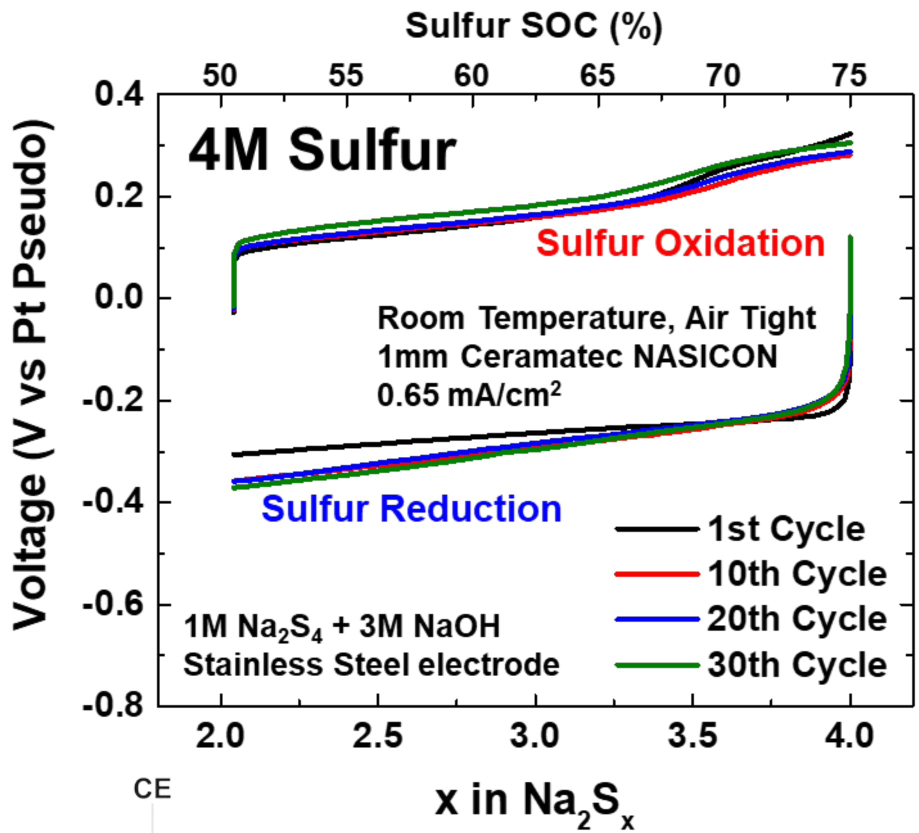
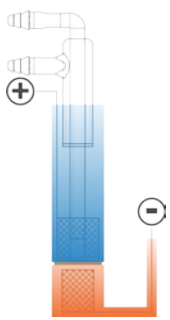
Demonstration of ~1000h stability for catholyte and anolyte using non-flowing cells

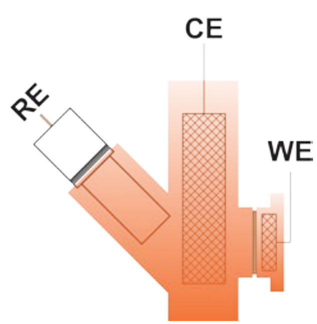
Li catholyte, 1600h, 96% SOC

Na anolyte, 720h, Na_2S_2 to Na_2S_4





$$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O$$



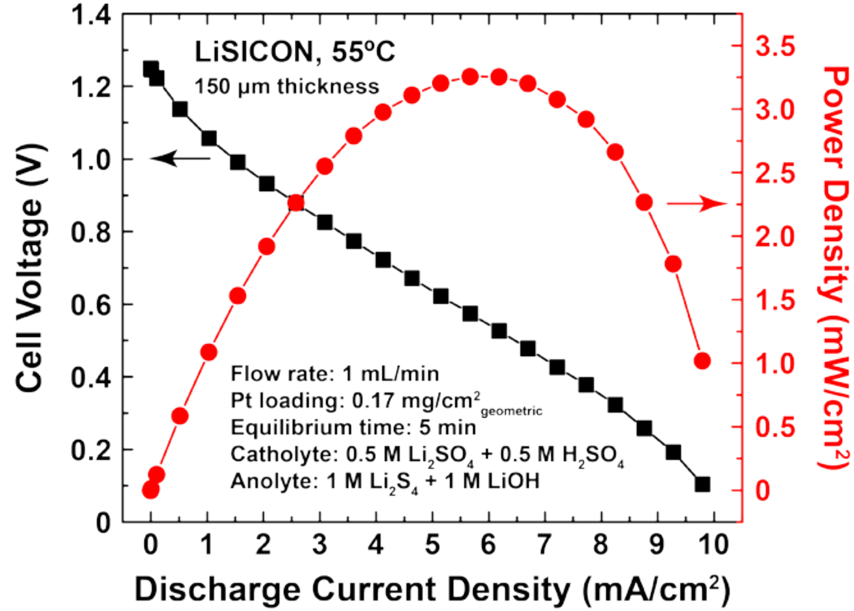
$$Na_2S_4 + 2Na^+ + 2e^- \leftrightarrow 2Na_2S_2$$

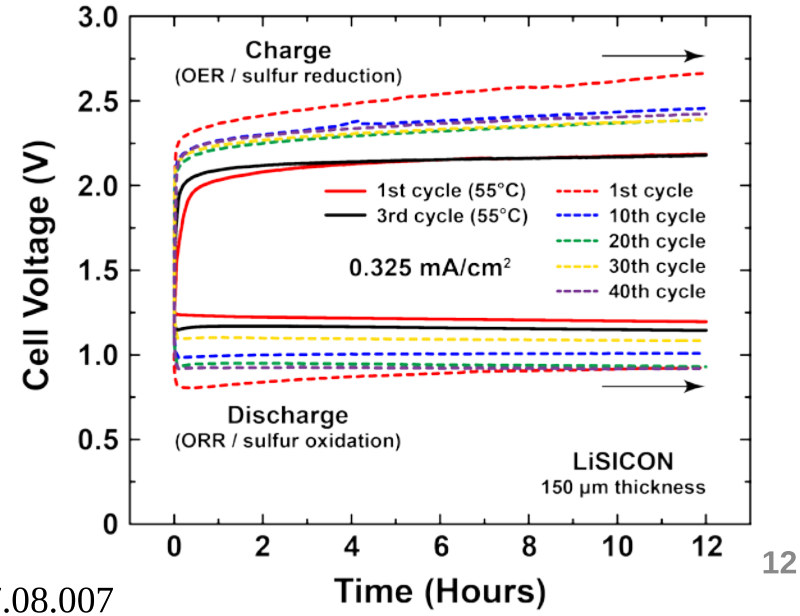
Lab-scale flow cell prototyping in the air-breathing mode (Li$^+$ working ion)

Cell

Pump

Reservoirs





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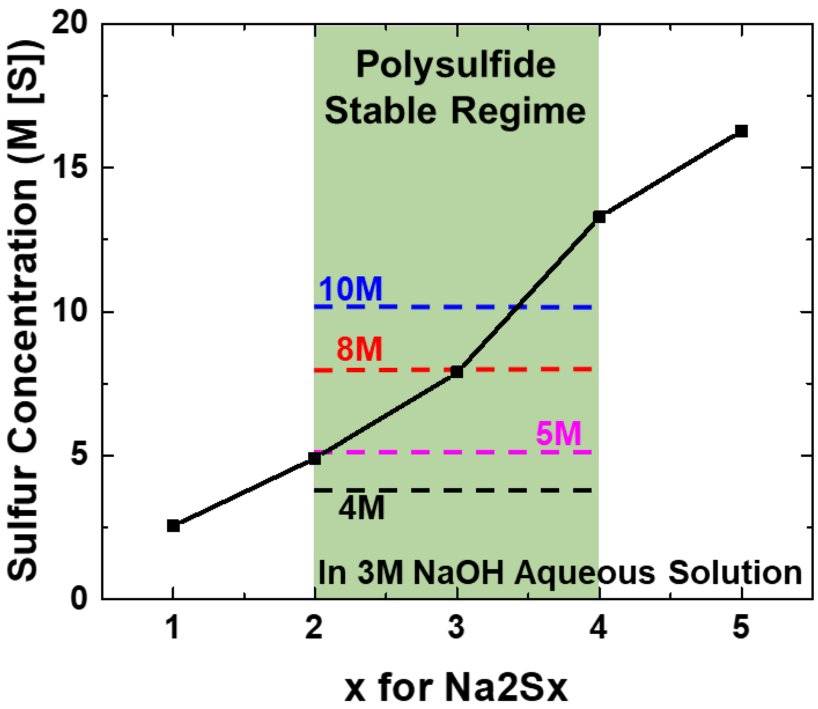
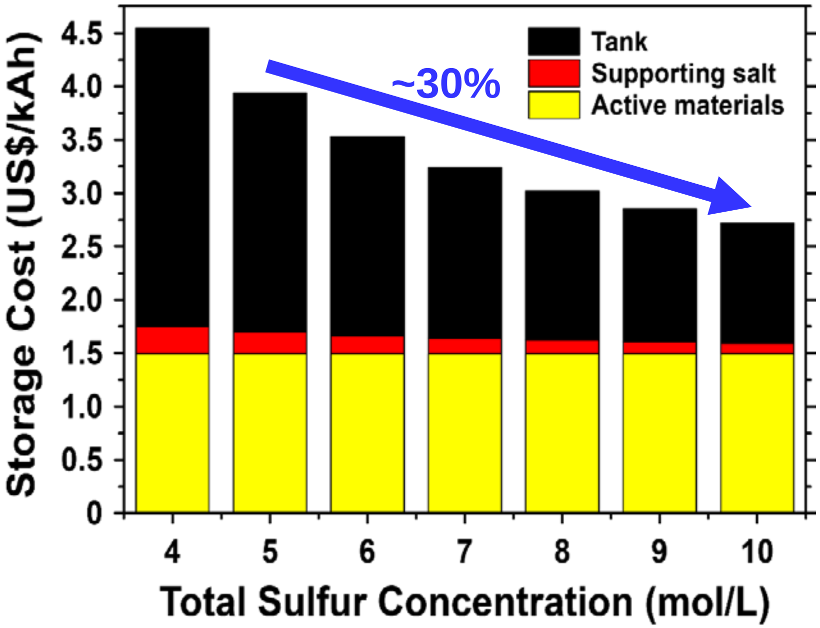
Towards higher energy density (for lower cost)

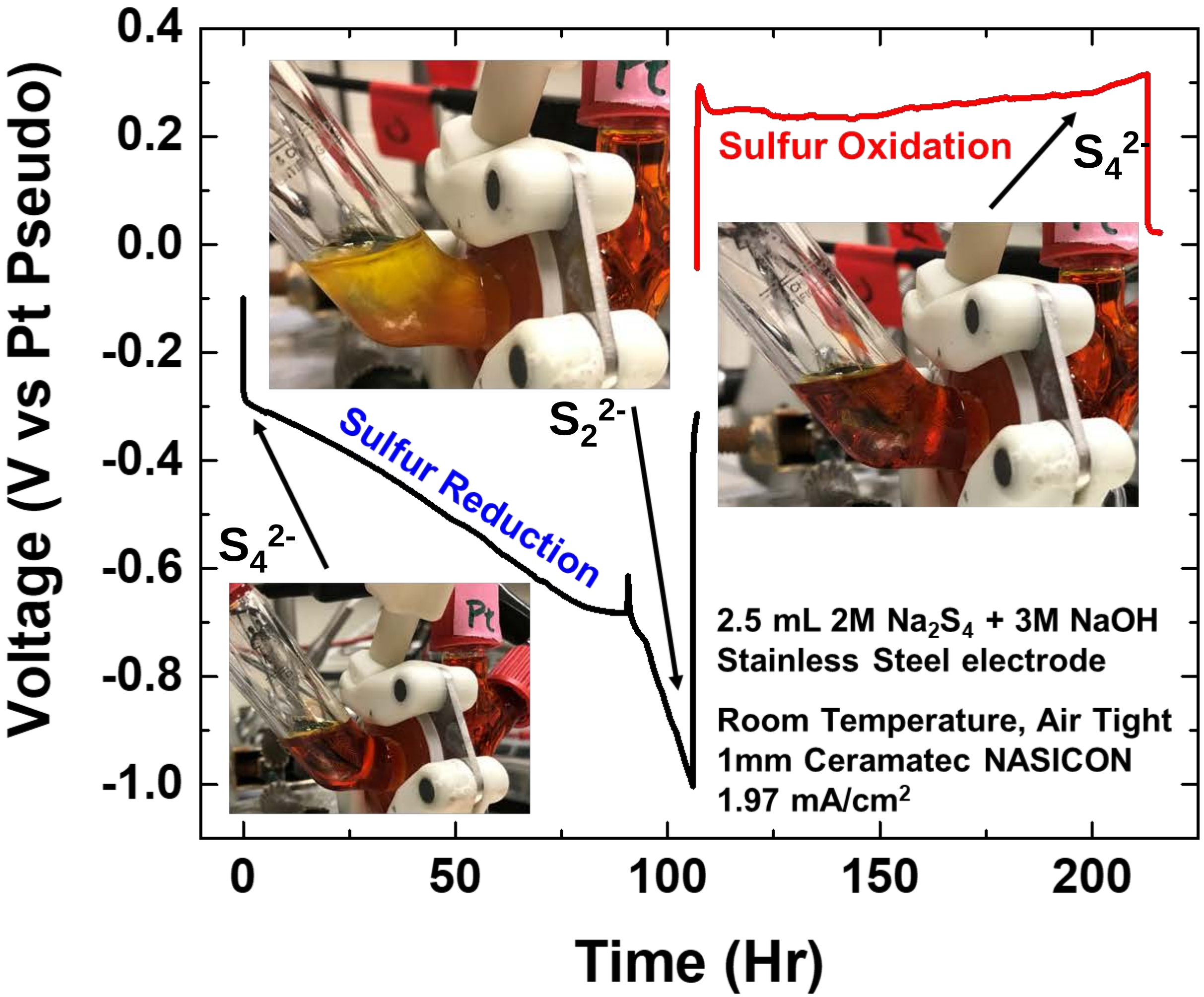
Sodium polysulfide stability limits are defined by *speciation* and *solubility*



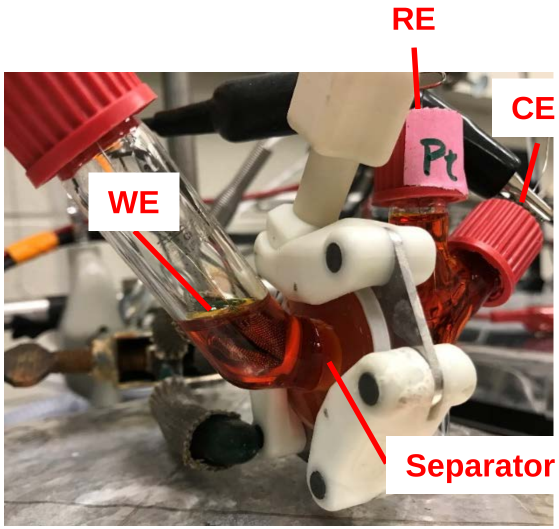


Conventional redox flow batteries use fully soluble electrodes, thus, **constrained by the solubility of the active materials**. For aqueous polysulfide, the upper solubility limit is **5M sulfur** as demonstrated previously.

Reversible precipitation in an 8M sulfur solution during reduction from Na_2S_4 to Na_2S_2 (S_4^{2-} to S_2^{2-})



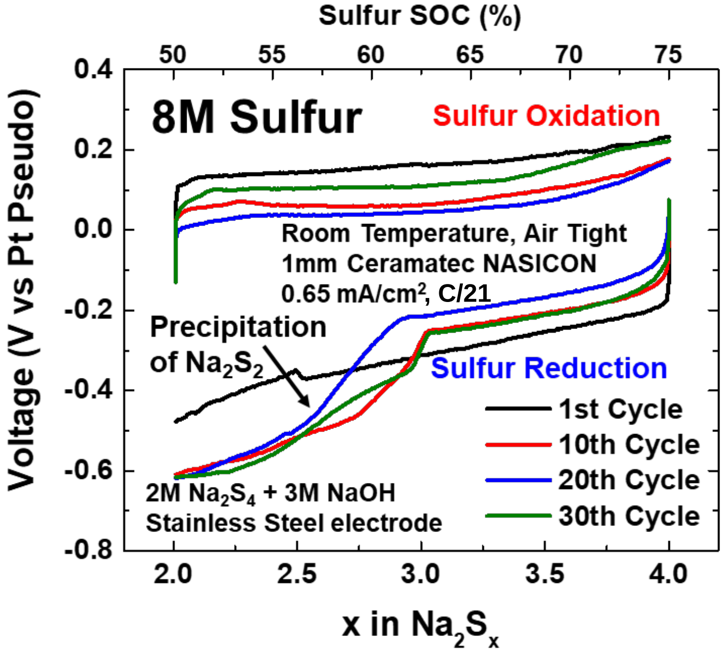
(C/21 galvanostatic cycling)



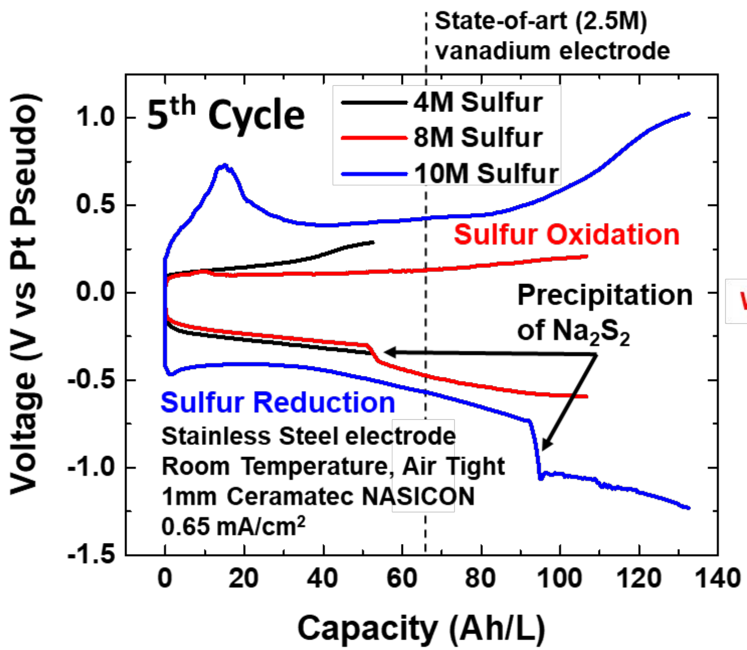
Asymmetric anolyte-anolyte cell

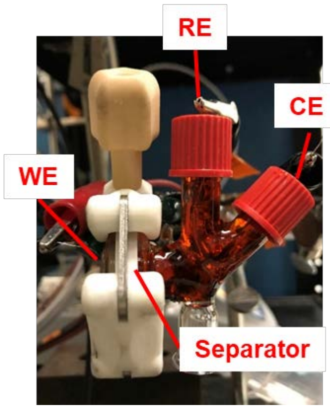
Stable cycling through reversible preciptation

Driven to precipitation when reduced



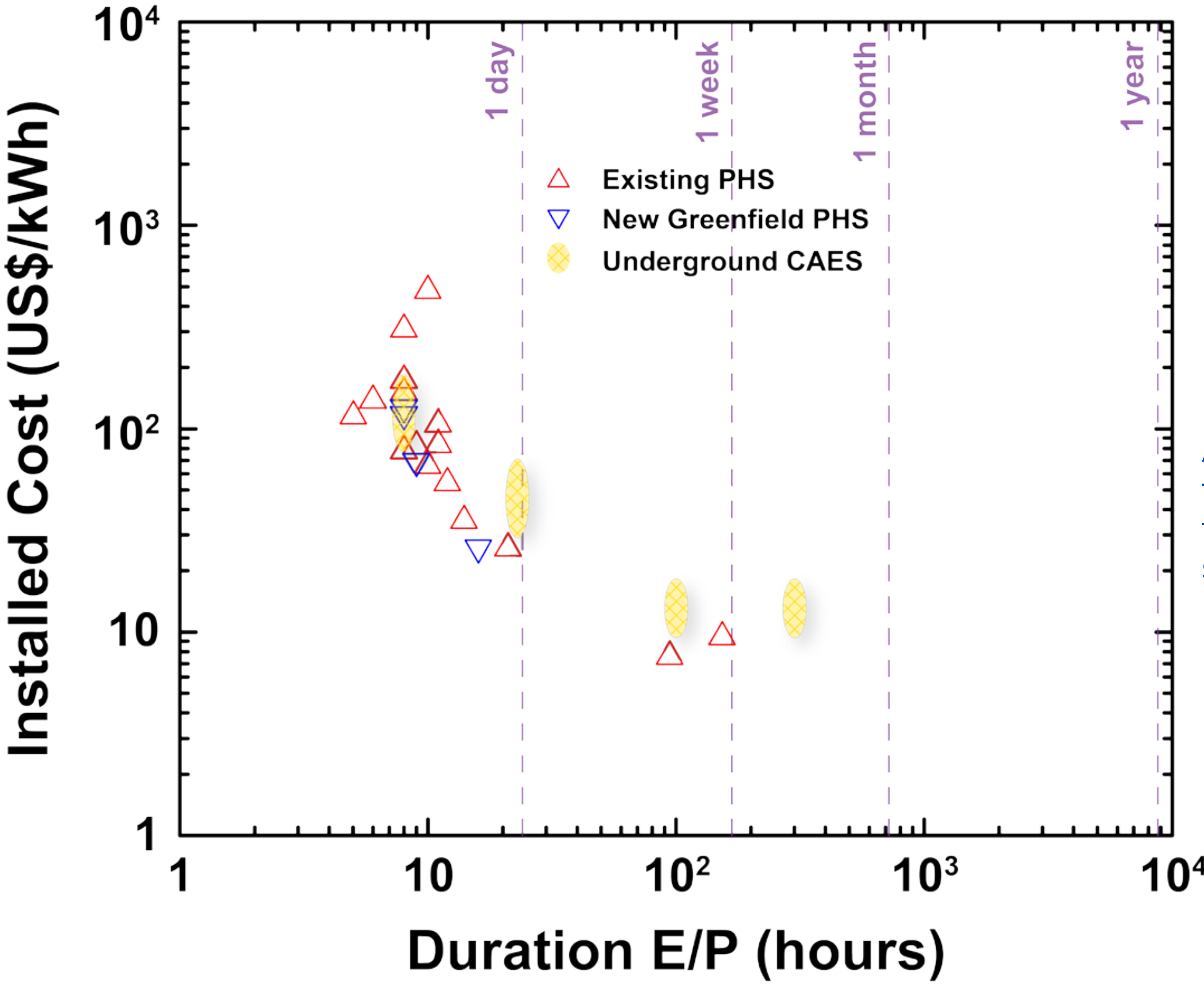
Capacity enhancement





- **Faster dissolution rate** of polysulfide precipitates than in non-aqueous Li-S batteries enabling recovery of capacity from electrically disconnected precipitates.
- **Signs of precipitation** in voltage profile.
- Stable cycling for **>1600 hours**.
- 5M Sulfur: 67 Ah/L → 8M Sulfur: **107 Ah/L** → 10M Sulfur: **134 Ah/L**.

Installed cost comparison between storage technologies – PHS and CAES

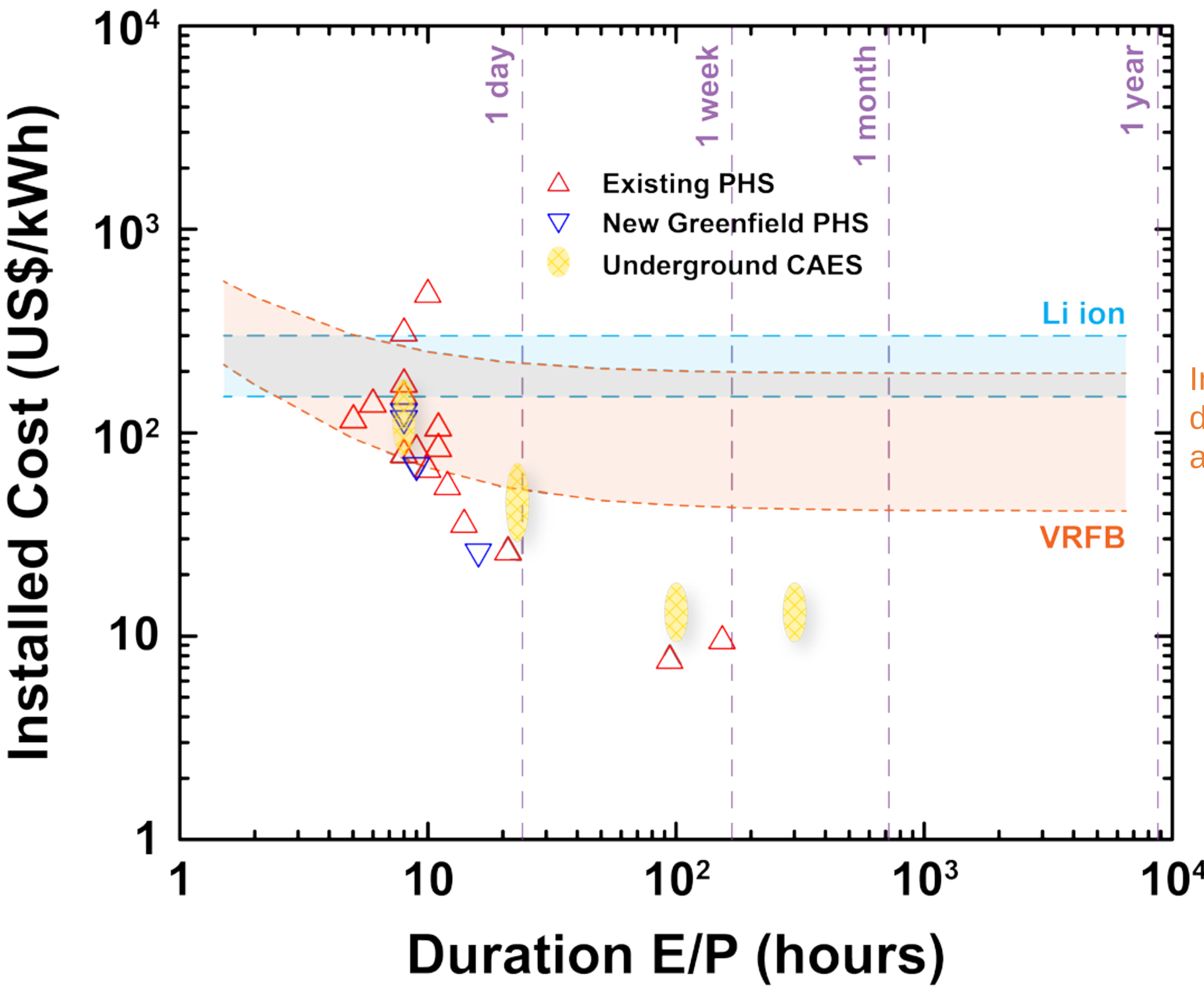


PHS – using water as the working fluid

CAES – using air as the working fluid

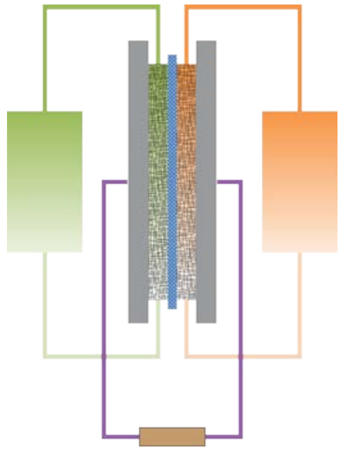
At long storage durations, the cost contribution of turbines is "diluted" and system cost drops

Installed cost comparison between storage technologies – PHS, CAES, Li-ion, and VRFB

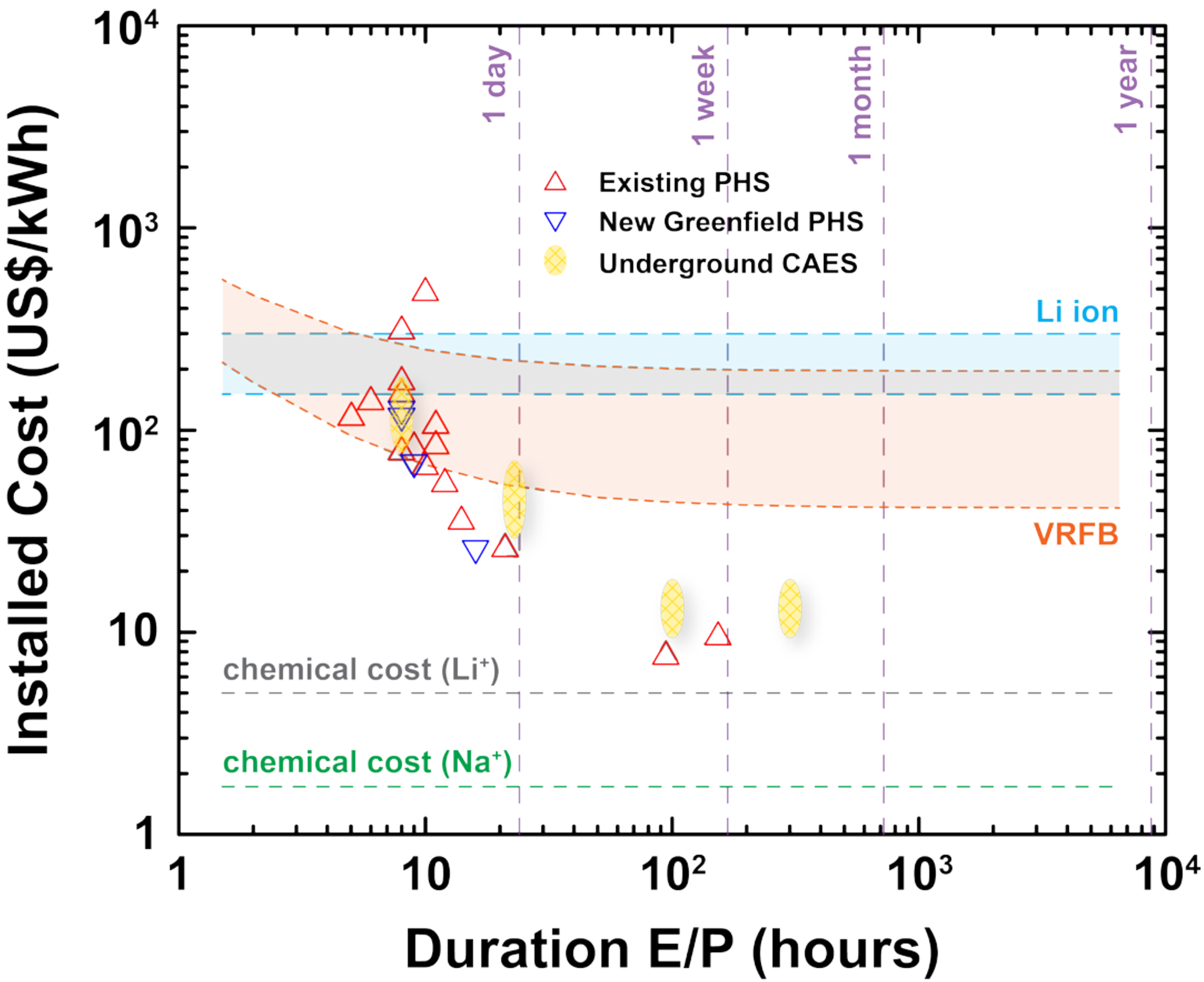


VRFB – decoupled energy and cost but vanadium is expensive

Installed cost at long duration asymptotically approaches energy cost



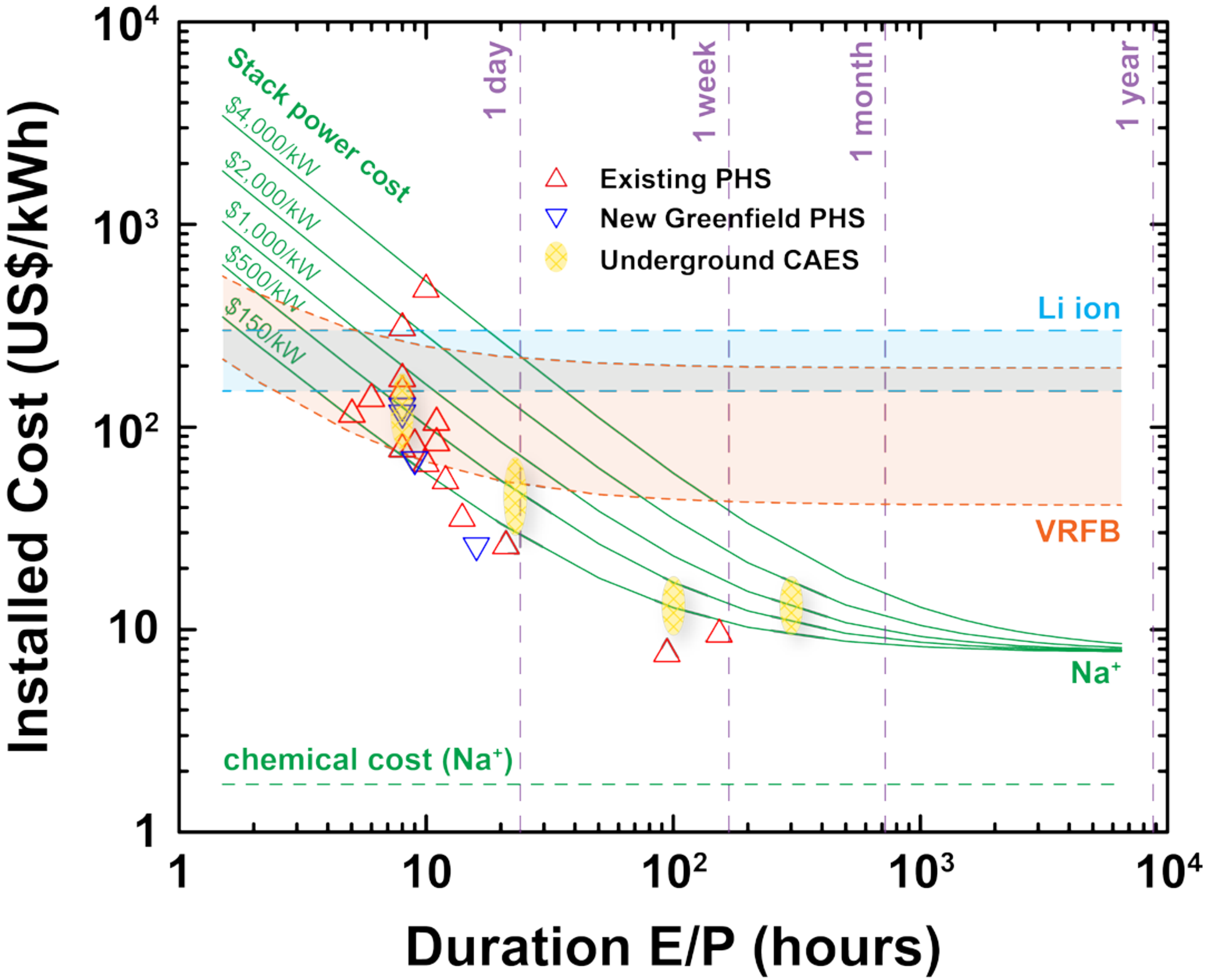
Installed cost comparison between storage technologies – PHS, CAES, Li-ion, VRFB, and our work



Air-breathing aqueous sulfur battery – ultralow chemical cost

Assume:
acidic catholyte, 5 M working ion, and 5 M total sulfur, S_2^{2-} to S_4^{2-} with experimentally determined OCV

Installed cost comparison between storage technologies – PHS, CAES, Li-ion, VRFB, and our work



Overall cost of our battery matches that of PHS or CAES

Assume:
ASR 15 – 100 Ω cm² (peak power 4 – 30 mW/cm²) and membrane cost 10 – 100 \$/m²; 1.7 \$/kWh energy cost (Na⁺)

Key Takeaways

- We developed an air-breathing aqueous sulfur battery with low chemical cost of storage ~1US$/kWh.
- In a flow battery architecture, the installed cost of this battery technology can compete with that of PHS or CAES, without geographical constraints.
- Future work should be focusing on decreasing the stack power cost by reducing the membrane resistance and cost, streamlining the cell designs, and using less or lower-cost catalyst.