Electrochemical Systems for Large-Scale Energy Storage

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Cal ACS Science Café

September 28th, 2024

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Nuclear Deterrence

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Stockpile & Enterprise Transformation

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Threat Preparedness and Response

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Bio Resilience

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Climate & Energy Security

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Climate Impacts & Resilience

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Multi-Domain Deterrence

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Integrated Deterrence & Tech Competition

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Multi-Domain Deterrence

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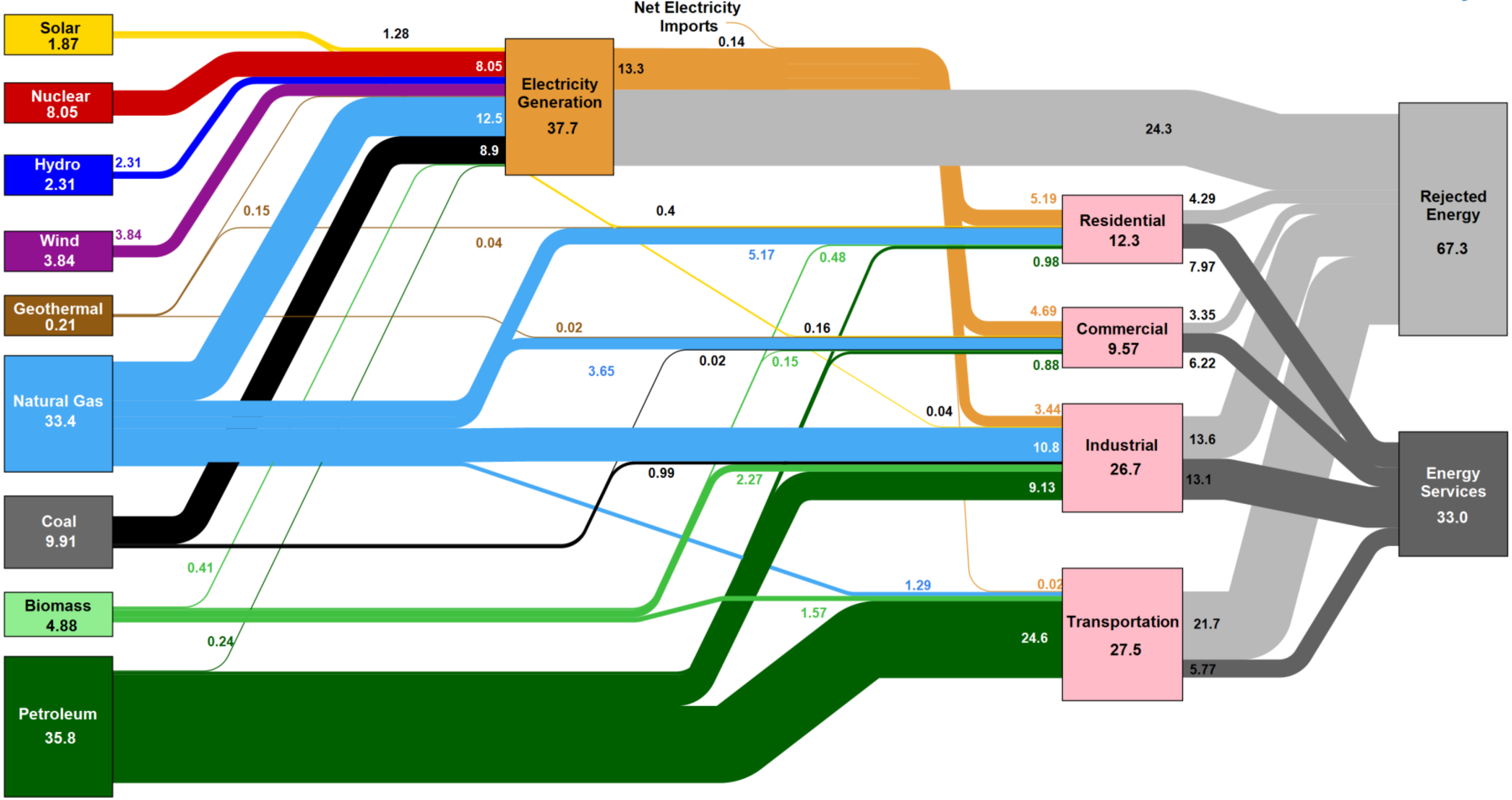
Integrated Deterrence & Tech Competition

Develop and apply tools for predicting, mitigating, and adapting

Estimated U.S. Energy Consumption in 2022: 100.3 Quads

Lawrence Livermore National Laboratory

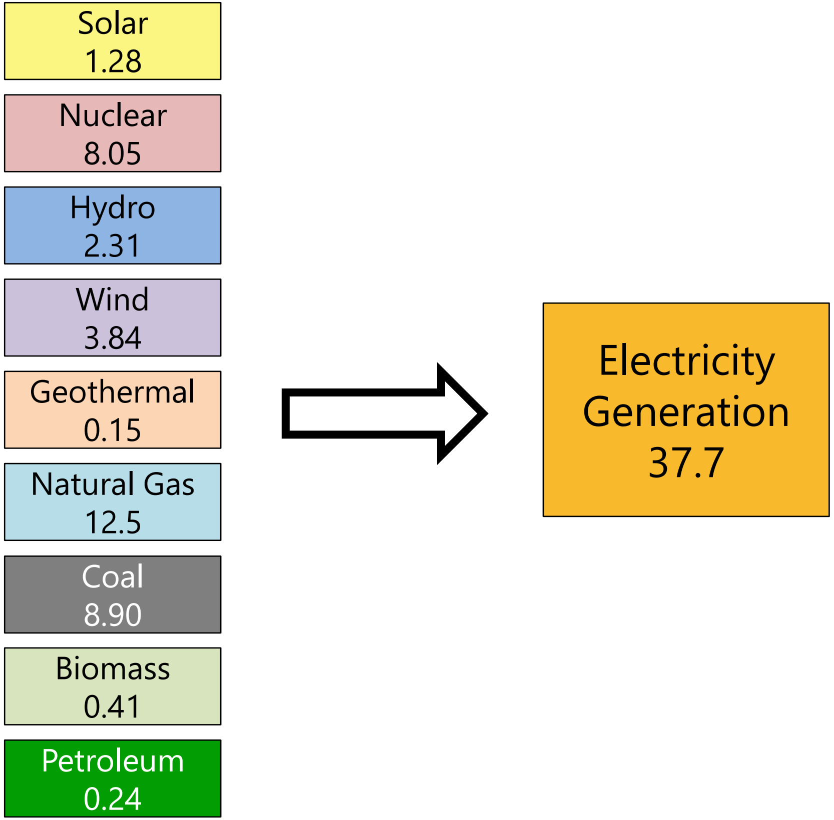


Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Renewables are a sizeable and growing part of the US energy mix

41% of electricity generation is currently produced by non-fossil sources

Need to decarbonize 22 quadrillion BTUs of energy production by 2035!



Solar
1.28

Nuclear
8.05

Hydro
2.31

Wind
3.84

Geothermal
0.15

Natural Gas
12.5

Coal
8.90

Biomass
0.41

Petroleum
0.24

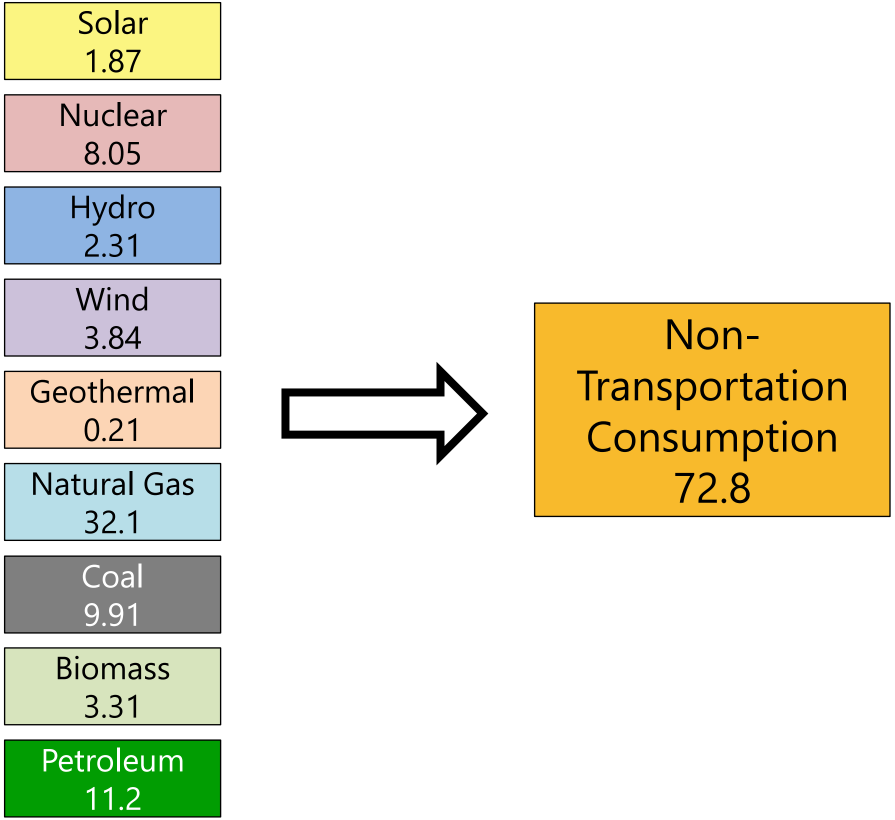
Electricity
Generation
37.7

Values in Quadrillion BTUs

Renewables are a sizeable and growing part of the US energy mix

22% of energy generation for all sectors is currently produced by non-fossil sources

Need to decarbonize 56.5 quadrillion BTUs of energy production by 2050!



Solar
1.87

Nuclear
8.05

Hydro
2.31

Wind
3.84

Geothermal
0.21

Natural Gas
32.1

Coal
9.91

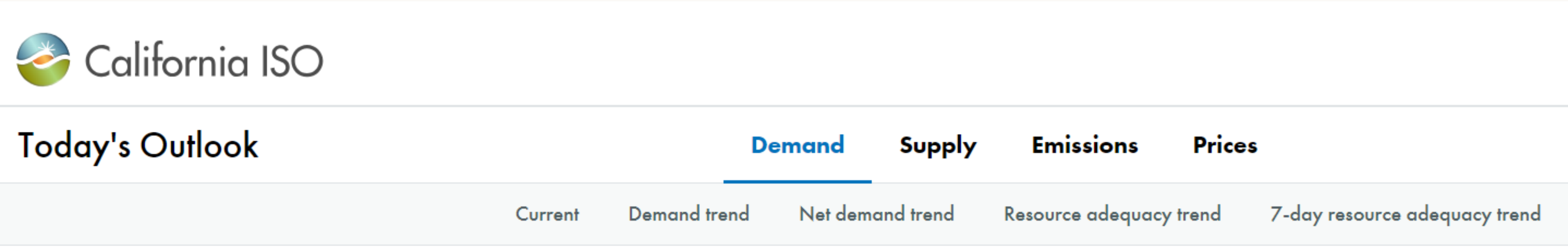
Biomass
3.31

Petroleum
11.2

Non-Transportation Consumption
72.8

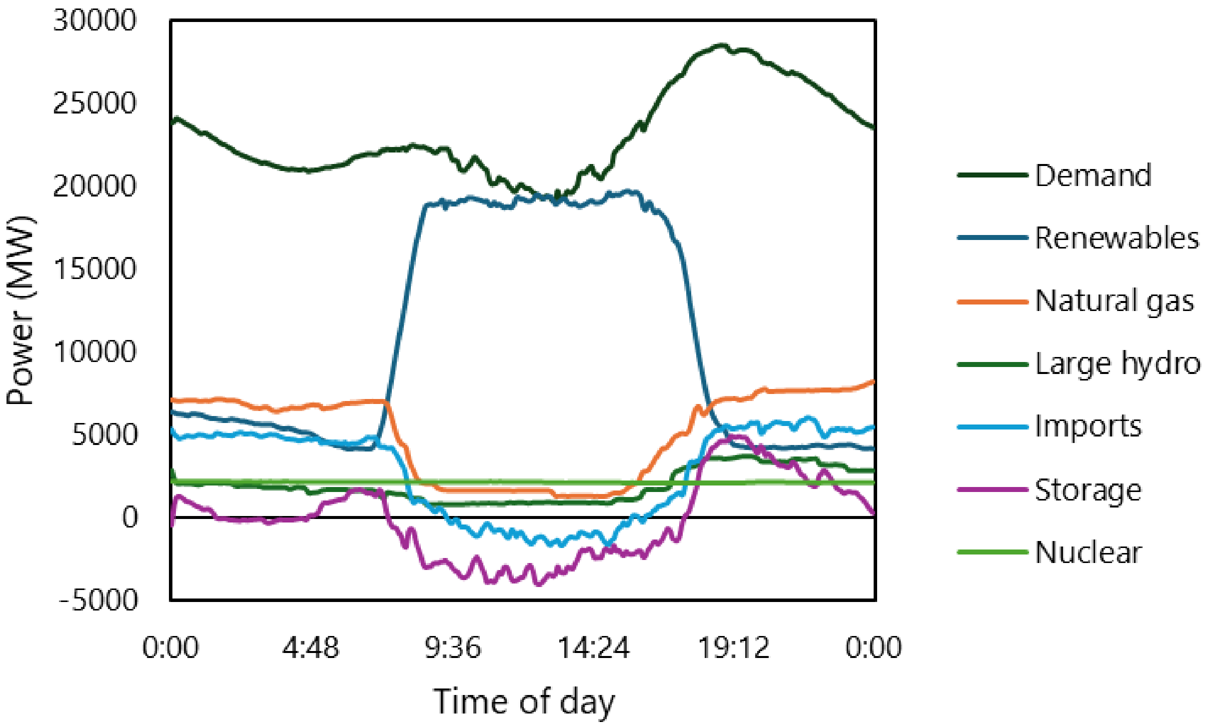
Values in Quadrillion BTUs

You can track grid supply and demand in real time in California

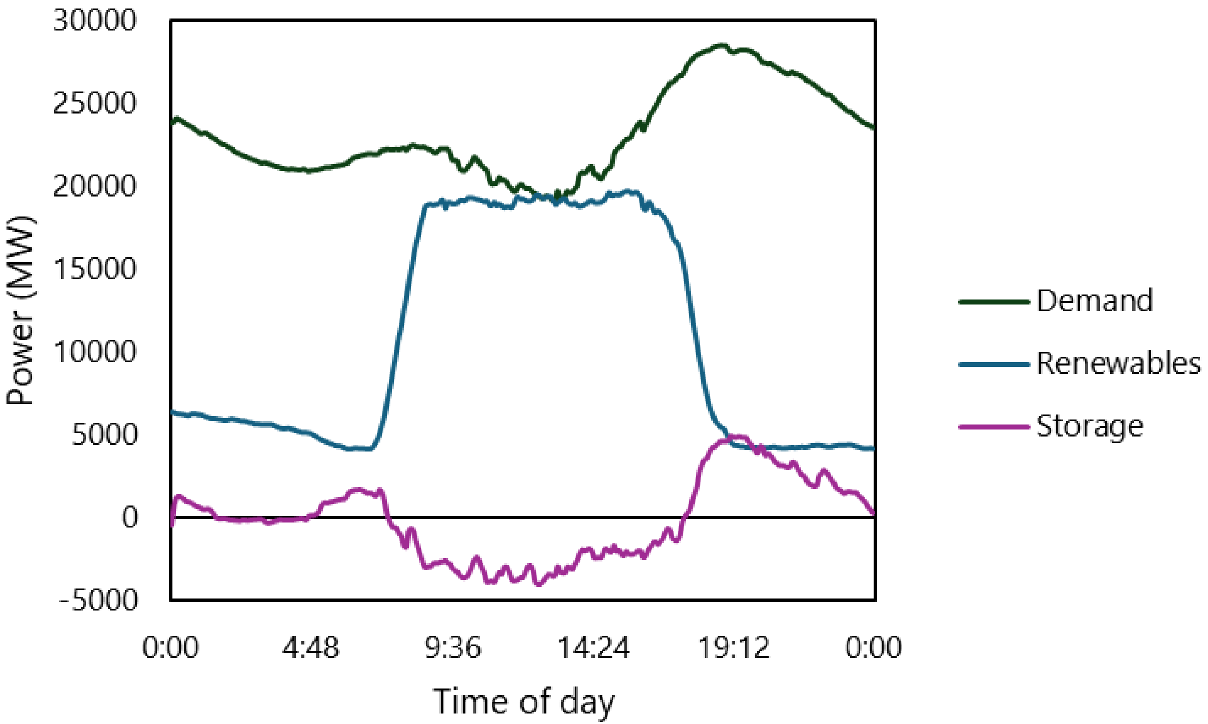


www.caiso.com/todays-outlook/

Overlaying supply and demand shows the need to time-shift the energy



Overlaying supply and demand shows the need to time-shift the energy



What are the different large-scale energy storage technologies?

Mechanical/Thermal	Electrochemical
Pumped hydropower	Lithium-ion batteries
Compressed air	Sodium-ion batteries
Flywheels	Flow batteries
Molten salt	Supercapacitors
	Hydrogen

What are the different large-scale energy storage technologies?

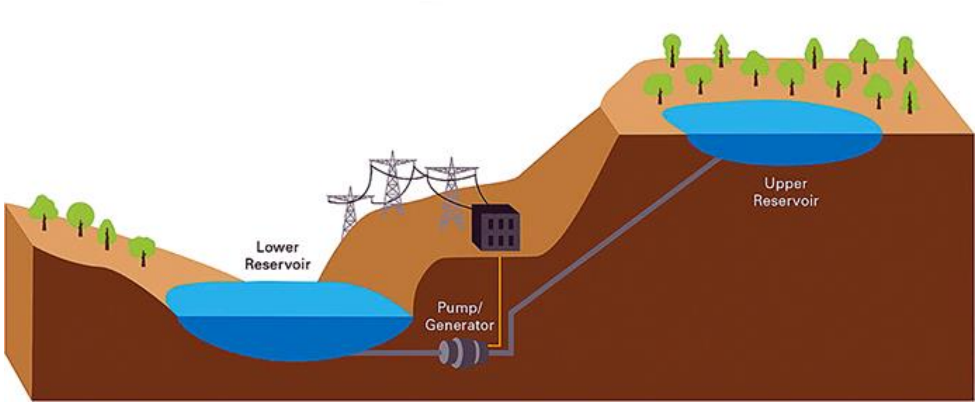
Mechanical/Thermal

- Pumped hydropower
- Compressed air
- Flywheels
- Molten salt

Electrochemical

- Lithium-ion batteries
- Sodium-ion batteries
- Flow batteries
- Supercapacitors
- Hydrogen

The oldie but goodie: pumped hydropower



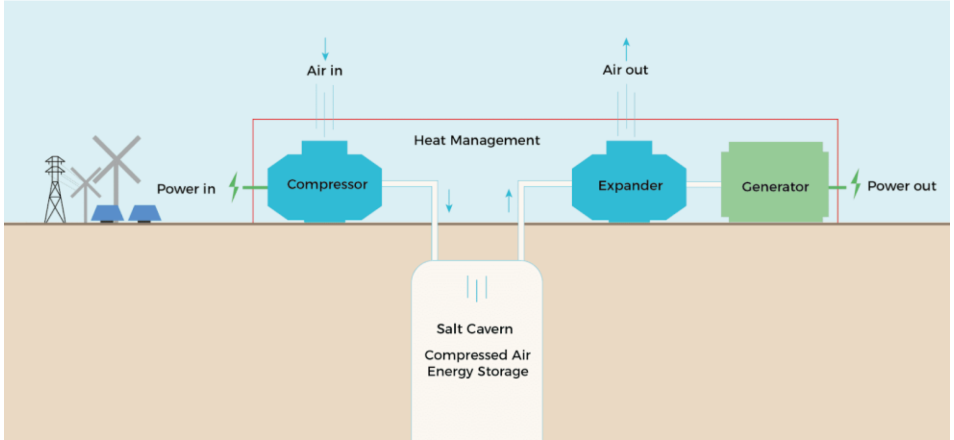
Mature

Cheap

Geographically Limited

theengineer.co.uk/content/in-depth/how-pumped-hydro-storage-can-help-save-the-planet

Compressed air is also a cheap, but limited method for storing energy



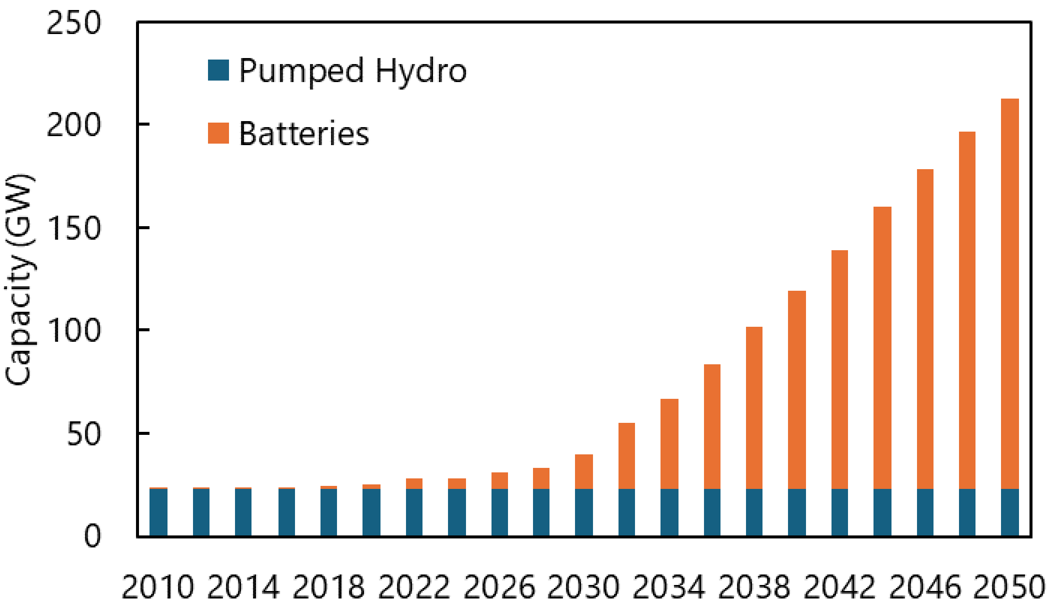
Mature

Cheap

Geographically Limited

https://www.greyb.com/blog/compressed-air-energy-storage-startups/

Battery energy storage is projected to grow from 20 to 200 GW of capacity by 2050



"Storage Futures Study", *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy21osti/77449.pdf

Electrochemical systems: a “battery” of choices

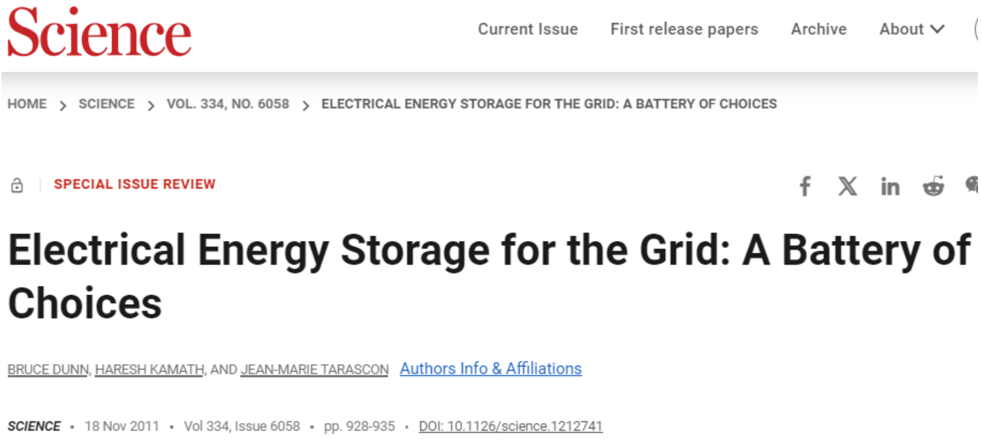
Mechanical/Thermal

- Pumped hydropower
- Compressed air
- Flywheels
- Molten salt

Electrochemical

- Lithium-ion batteries
- Sodium-ion batteries
- Flow batteries
- Supercapacitors
- Hydrogen

Electrochemical systems: a “battery” of choices



Science

HOME > SCIENCE > VOL. 334, NO. 6058 > ELECTRICAL ENERGY STORAGE FOR THE GRID: A BATTERY OF CHOICES

SPECIAL ISSUE REVIEW

Electrical Energy Storage for the Grid: A Battery of Choices

BRUCE DUNN, HARESH KAMATH, AND JEAN-MARIE TARASCON Authors Info & Affiliations

SCIENCE • 18 Nov 2011 • Vol 334, Issue 6058 • pp. 928-935 • DOI: 10.1126/science.1212741

<u>Electrochemical</u>

Lithium-ion batteries

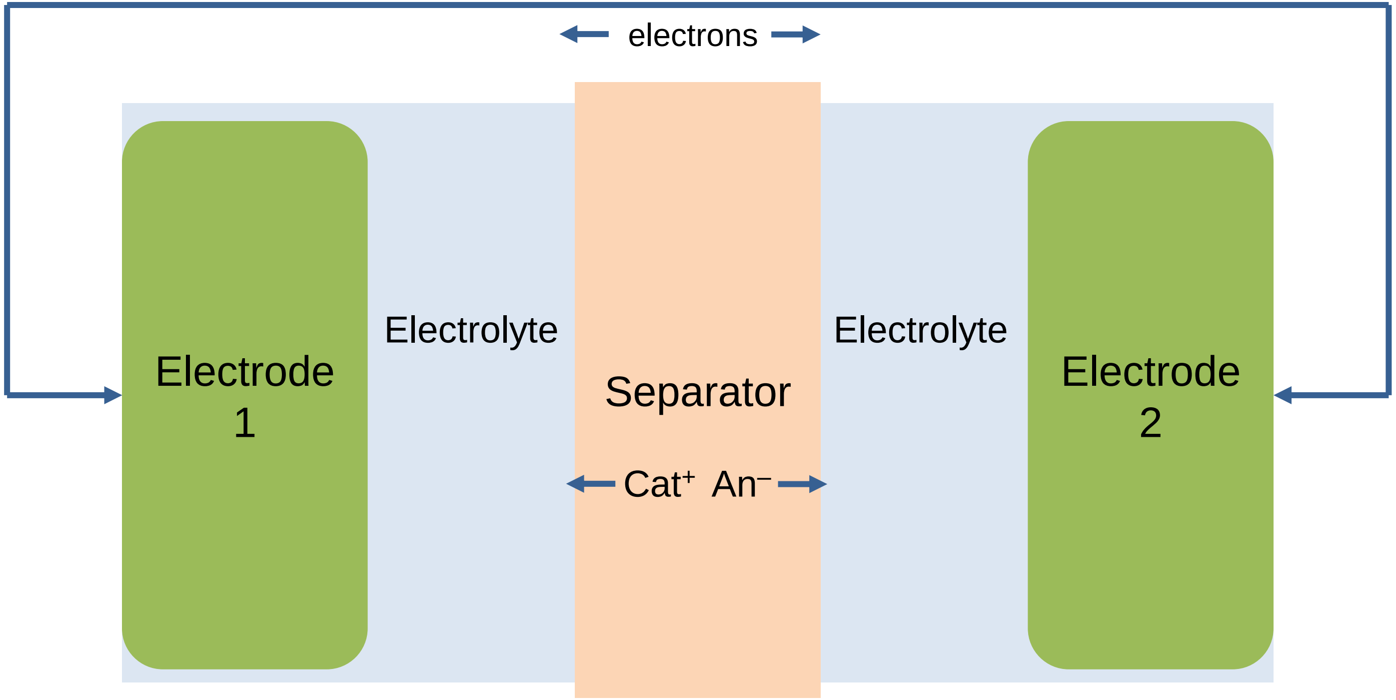
Sodium-ion batteries

Flow batteries

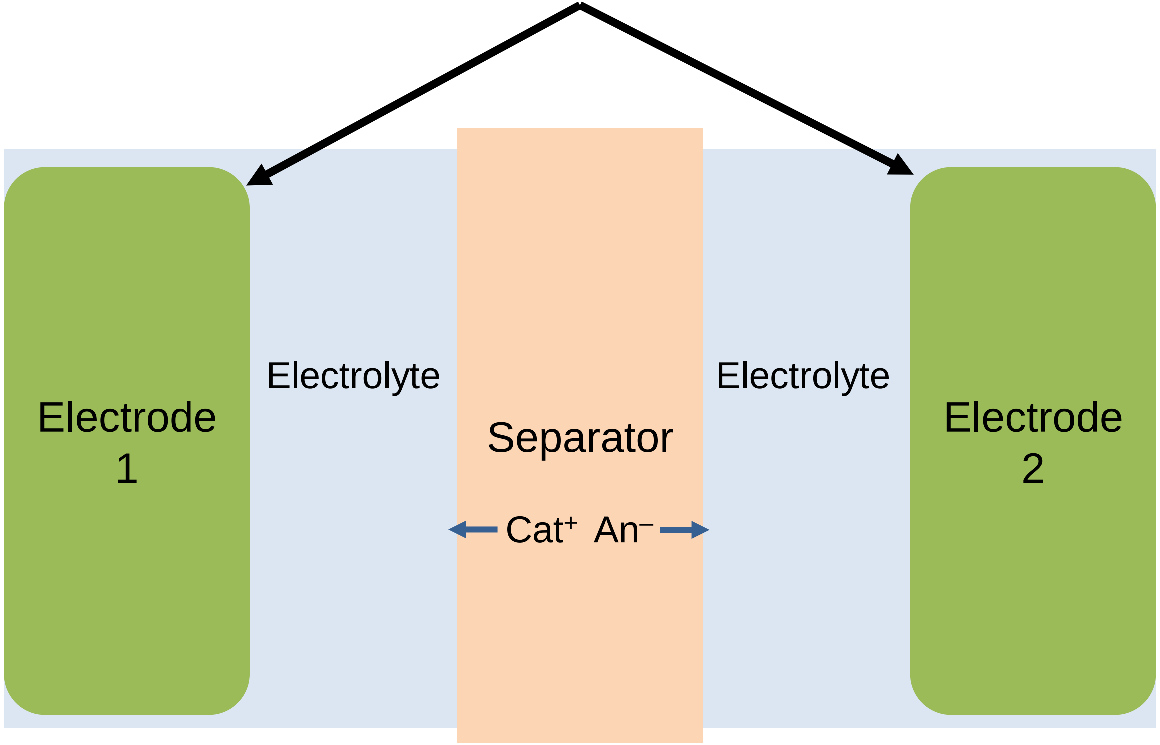
Supercapacitors

Hydrogen

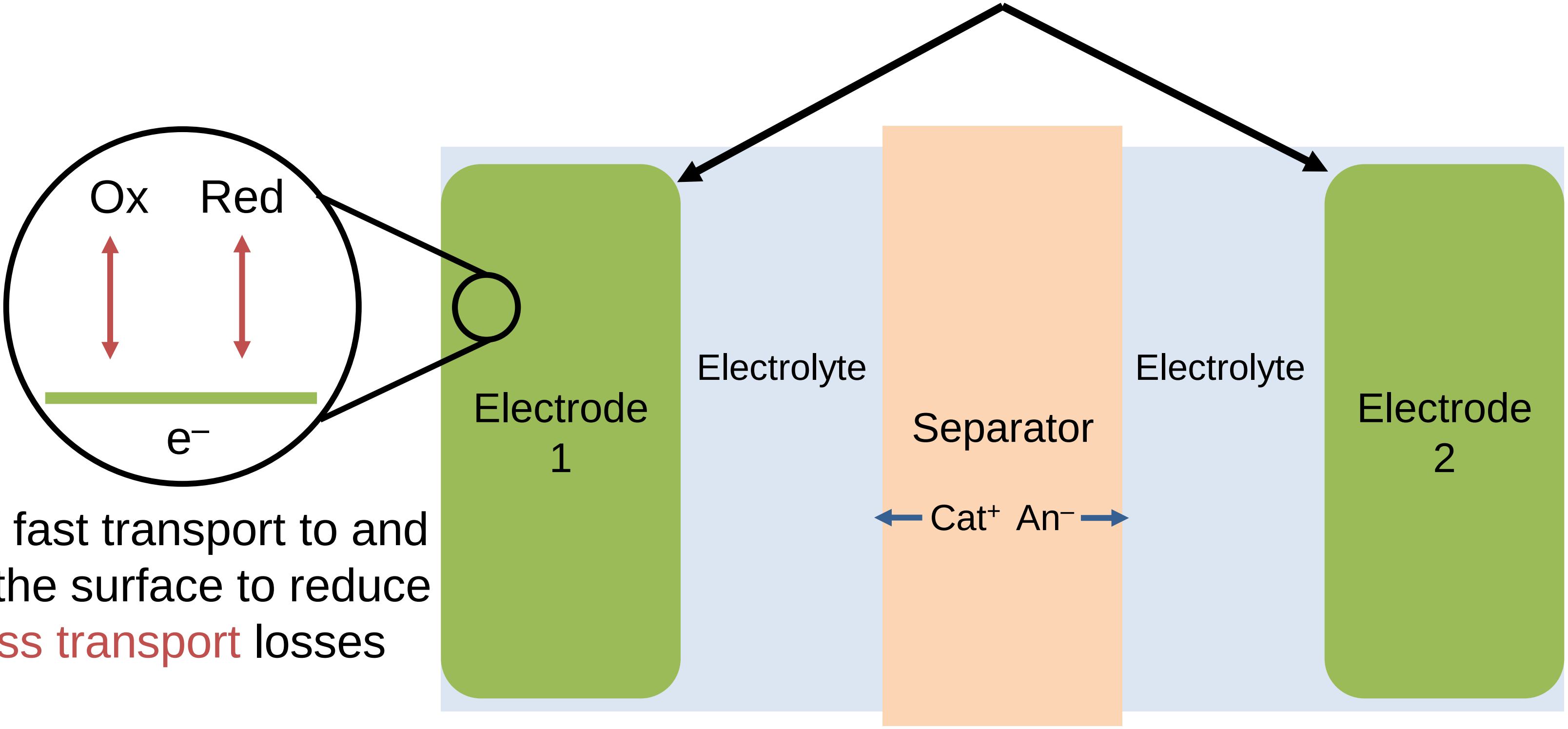
Electrochemical systems are comprised of two electrodes, an electrolyte, and (sometimes) a separator



Need unique reactions at each electrode to create a thermodynamic difference

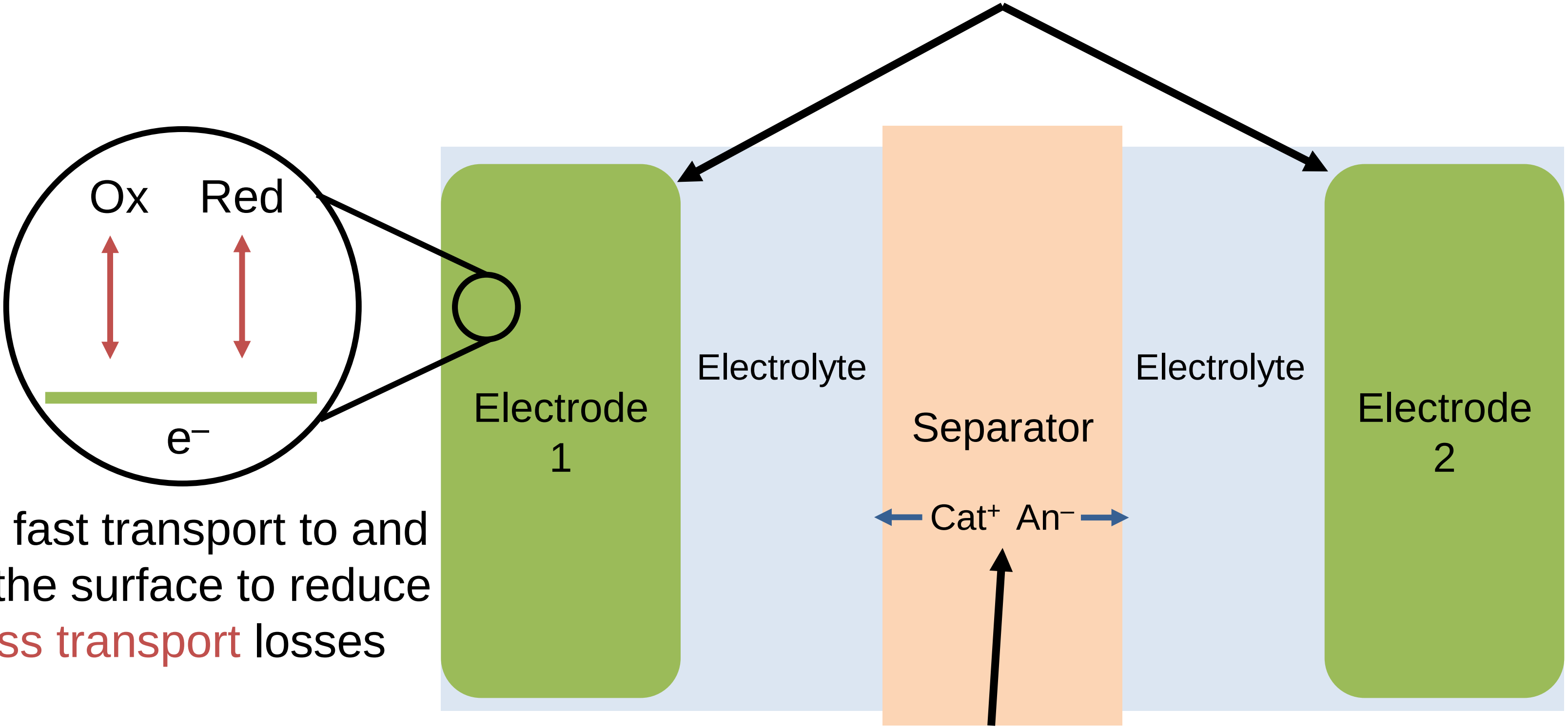


Need unique reactions at each electrode to create a thermodynamic difference



Need fast transport to and from the surface to reduce mass transport losses

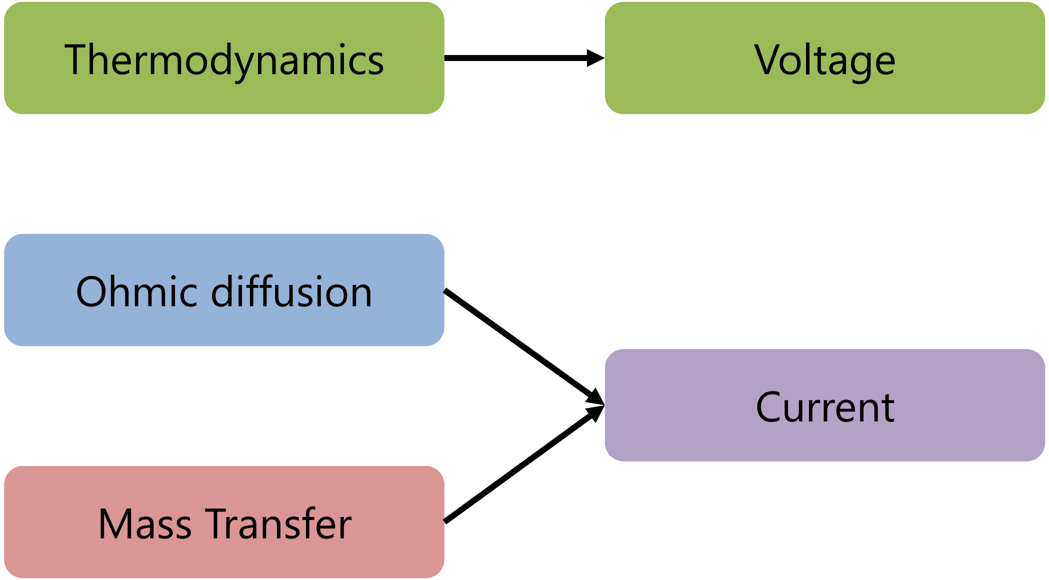
Need unique reactions at each electrode to create a thermodynamic difference



Need fast transport to and from the surface to reduce mass transport losses

Need fast diffusion through the electrolyte and separator to reduce ohmic losses

These three fundamental properties control battery performance



Thermodynamics

Voltage

Ohmic diffusion

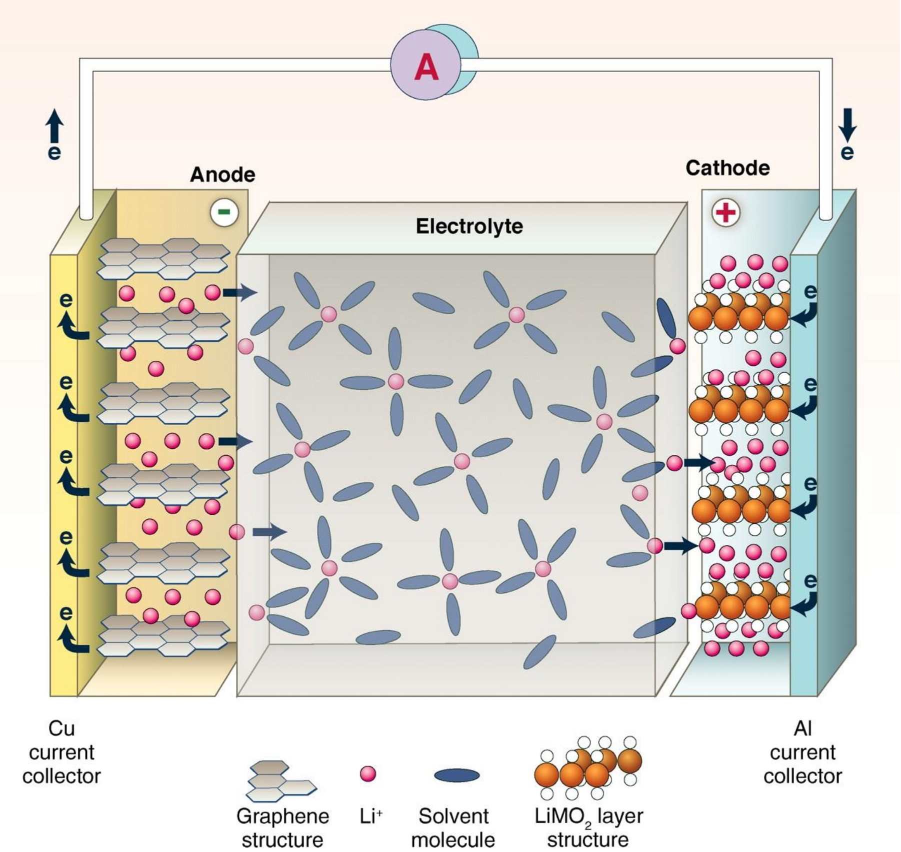
Mass Transfer

Current

$$Power = Current * Voltage$$

$$Energy = \int Power * Time$$

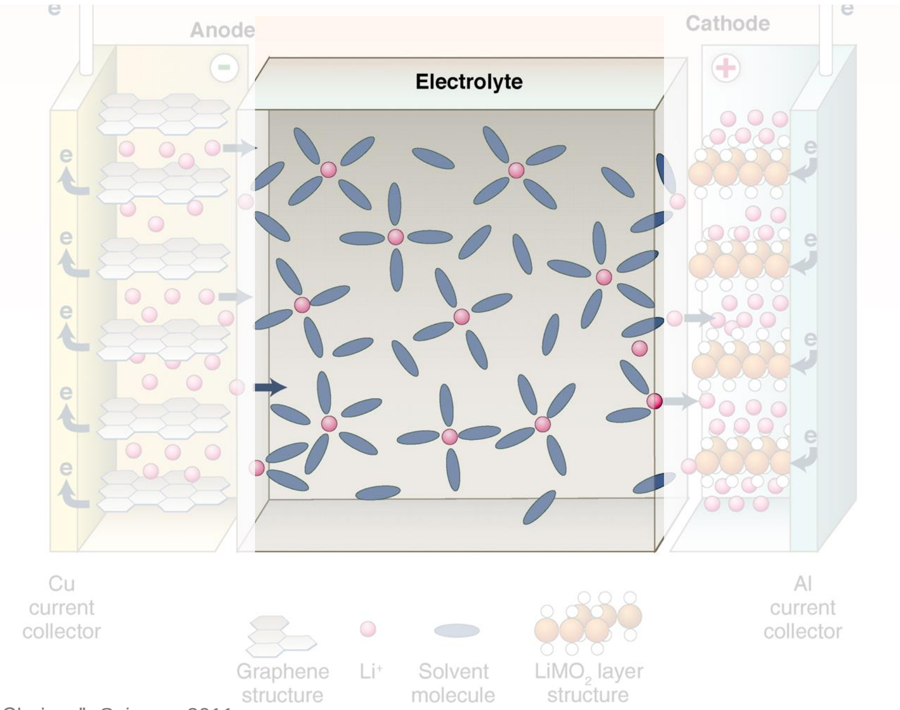
The battery you have probably heard of: the lithium-ion battery



“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

“Generation 2” electrolyte: $LiPF_6$ with a mixture of ethylene carbonate / ethylmethyl carbonate

Electrolyte needs: high lithium diffusivity, good temperature stability, high voltage window

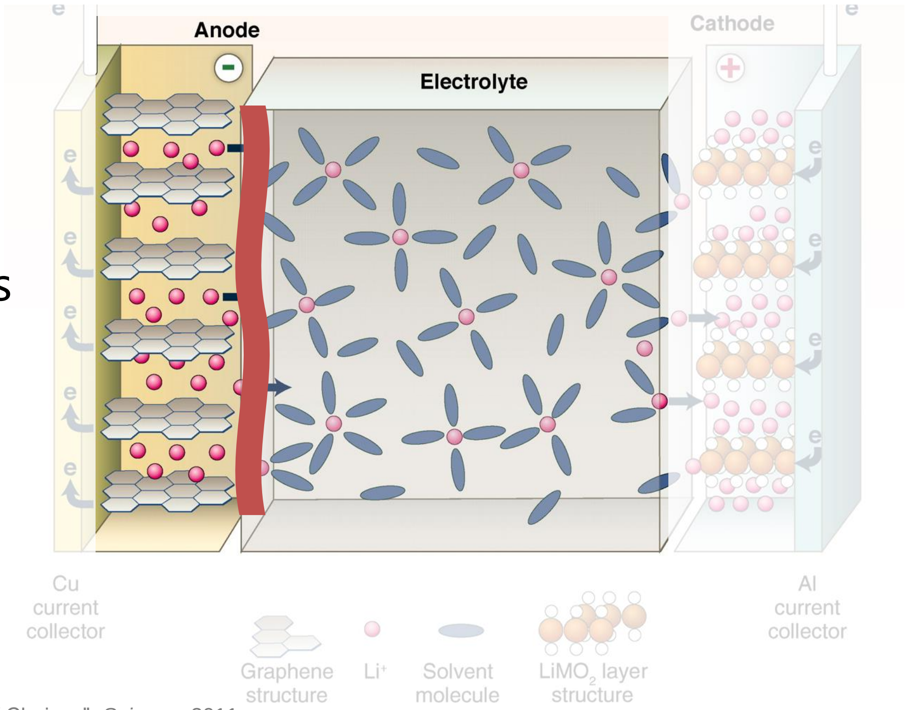


“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

"Generation 2" electrolyte:
$LiPF_6$ with a mixture of ethylene carbonate / ethylmethyl carbonate

Electrolyte needs: high lithium diffusivity, good temperature stability, high voltage window

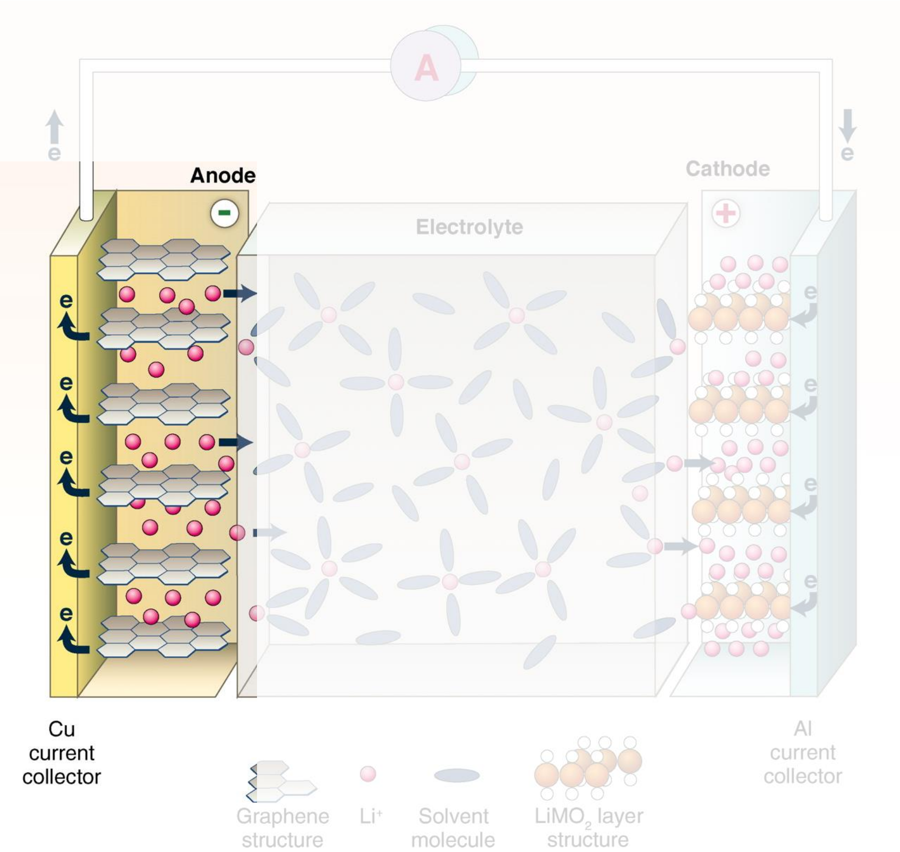
Electrolyte can breakdown to form a resistive film known as the "solid electrolyte interphase" (SEI)



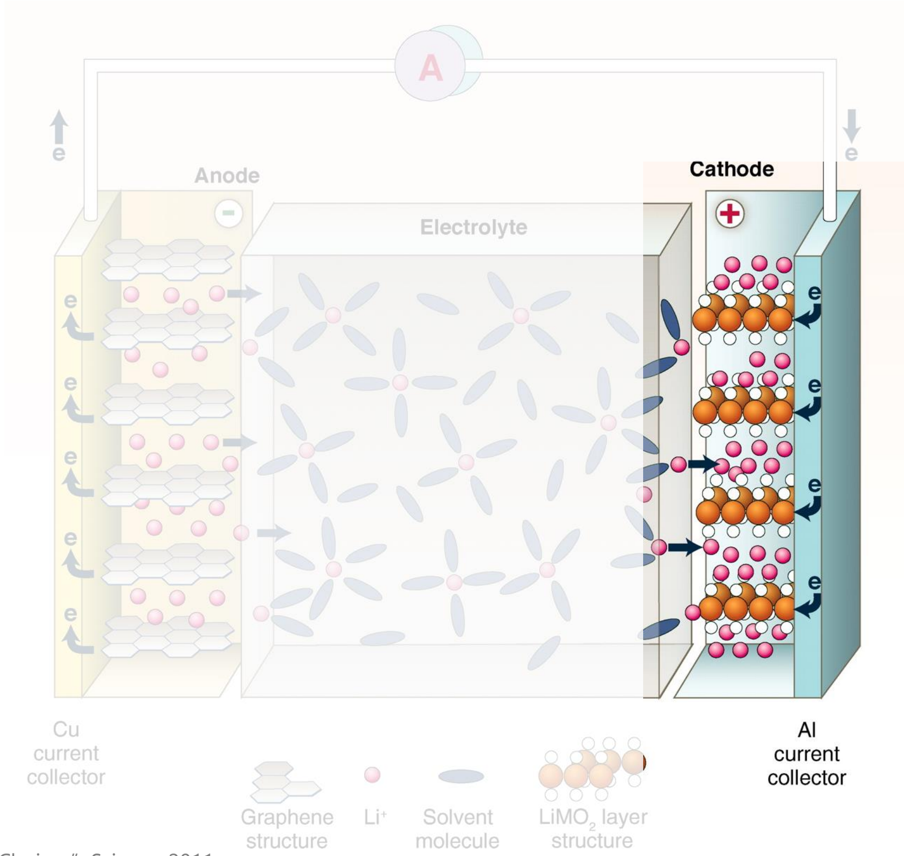
"Electrical Energy Storage for the Grid: A Battery of Choices", *Science*, 2011

Graphitic carbon
$LiC_6 \leftrightarrow C_6 + Li$

Most of the mass
is graphite!



"Electrical Energy Storage for the Grid: A Battery of Choices", *Science*, 2011



Two most common:

L Lithium
F Fe (iron)
P Phosphate

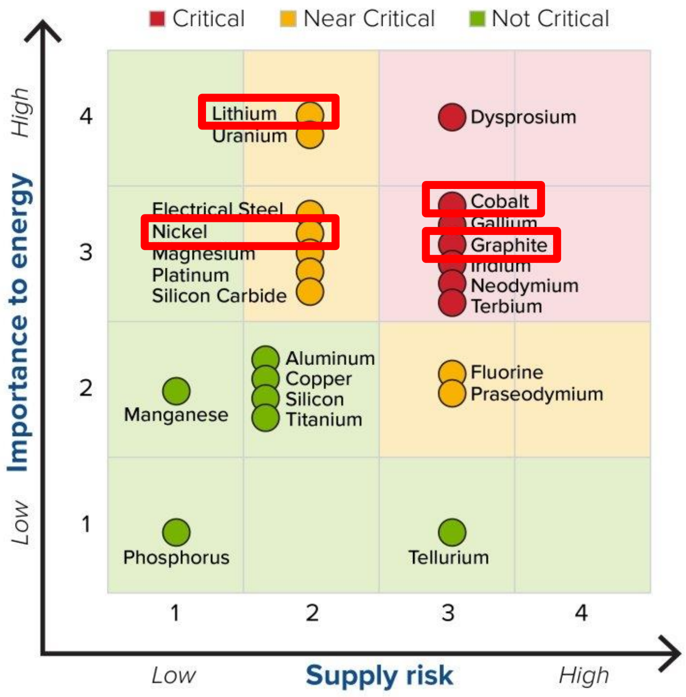
N Nickel
M Manganese
C Cobalt oxide

Not very conductive!
Add: carbon, PVDF, etc.

“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

Materials for lithium-ion batteries have high supply risk

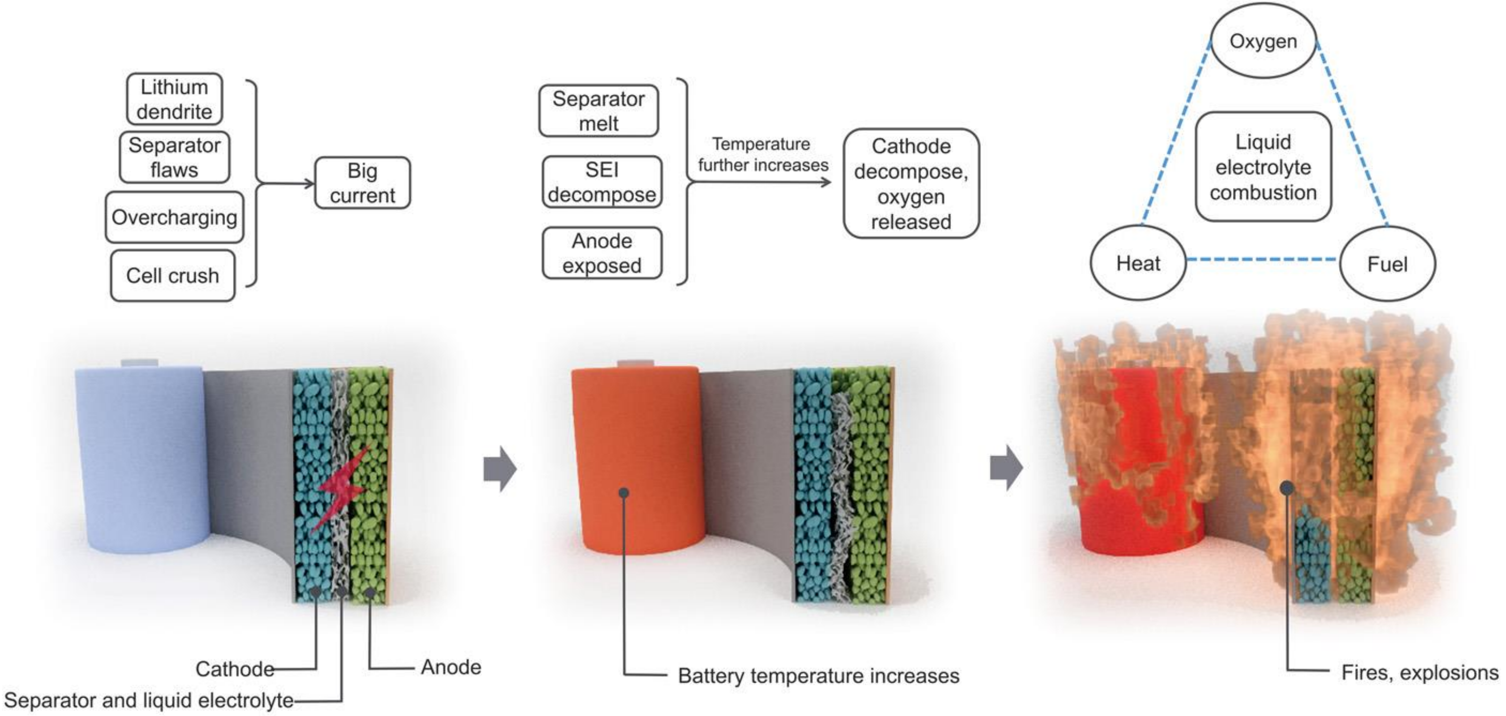
SHORT TERM 2020-2025



MEDIUM TERM 2025-2035

“Critical Materials Assessment”, U.S. Department of Energy, July 2023

Thermal runaway can cause them to catch fire



Stage 1: The onset of overheating

Stage 2: Heat accumulation and gas release process

Stage 3: Combustion and explosion

“Materials for lithium-ion battery safety”, *Science Advances*, 2018

While these events are somewhat infrequent, they can still cause concern

Lithium Battery Fire Continues to Burn as County Considers Moratorium

TIMES of SAN DIEGO

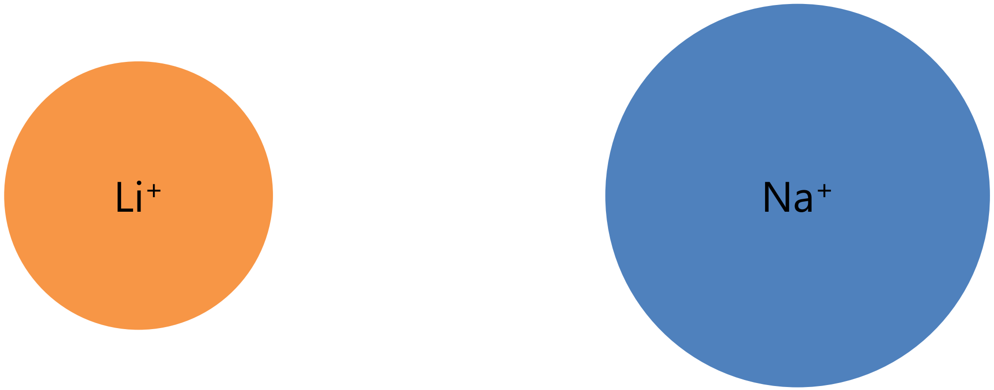
Sept. 7th, 2024

What is very similar to lithium, but not quite lithium?

Sodium!

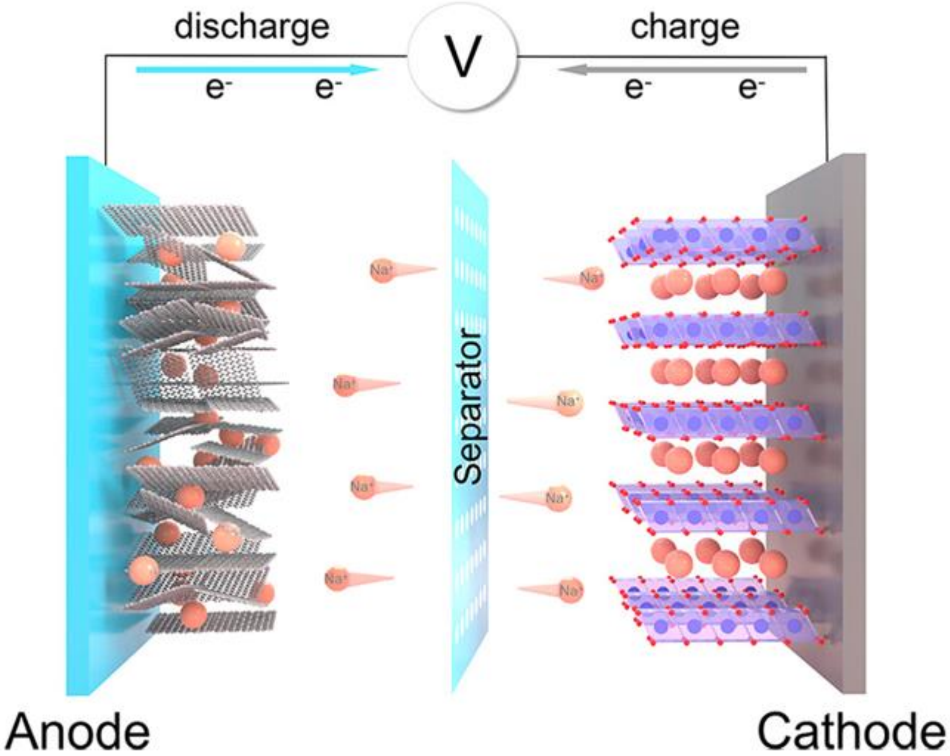
What is different about lithium and sodium?

Molecular size!



This impacts
→ solvent-ion relationship changing diffusivity
→ ion intercalation into electrode materials
→ weight of the battery

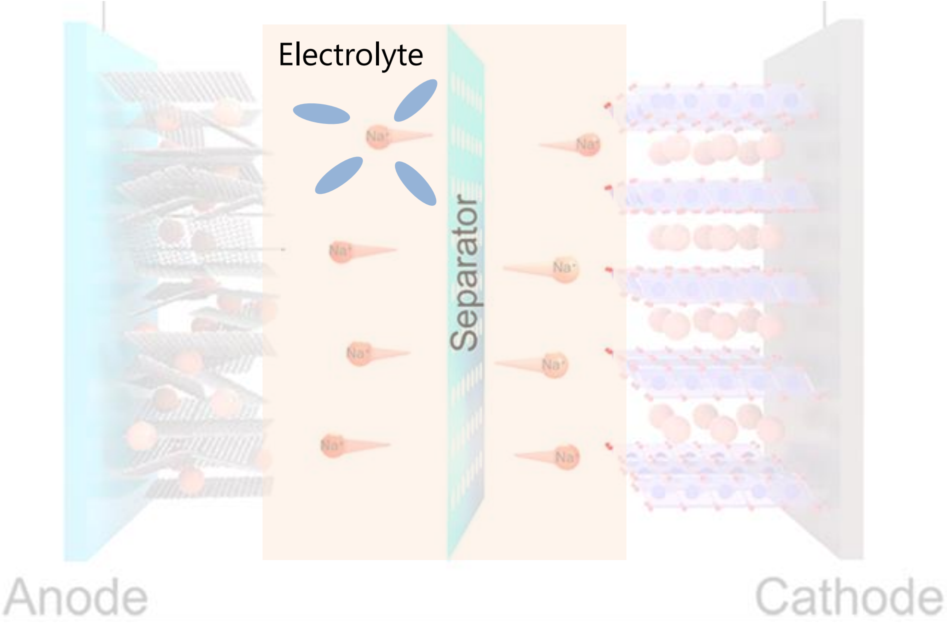
How does that change the materials needed?



“Advanced Anode Materials for Rechargeable Sodium-Ion Batteries”, *ACS Nano*, 2023

Electrolyte can vary, but is quite similar to lithium
$NaPF_6$ or $NaClO_4$ with a mixture of
ethylene carbonate / diethyl carbonate or propylene carbonate

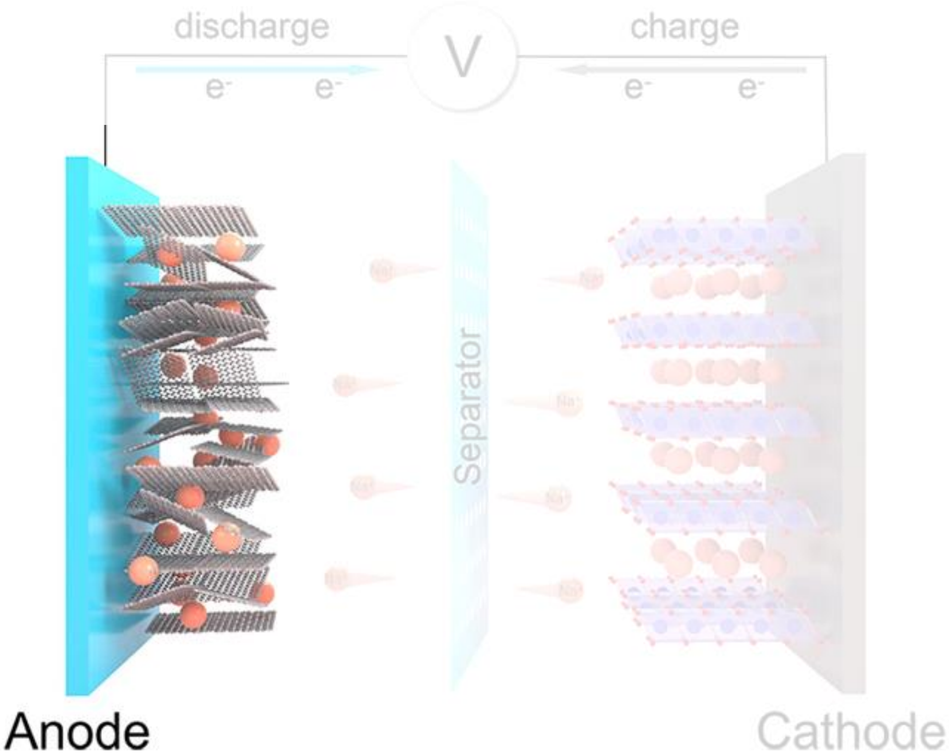
Conductivities are just slightly lower



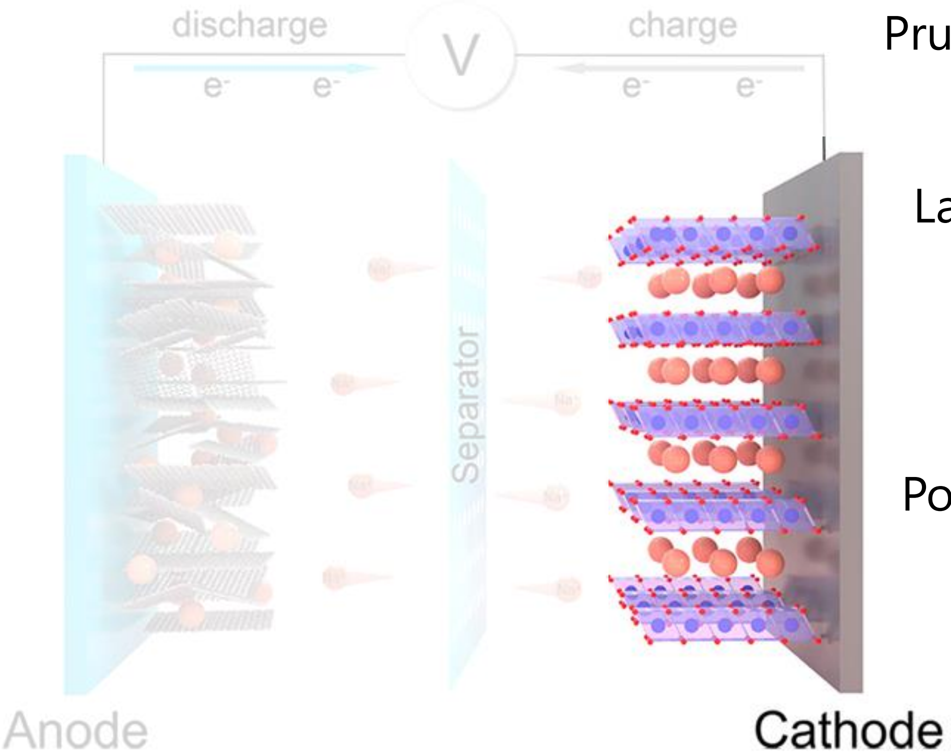
“Advanced Anode Materials for Rechargeable Sodium-Ion Batteries”, *ACS Nano*, 2023

Sodium insertion into graphitic carbon is poor!

"Hard" Carbon (similar to charcoal) or graphene are more often used



"Advanced Anode Materials for Rechargeable Sodium-Ion Batteries", *ACS Nano*, 2023



Prussian Blue Analogues

$Mn[Fe(CN)_6]_3$

Layered Metal Oxides

MnO_2

VO_2

FeO_2

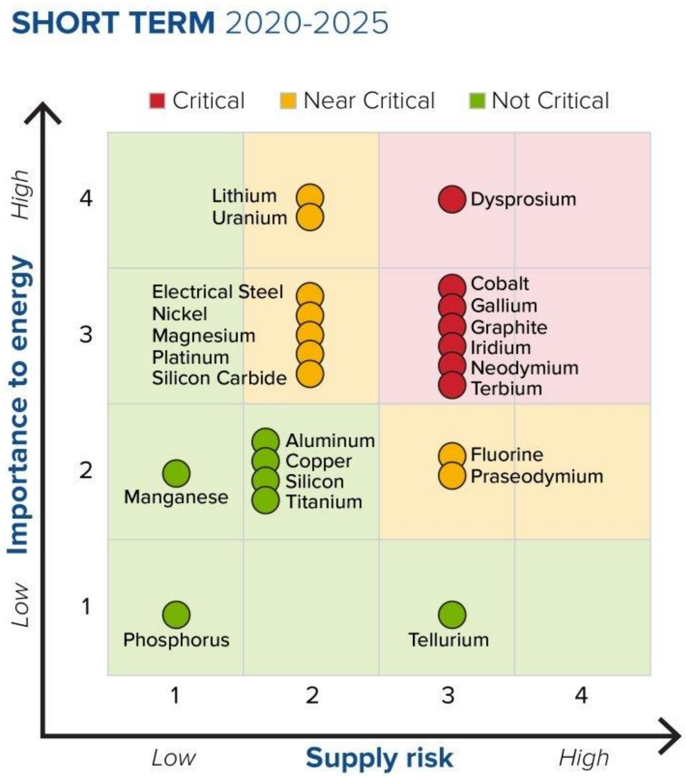
Polyanion Compounds

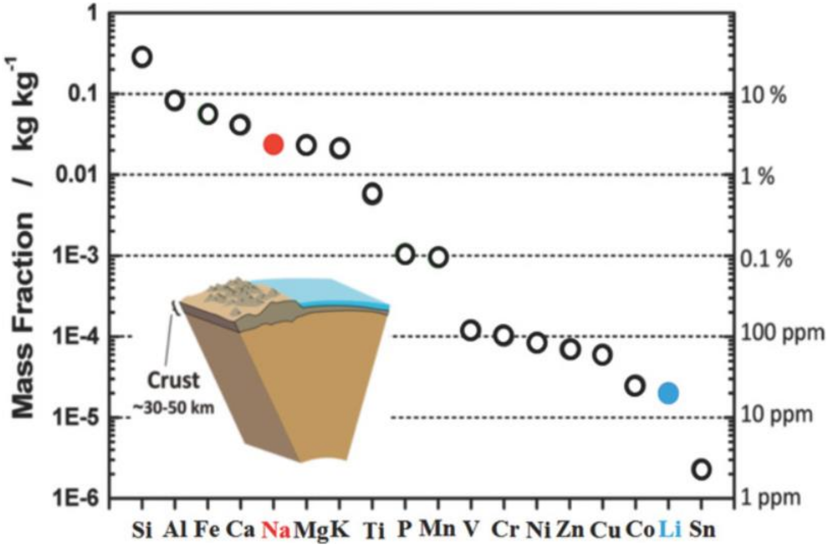
$V_2(PO_4)_3F$

$Fe_2(SO_4)_3$

“Advanced Anode Materials for Rechargeable Sodium-Ion Batteries”, *ACS Nano*, 2023

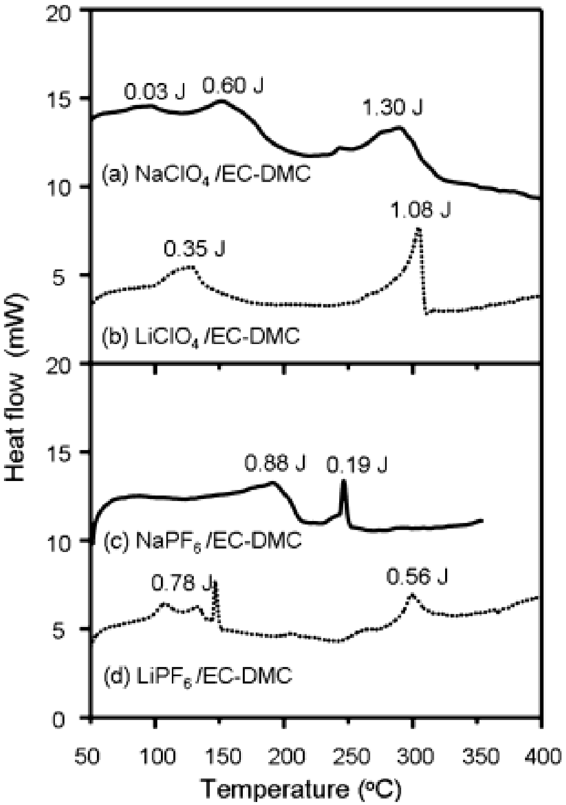
Materials for sodium ion batteries have low supply risk and are abundant

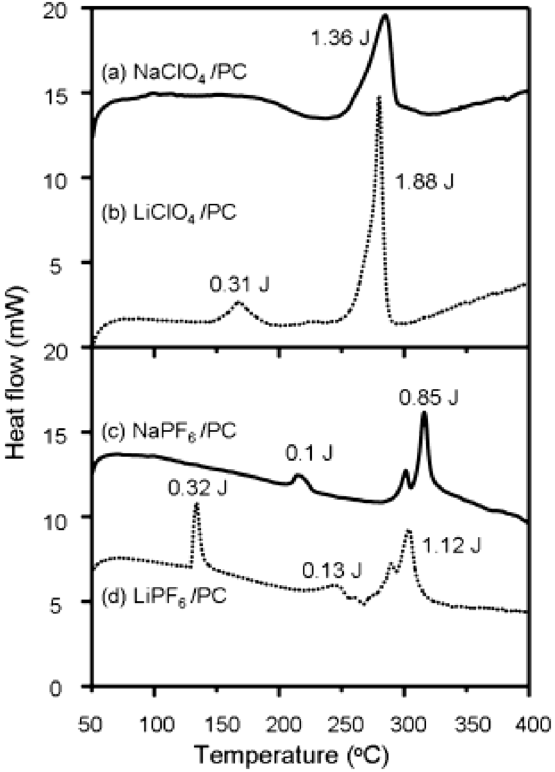




“Critical Materials Assessment”, U.S. Department of Energy, July 2023
“Sodium-Ion Battery Materials and Electrochemical Properties Reviewed”, *Advanced Energy Materials*, 2018

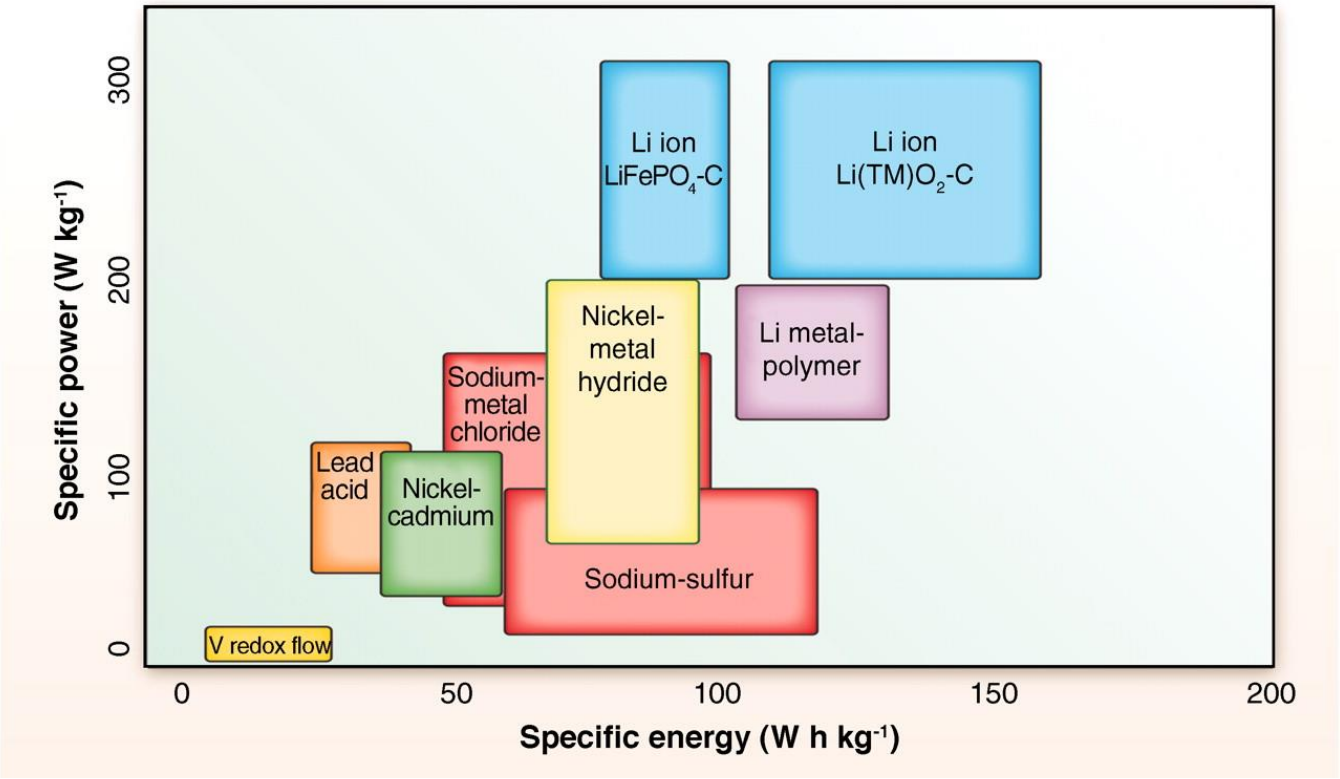
Sodium ion materials have been shown to be less prone to thermal runaway





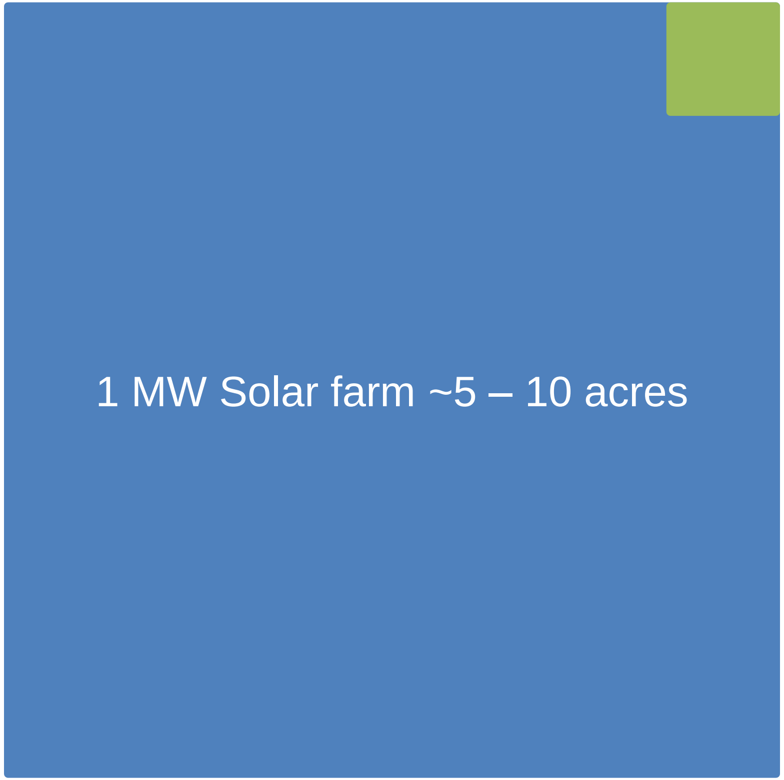
“Electrochemical and thermal properties of hard carbon-type anodes for Na-ion batteries”, *Journal of Power Sources*, 2013

Non-flow batteries are very power and energy dense



"Electrical Energy Storage for the Grid: A Battery of Choices", *Science*, 2011

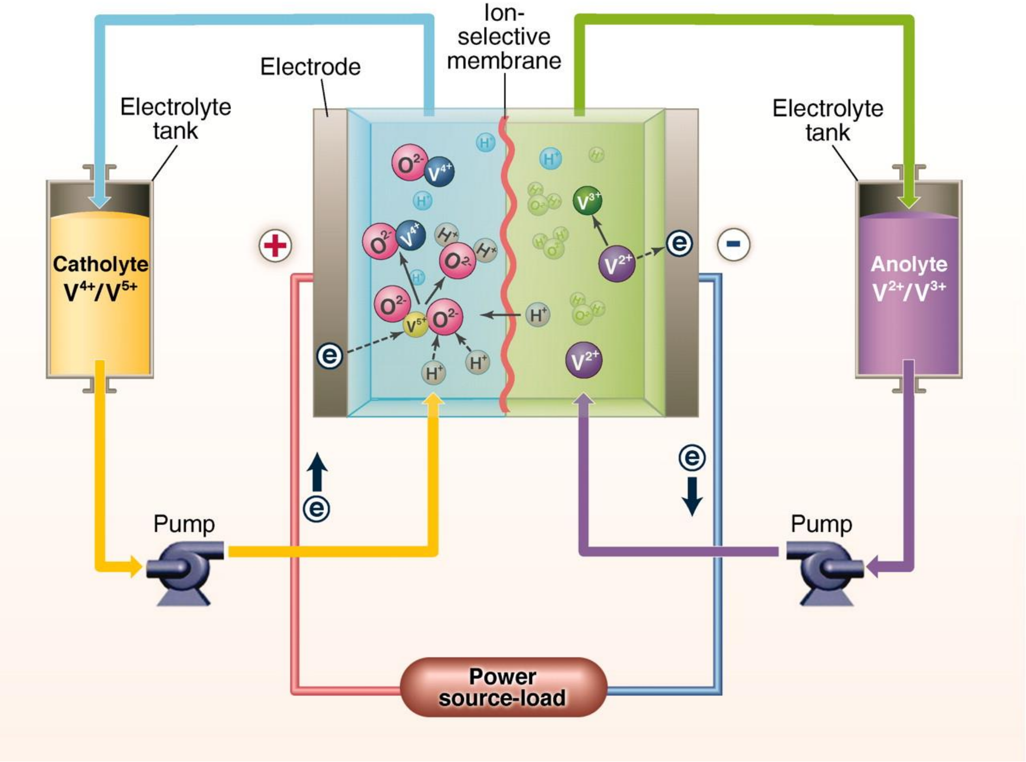
For grid scale storage, energy density is not a huge deal for system footprint



1 MW battery ~0.1 acres

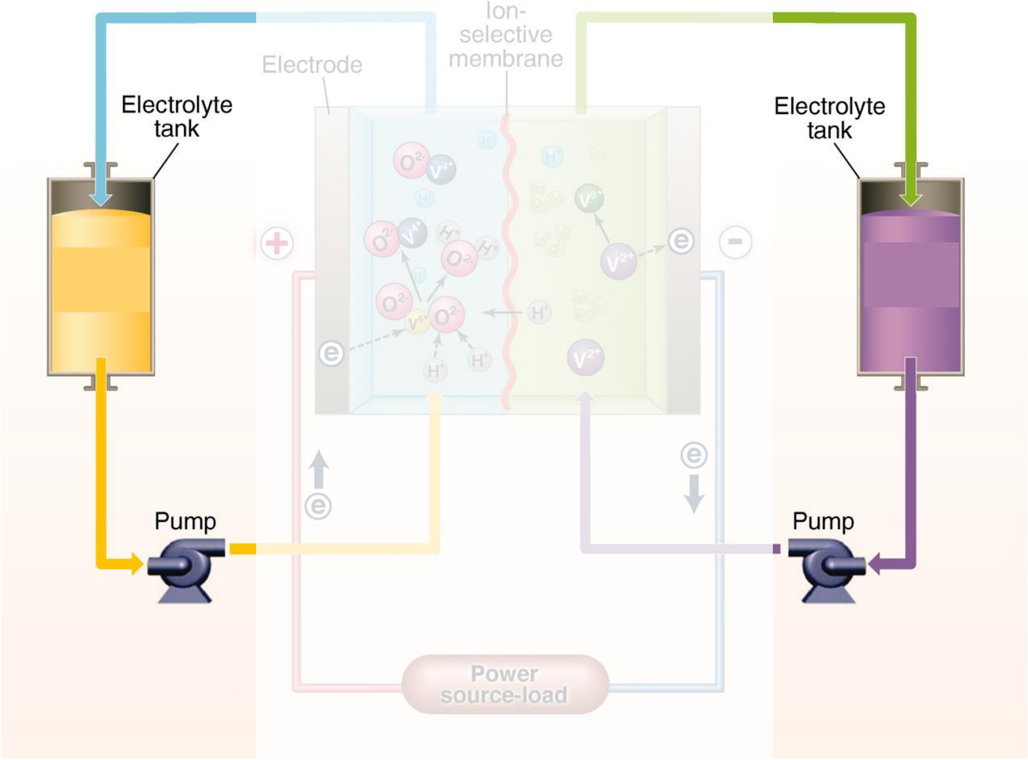
1 MW Solar farm ~5 – 10 acres

Flow batteries store the electrolytes in external tanks and pump them through the electrodes



“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

Positive electrolyte
“Posolyte”
Metal Salt 1
Supporting Salt
Water



Negative electrolyte
“Negolyte”
Metal Salt 2
Supporting Salt
Water

“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

There is a myriad of metal combinations for aqueous flow batteries

Aqueous Chemistries

Posolyte Negolyte

Vanadium FB

$V^{4+} \leftrightarrow V^{5+}$ $V^{2+} \leftrightarrow V^{3+}$

Supporting electrolyte: H_2SO_4, HNO_3

Iron-Chromium FB

$Fe^{2+} \leftrightarrow Fe^{3+}$ $Cr^{2+} \leftrightarrow Cr^{3+}$

Supporting electrolyte: HCl

"Hybrid" Chemistries

Posolyte Negolyte

All-Iron FB

$Fe^{2+} \leftrightarrow Fe^{3+}$ $Fe^{2+} \leftrightarrow Fe_{(s)}$

Supporting electrolyte: HAc, KCl

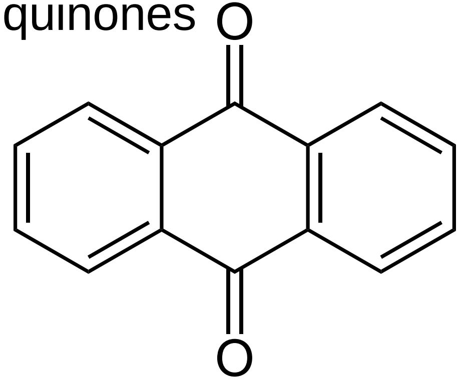
Zinc-Bromide FB

$Br_2 \leftrightarrow 2Br^-$ $Zn^{2+} \leftrightarrow Zn_{(s)}$

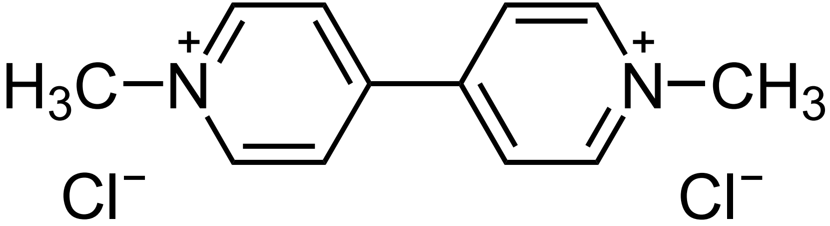
Supporting electrolyte: HBr

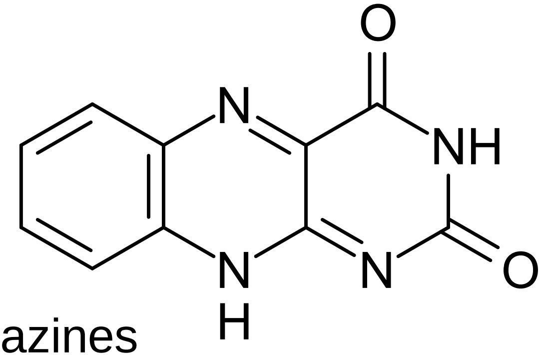
Organic chemists can have fun too!

(Anthra)quinones

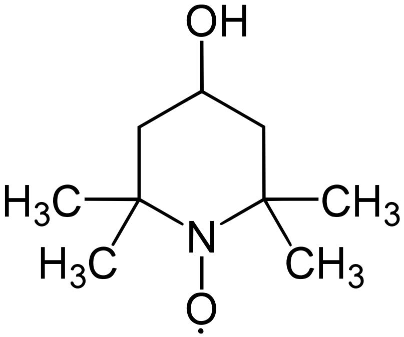


Viologens



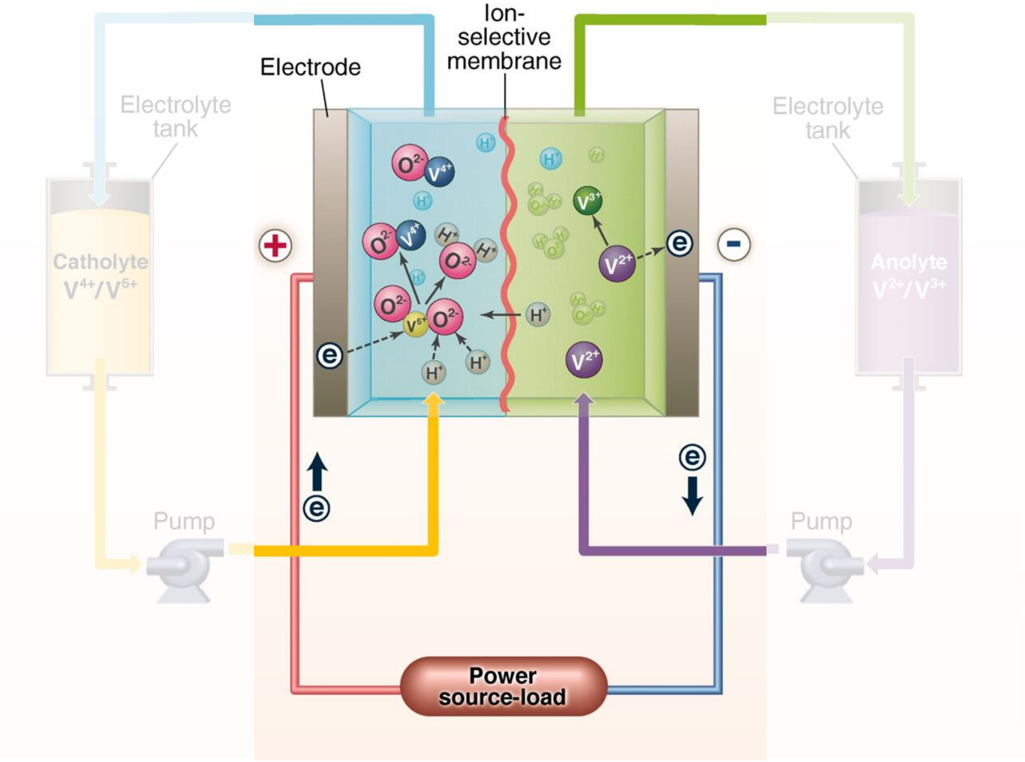


Alloxazines



TEMPO

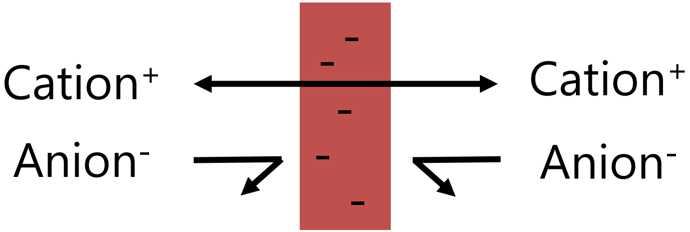
Charged polymeric membrane



“Electrical Energy Storage for the Grid: A Battery of Choices”, *Science*, 2011

Charged polymeric membrane

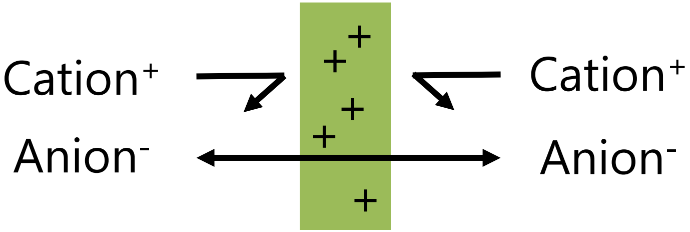
Cation Exchange



Cation$^+$ Cation$^+$

Anion$^-$ Anion$^-$

Anion Exchange

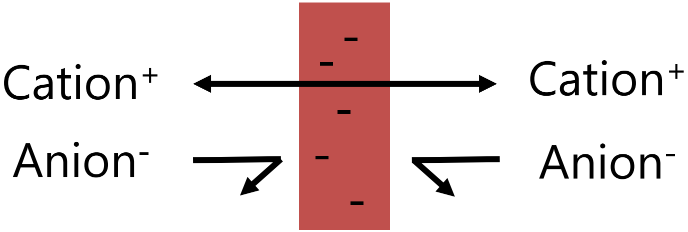


Cation$^+$ Cation$^+$

Anion$^-$ Anion$^-$

Charged polymeric membrane

Cation Exchange

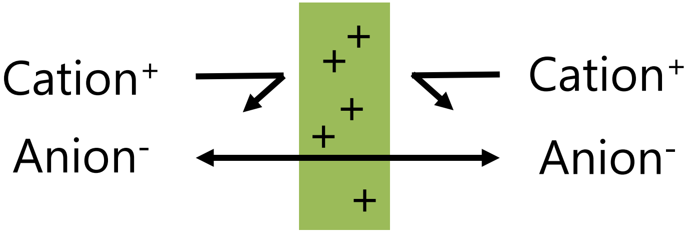


Most conductive cation: H^+

Cation$^+$ ⟷ Cation$^+$

Anion$^-$ Anion$^-$

Anion Exchange

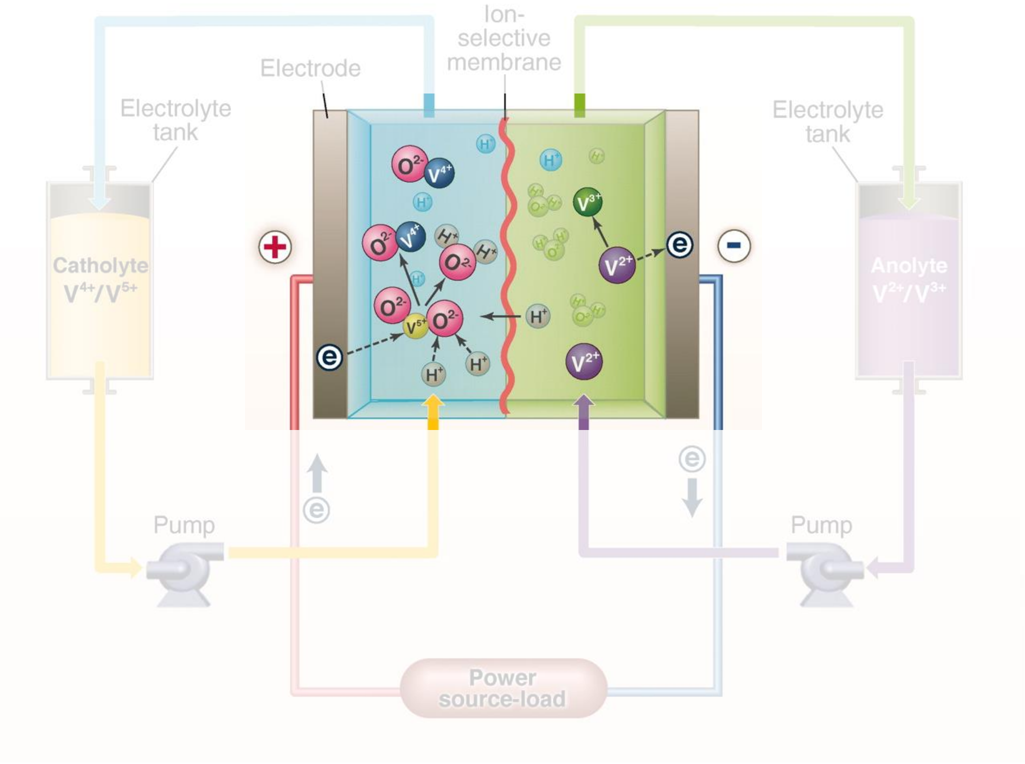


Most conductive anion: OH^-

Cation$^+$ Cation$^+$

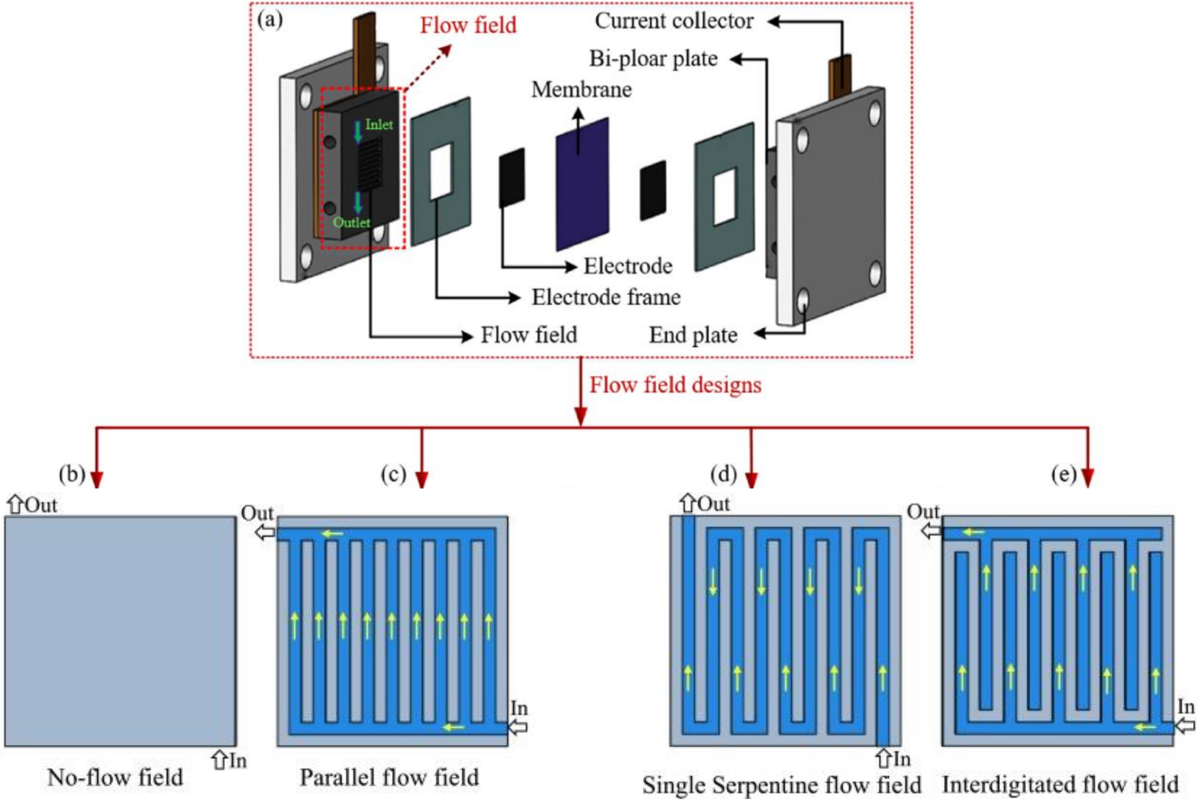
Anion$^-$ ⟷ Anion$^-$

How do we move the electrolyte through the electrodes?



"Electrical Energy Storage for the Grid: A Battery of Choices", *Science*, 2011

There are multiple common flow field designs



"Vanadium redox flow batteries: Flow field design and flow rate optimization", *Journal of Energy Storage*, 2022
"Flow field structure design for redox flow battery: Developments and Prospects", *Journal of Energy Storage*, 2024

Why are aqueous flow batteries safe?
They extinguish fire

Current flow battery limitations

Expensive materials (metals and membrane)

Strong acid electrolytes

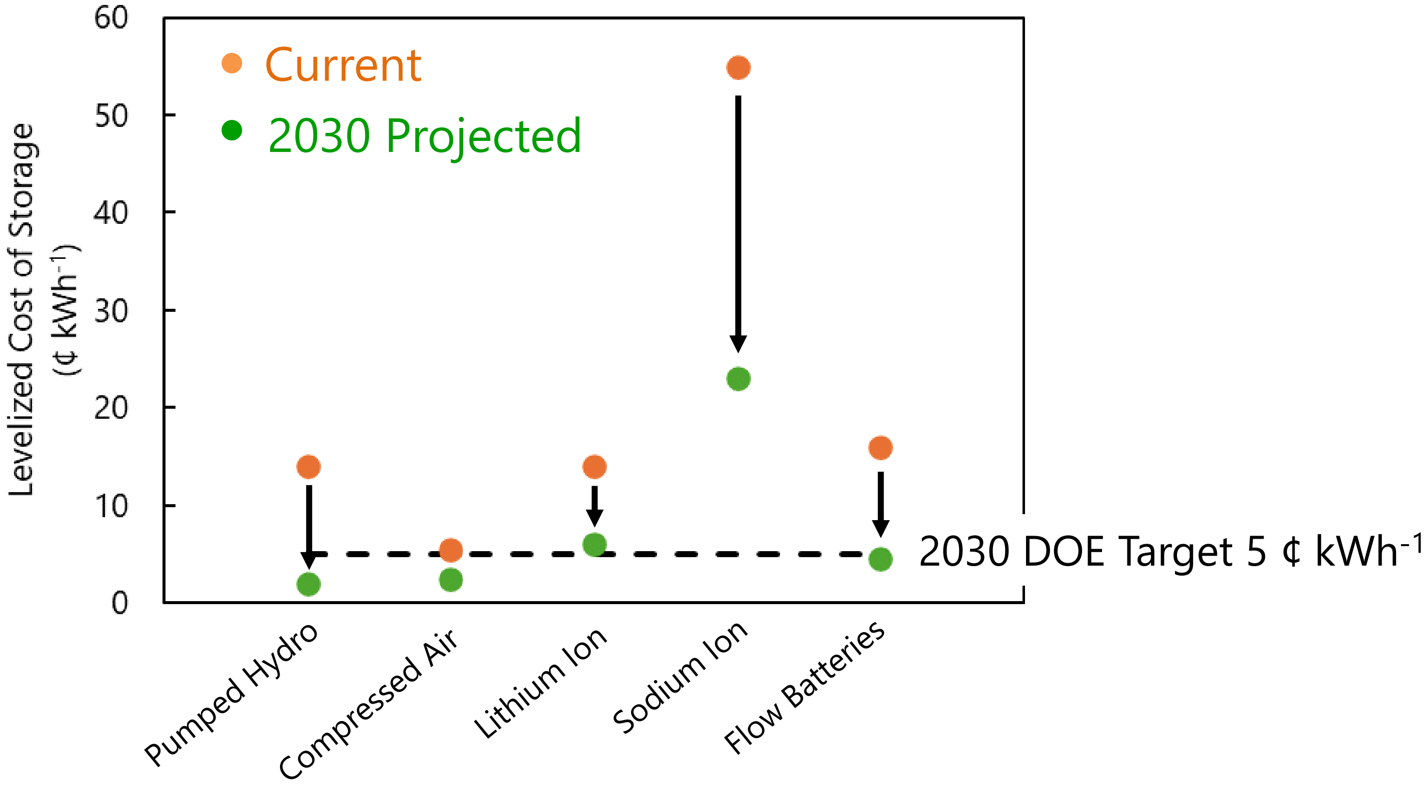
Low voltages to avoid water splitting

Low round-trip efficiency (~70%)

Now that we know the main technologies, we can compare them all with the universal metric:

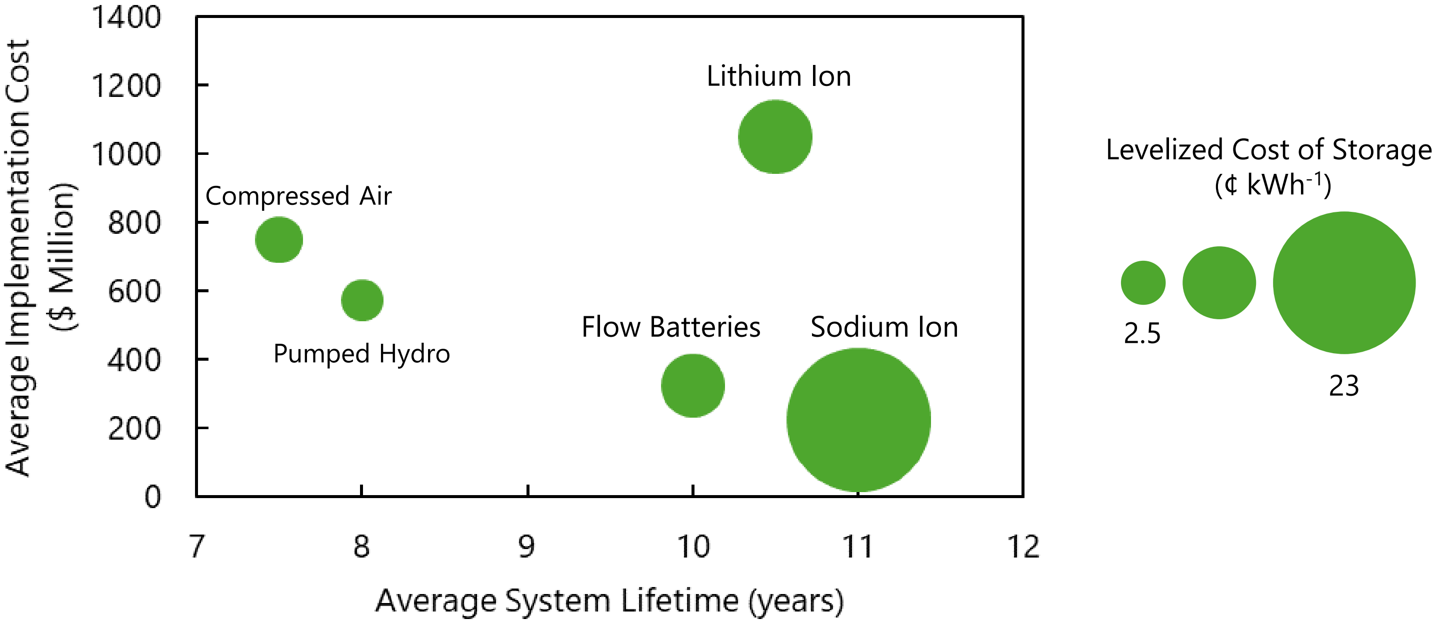
Money

Future cost of most technologies is below the US Department of Energy target



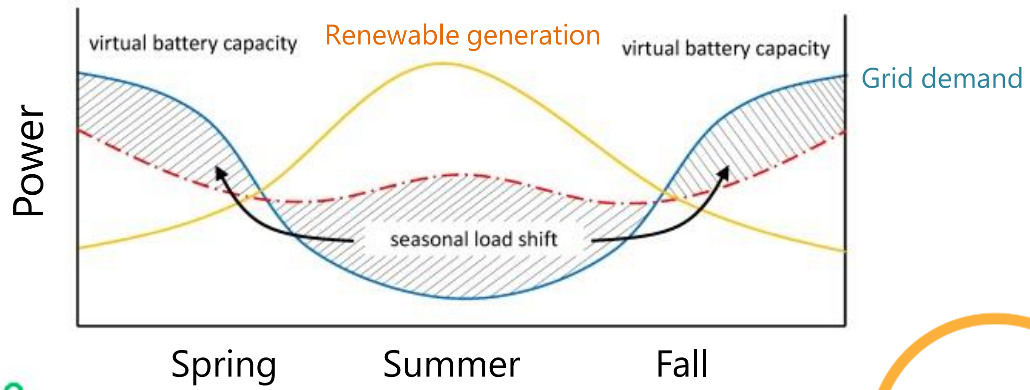
"Achieving the Promise of Low-Cost Long Duration Energy Storage", *US DOE*, 2024

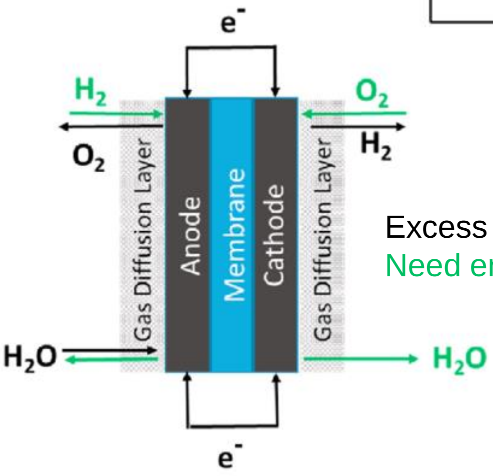
Capital cost and lifetime vary significantly



“Achieving the Promise of Low-Cost Long Duration Energy Storage”, *US DOE*, 2024

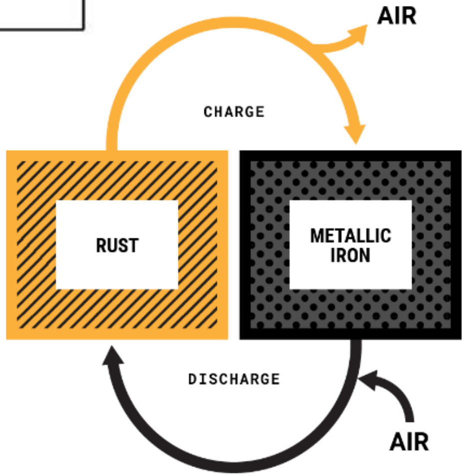
Other technologies that I didn't have time for: hydrogen and ultra-long duration storage





Excess energy: produce H_2

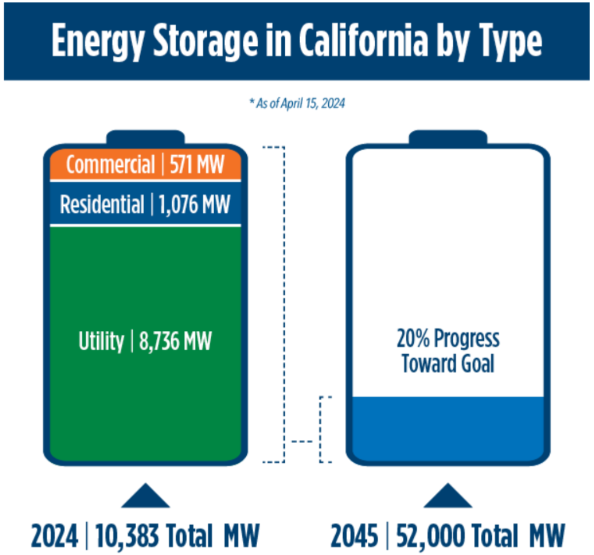
Need energy: consume H_2

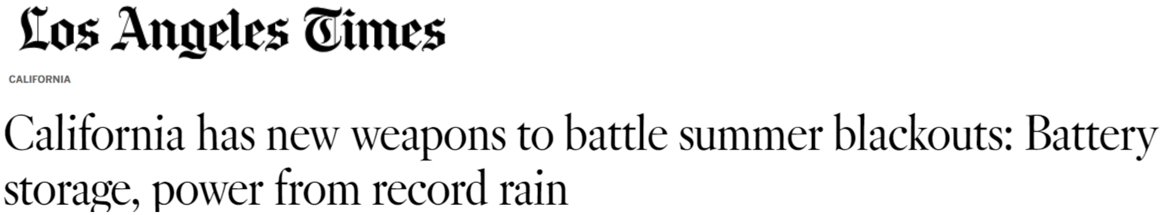


Form energy

"Seasonal Energy Flexibility Through Integration…", *energies*, 2020
"Economics of the Li-ion batteries and reversible fuel cells…", *Energy*, 2021

Progress in California: 10 GW of storage added has already helped prevent blackouts during heatwaves




Los Angeles Times

CALIFORNIA

California has new weapons to battle summer blackouts: Battery storage, power from record rain


The Mercury News Environment | 'A game changer': How giant batteries are...

NEWS > ENVIRONMENT • News

'A game changer': How giant batteries are making California's power grid stronger, and reducing the risk of blackouts during heat waves

Source: California Energy Commission

Thank you!

Lawrence Livermore
National Laboratory