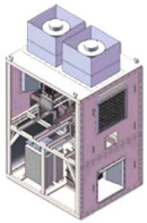
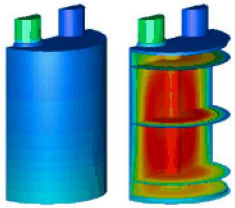
SAND2019-2719C

Molten Sodium Batteries: Promise for Advancing Grid-Scale Battery Utility





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NAATBatt 2019 Annual Meeting and Conference
March 11-14, 2019
Litchfield Park, AZ USA

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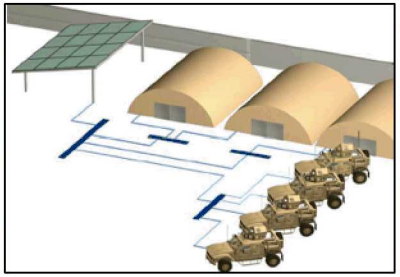
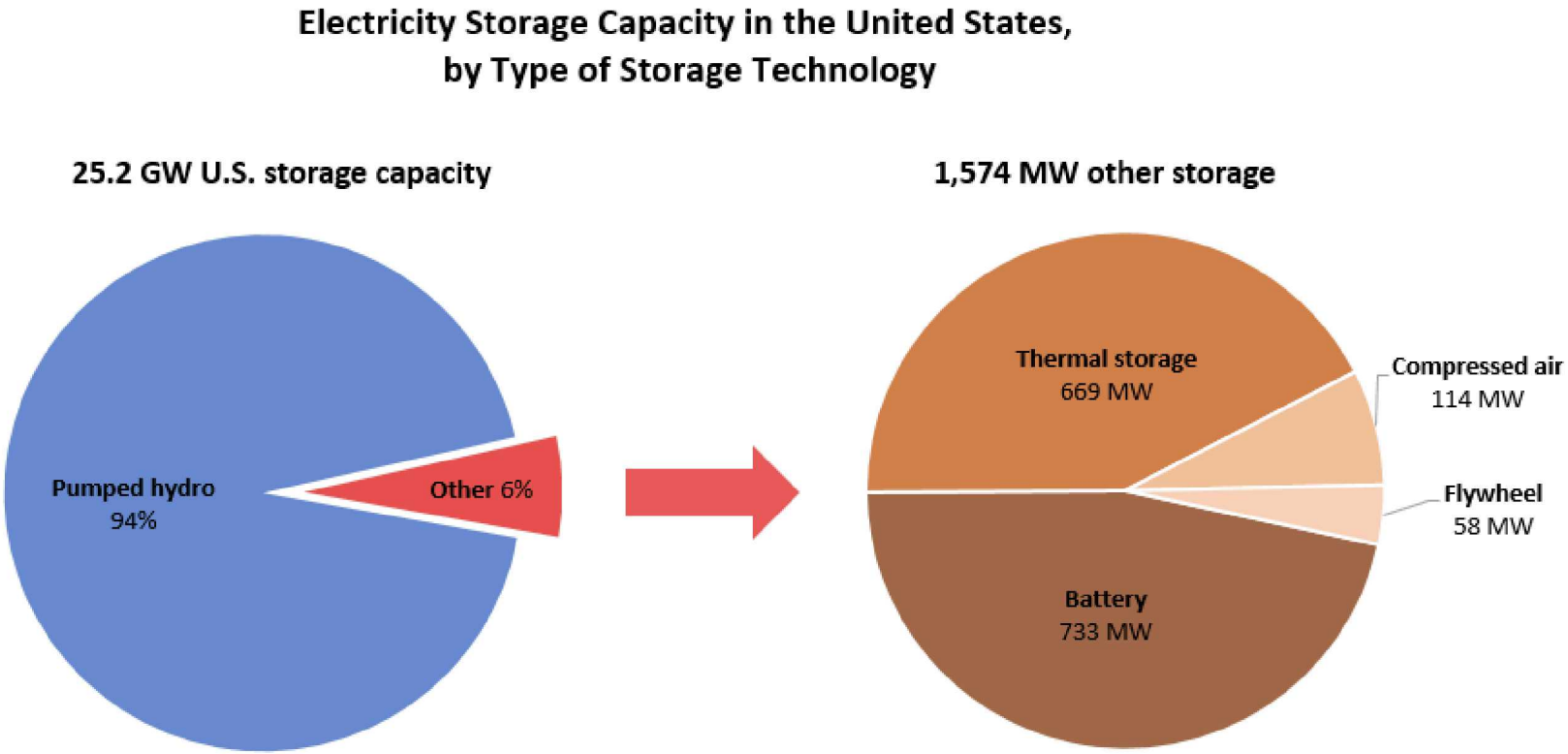
A Need for Grid-Scale Energy Storage Research


Renewable/Remote Energy


Grid Reliability

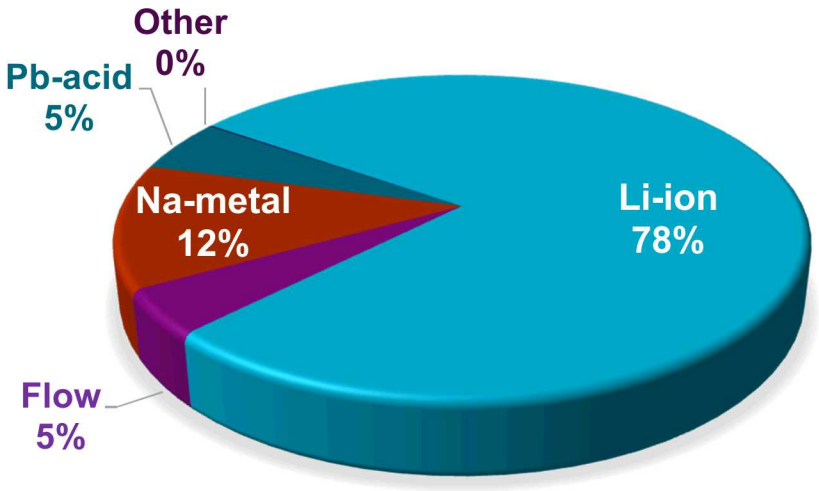

National Defense


Emergency Aid



Source: *DOE Global Energy Storage Database http://www.energystorageexchange.org/ March, 2018*

Current Battery Storage Deployments



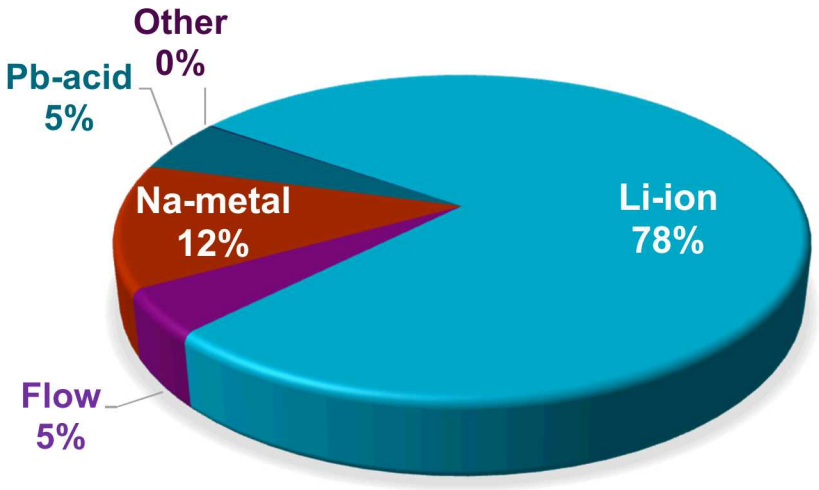
DOE Global Energy Storage Database:
http://www.energystorageexchange.org/ Nov. 2017

Rapid recent growth in Li-ion battery production has led to significant utilization in grid-scale applications, but it is not the only viable choice.

Na-metal batteries have a role to play…

We will need much, much more storage on our grid to accommodate increasing renewable penetration and the transition to a clean energy economy.

Current Battery Storage Deployments



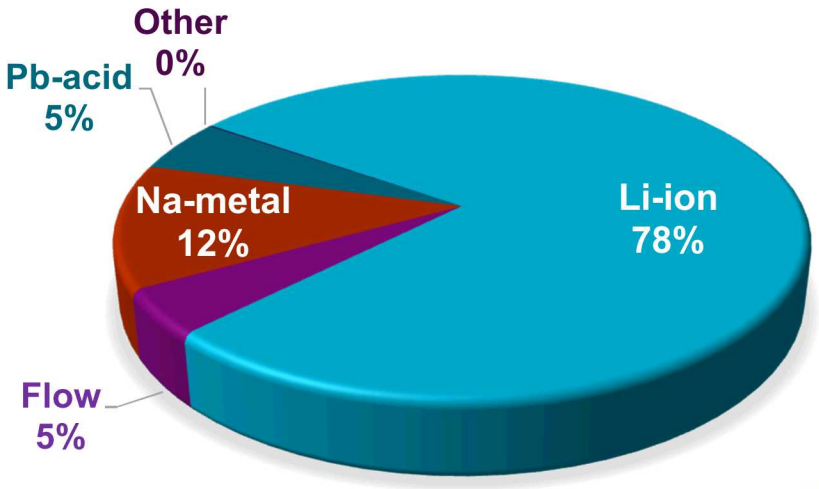
DOE Global Energy Storage Database:
http://www.energystorageexchange.org/ Nov. 2017

Li-ion batteries can not and should not become our singular grid-scale storage solution.

It's going to be a really big pie!!!

Nappanee Apple Festival (Nappanee, Indiana)

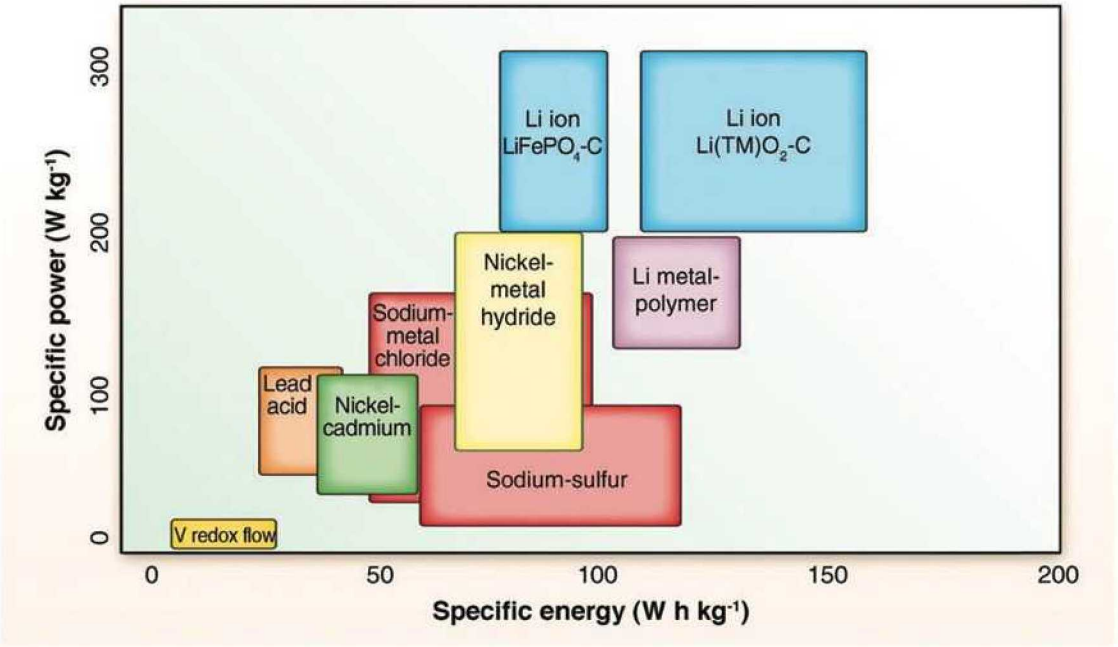
Current Battery Storage Deployments



DOE Global Energy Storage Database: http://www.energystorageexchange.org/ Nov. 2017

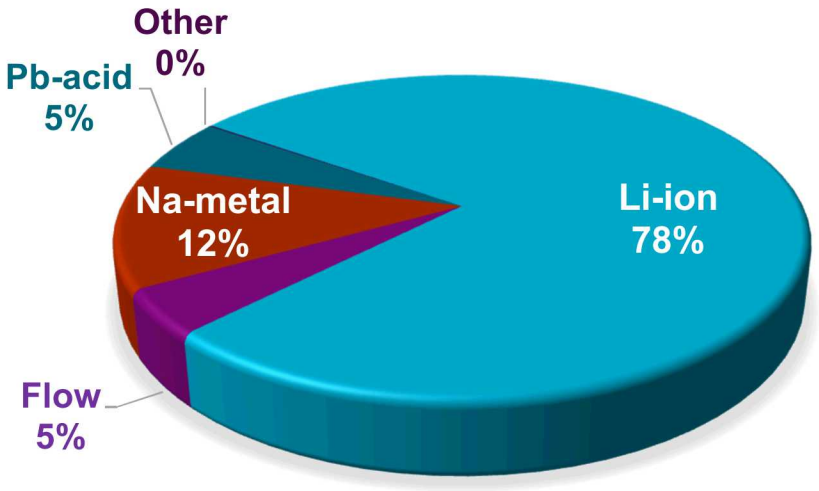
Li-ion batteries can not and should not become our singular grid-scale storage solution.

Different batteries have variable energy densities and power densities….



From: B. Dunn, *et al.*, *Science*, 2011, 334, 928–935.

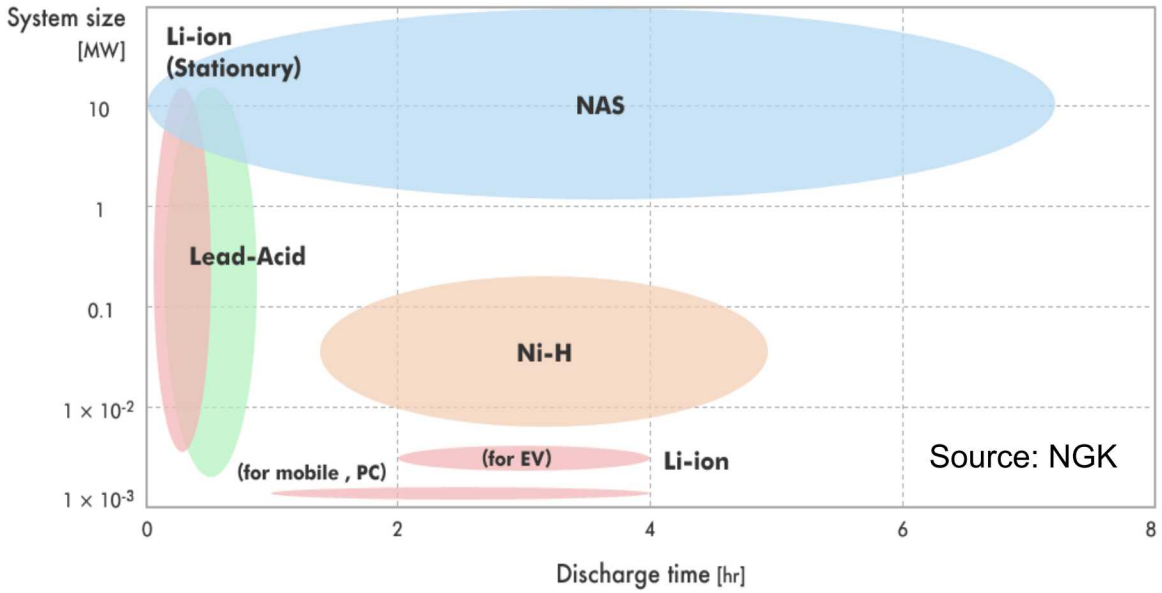
Current Battery Storage Deployments



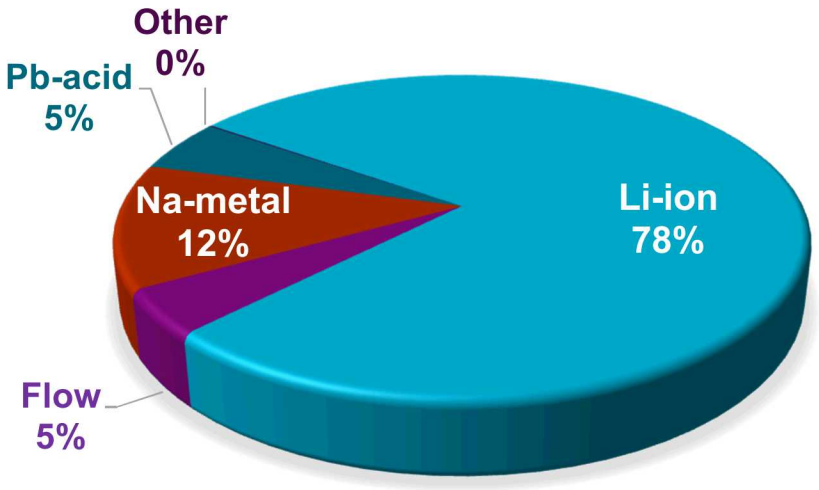
Li-ion batteries can not and should not become our singular grid-scale storage solution.

DOE Global Energy Storage Database: http://www.energystorageexchange.org/ Nov. 2017

Different batteries have variable discharge durations…



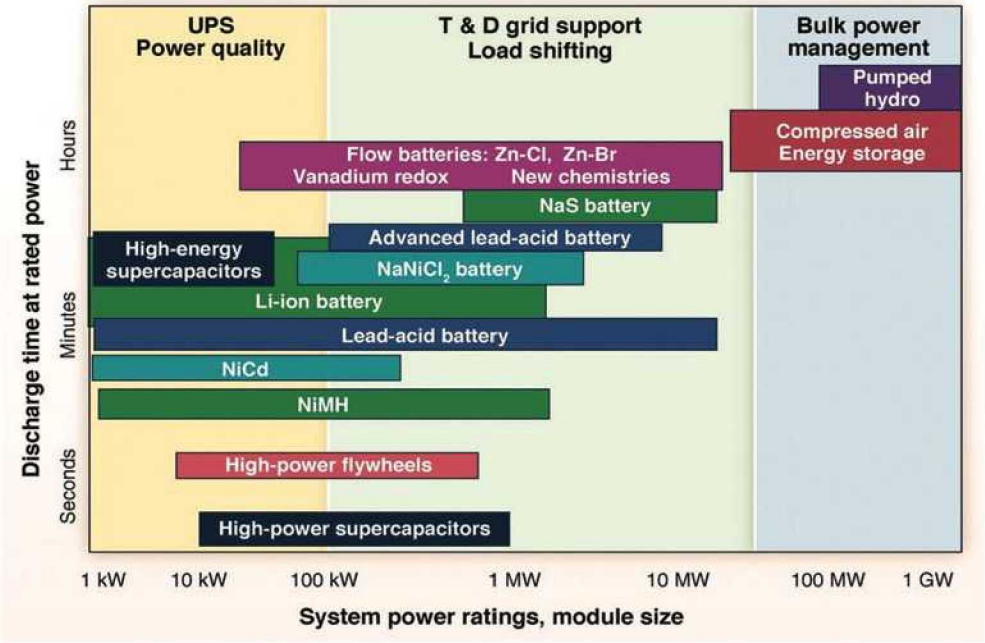
Current Battery Storage Deployments



DOE Global Energy Storage Database: http://www.energystorageexchange.org/ Nov. 2017

Li-ion batteries can not and should not become our singular grid-scale storage solution.

The variable properties of the batteries make them suitable for different applications.



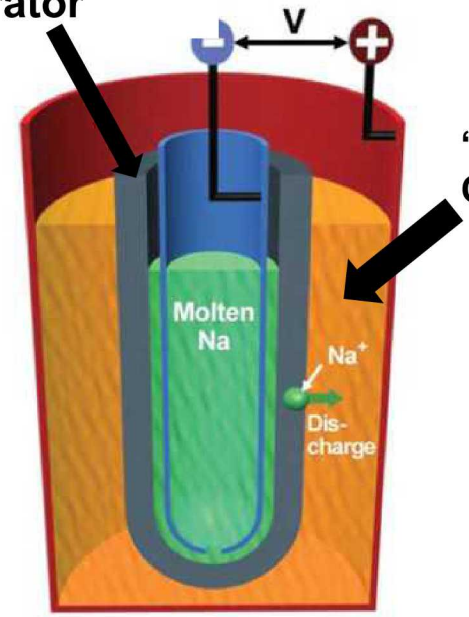
From: B. Dunn, *et al.*, *Science*, 2011, 334, 928–

Sodium-Based Batteries

Sodium based Batteries

- 6th most abundant element on earth.
- 5X the annual production of aluminum.
- Proven technology base with NGK Sodium –Sulfur (NaS) FzSoNick ZEBRA ($Na\text{-}NiCl_2$) Technologies.
- Utilizes zero-crossover solid state separators.
- Favorable battery voltages (>2V)

Ion Conducting Ceramic Separator



"Molten Catholyte"
- **Sulfur**
- **M-Halide Salts**

Candidate molten sodium batteries

Sodium-sulfur (~300°C, E_{cell}~2V):
$2Na + 4S \leftrightarrows Na_2S_4$

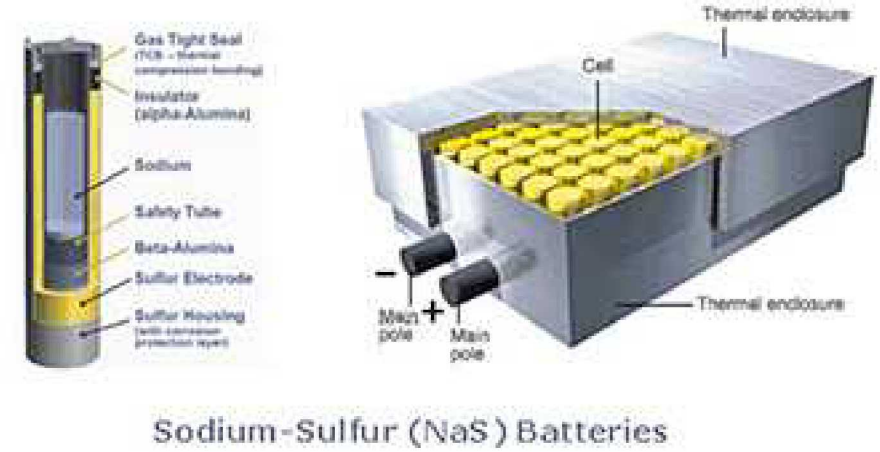
Sodium-nickel chloride (~195-300°C, E_{cell}~2.6V):
$Na + \frac{1}{2} NiCl_2 \leftrightarrows Na^+ + Cl^- + Ni(s)$

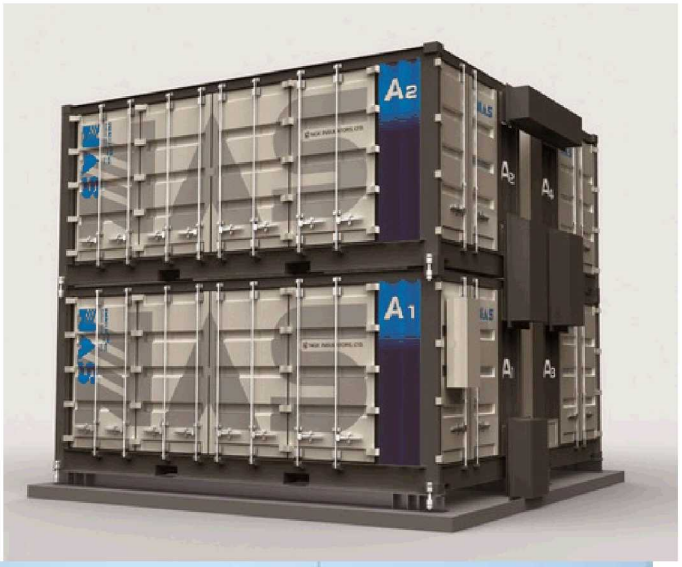
Sodium-iodide (~100-180°C, E_{cell}~ 3.2V):
$2Na + Na^+ + I_3^- \leftrightarrows 3Na^+ + 3I^-$

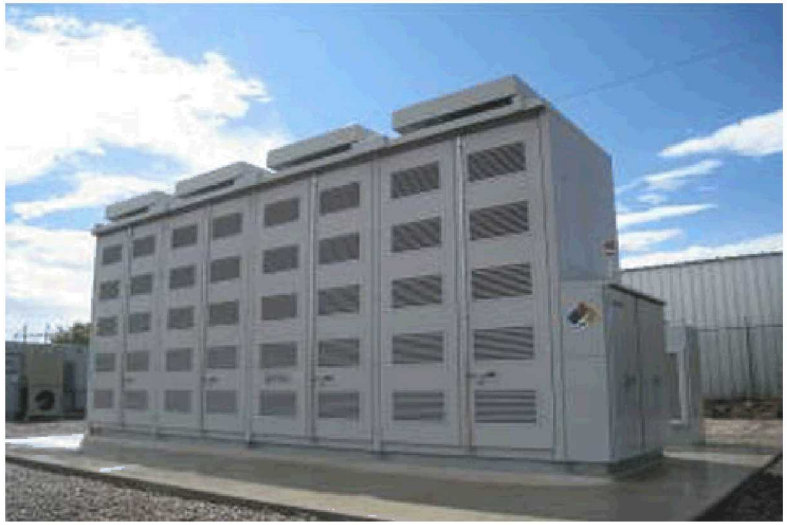
Additional Sodium Battery Technologies

- Room Temperature Na-S (Electrolyte Based)
- Sodium-Ion
- Alternative Sodium (e.g., Natron, Aquion)

Sodium-Sulfur (NaS) Batteries (NGK)







Los Alamos, NM USA (1 MW)

Rokkasho village, Aomori, Japan (56 MW)

NaS Battery Deployment (NGK)

Approximately 560 MW / 4 GWh deployed in more than 200 locations globally.

Na-$NiCl_2$ ("ZEBRA") Batteries (FIAMM)

FIAMM SoNick (Na-$NiCl_2$) Batteries

- ~300°C operation, no cooling required
- 2-4 hour energy applications
- Operational from -20°C to +60°C
- 20 year design life (3500-4500 cycles)
- Environmentally friendly and *recyclable*
- "No maintenance"

48 V (200Ah) module

620V module

620 V 90 kWh (25kW)

620 V 1.4 MWh (400 kW)

Sacramento, CA (USA)
190 kWh (50kW)

"Behind the meter"

Codrongianos, Sardinia (Italy)
4.15 MWh (1.2 MW)

Grid Regulation

French Guyanne (S. America)
4.5 MWh (1.5 MW)

Renewable Integration

SONICK

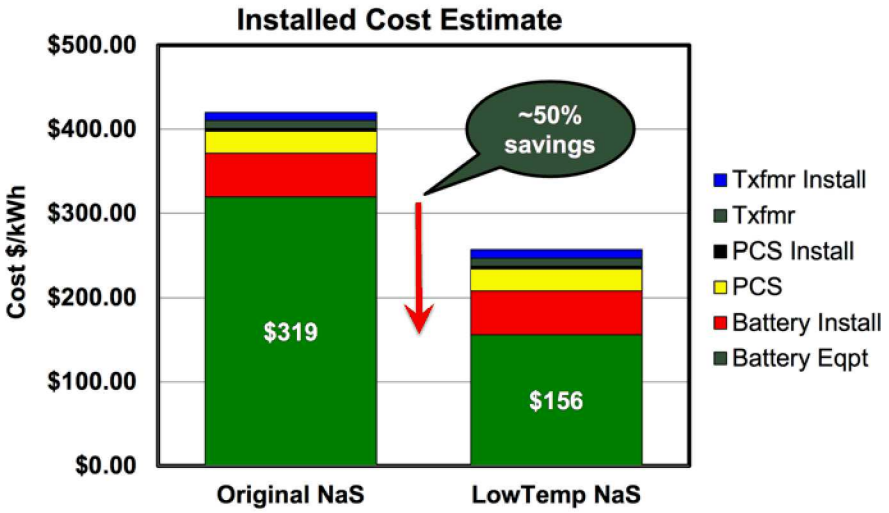
FIAMM
Energy Storage Solutions

Motivating Low Temperature Sodium Batteries

Low Temperature Operation of a Molten Na Battery is Tremendously Enabling

- Improved Lifetime
  - Reduced material degradation
  - Decreased reagent volatility
  - Fewer side reactions
- Lower material cost and processing
  - Seals
  - Separators
  - Cell body
  - Polymer components become realistic!
- Reduced operating costs
- Simplified heat management costs
  - Enabled freeze-thaw capability

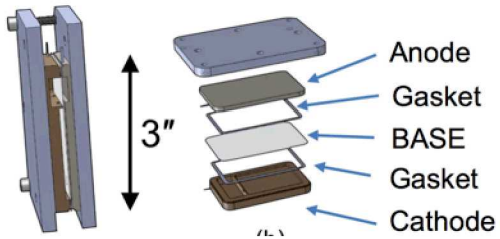
Reducing operating temperature is predicted to significantly reduce NaS installed costs.

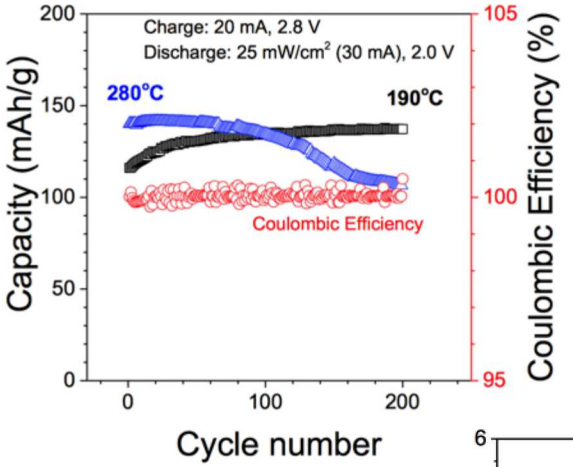


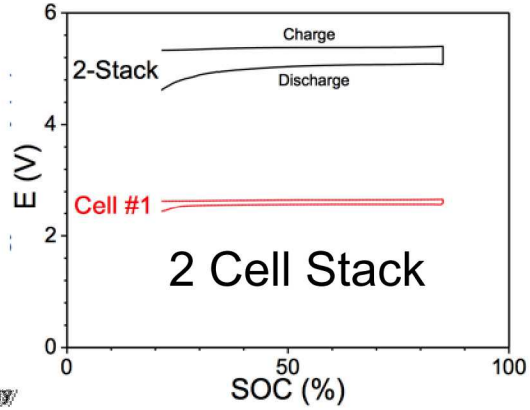
Gao Liu, et al. "A Storage Revolution." 12-Feb-2015 (online): https://ei.haas.berkeley.edu/education/c2m/docs/Sulfur%20and%20Sodium%20Metal%20Battery.pdf

Intermediate Temperature "ZEBRA" Batteries

Planar Stack Configuration







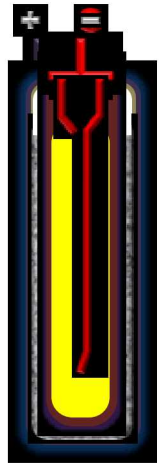
Pacific Northwest NATIONAL LABORATORY

RIST Research Institute of Industrial Science & Technology

Tubular Configuration

100Wh

250Wh



Multiscale Prototype Demonstrations

13 Wh Na-$NiCl_2$ Cell
- Operational for 9+ months.
- Energy efficiency >85%
- 65 mA /cm^2

100 Wh Na-$NiCl_2$ Cell:
- Operational for 4+ months.
- energy efficiency 81.5%
- 53 mA/cm^2

250 Wh Na-$NiCl_2$ Cell:
- operational for 3+ months
- energy efficiency 80%
- 53 mA/cm^2

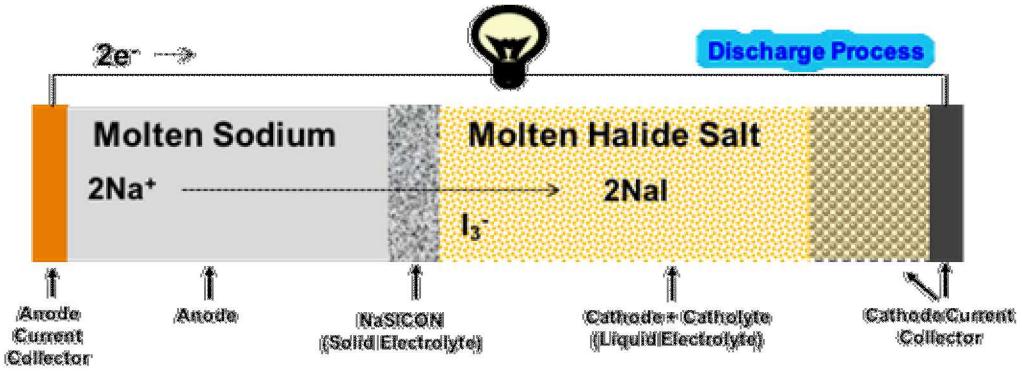
* All cycled to 70% DOD at C/7 rate.

SK

CERAMATEC TOMORROW'S CERAMIC SYSTEMS

Low Temperature Molten Na-Halide Batteries

Our Vision: A molten sodium-based battery that comprises a robust, highly Na^+-conductive, zero-crossover separator and a fully liquid, highly cyclable molten catholyte that operates at low temperatures.



Na-NaI battery:

$Na \rightarrow Na^+ + e^-$ $E^0 = 0V$

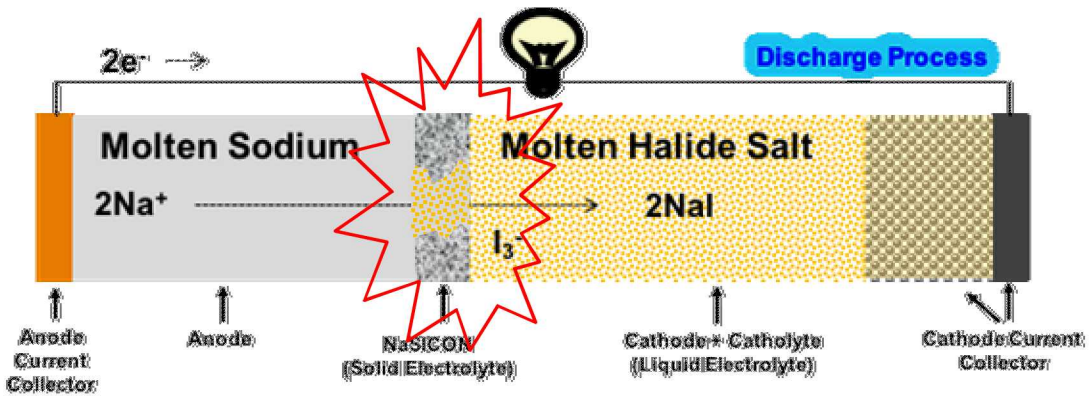
$I_3^- + 2e^- \rightarrow 3I^-$ $E^0 = 3.24$

$2Na + I_3^- \rightarrow 2Na^+ + 3I^-$ $E^0_{cell} = 3.24V$

Na-NaI batteries show promise as safe, low-cost, highly cyclable battery with functional energy density.

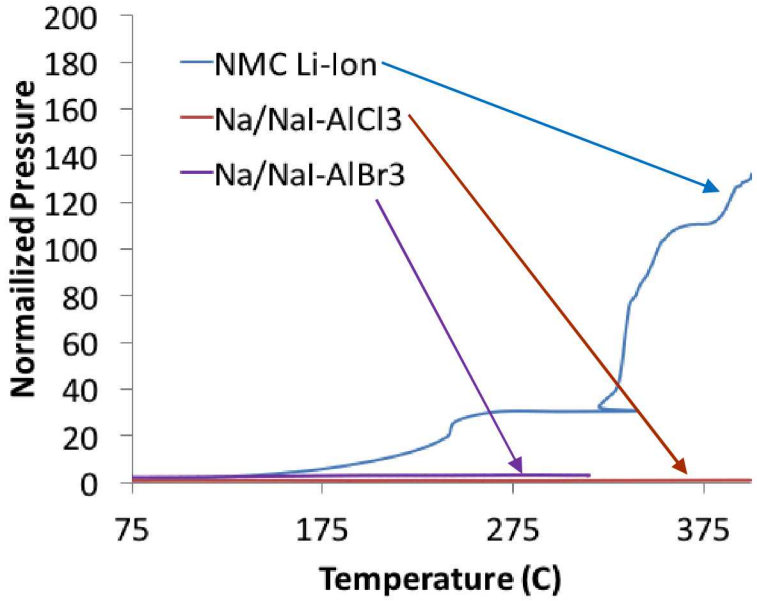
- Inherent Safety
- Long Cycle Life
- Functional Energy Density (voltage, capacity)
- Low to Intermediate Temperature Operation
- Low Cost and Scalable

Na-NaI Battery Safety



Simulating separator failure, metallic Na and NaI/AlX_3 were combined and heated.

Byproducts of reaction are aluminum metal and harmless sodium halide salts.

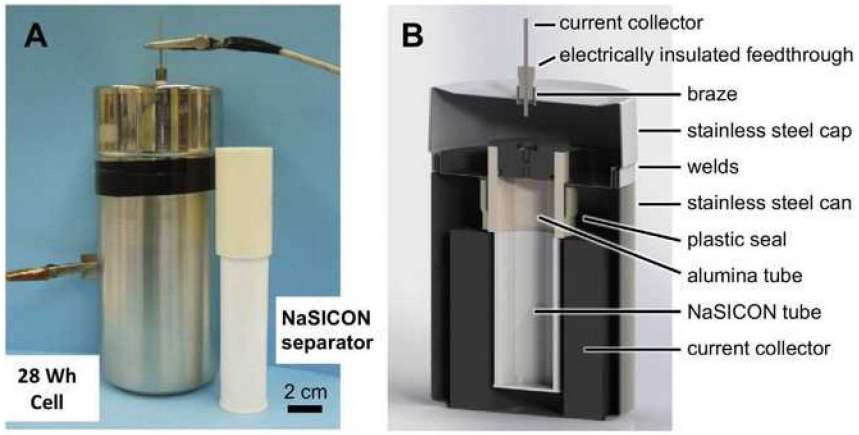


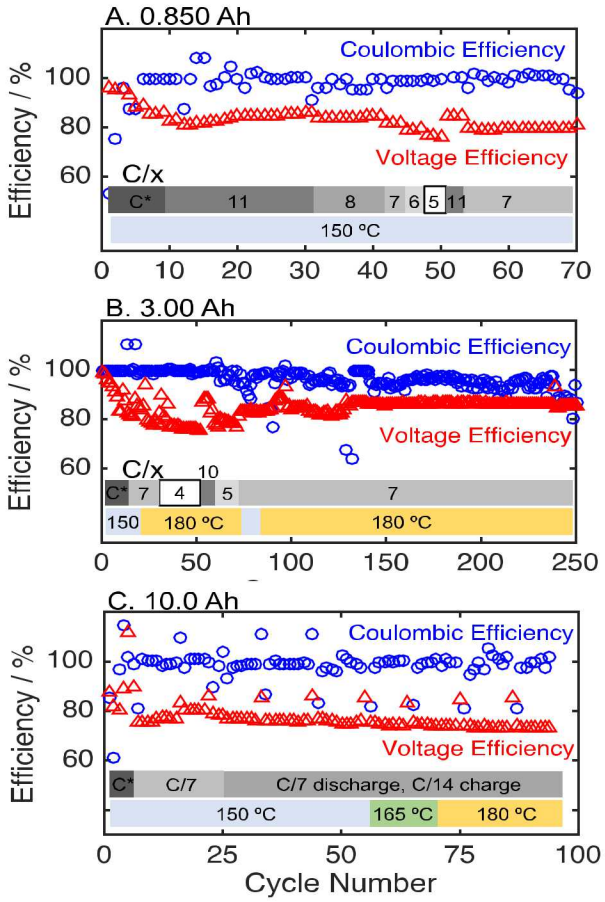
Accelerating rate calorimetry reveals that Na-NaI/AlX_3 mixtures exhibit:

1) *no significant exothermic behavior*
2) *no significant gas generation of pressurization*

An Intermediate Temperature Na-NaI Battery

Na-NaI battery was demonstrated across several scales at 150-180°C.

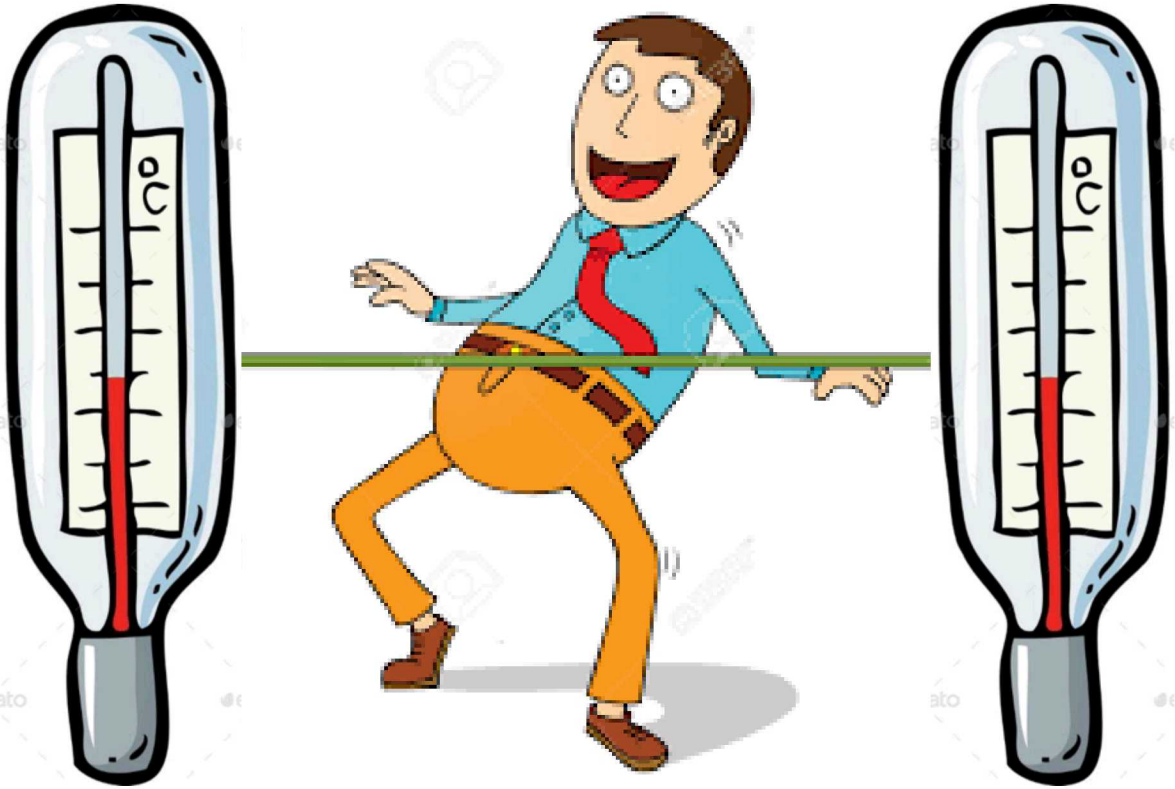




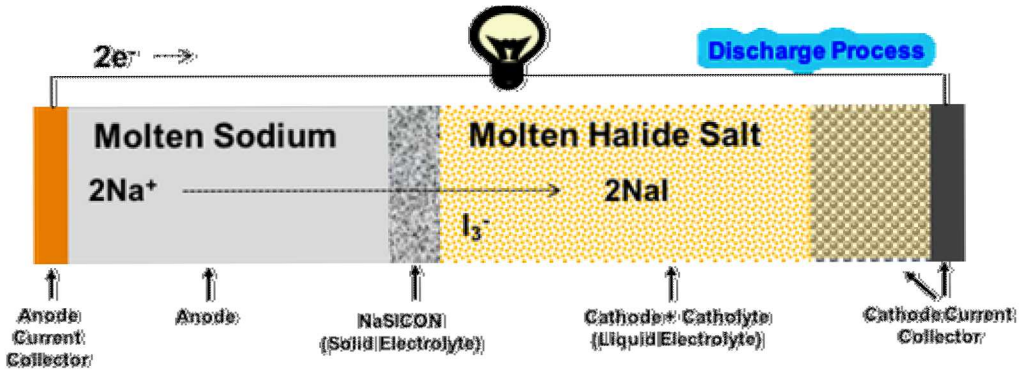
L.J. Small, *et al. J. Power Sources* (2017) **360** 569-574

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

How low can we go?



Lowest Temperature Molten Na-NaI Batteries



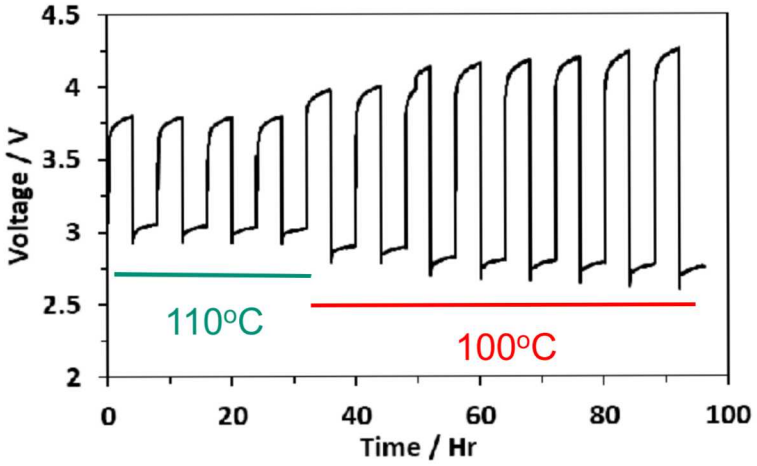
Na-NaI battery:

$Na \rightarrow Na^+ + e^-$ $E^0 = 0V$

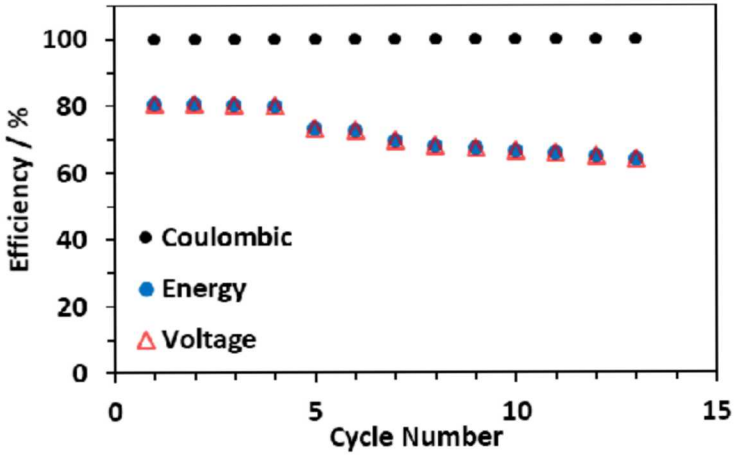
$I_3^- + 2e^- \rightarrow 3I^-$ $E^0 = 3.24$

$2Na + I_3^- \rightarrow 2Na^+ + 3I^-$ $E^0_{cell} = 3.24V$

Battery cycling at **100° - 110°C**!

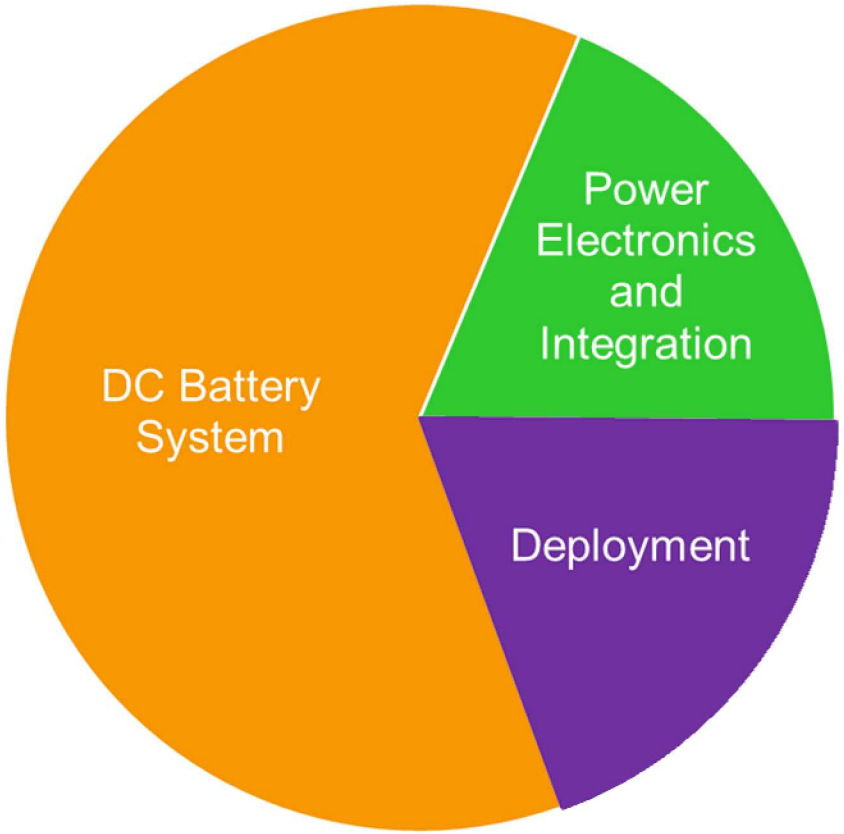


25 mol% NaI-$AlBr_3$ with NaSICON separator.



Still Work to Do…

- Improve high performance, zero-crossover solid state separator technology
  - Low temperature conductance
  - Mechanical properties
  - Chemical compatibility
- Optimize cost-effective catholyte and cathode current collectors
- Identify lower cost battery packaging materials
- Demonstrate extended battery lifetime
- Improve understanding of emerging electrochemistries and interfaces
- Integrate batteries with power electronics
- Engineer effective deployment strategies



Summary

- Growing grid-scale energy storage demands are expected to exceed the scale and capability of Li-ion batteries.
- Sodium-based batteries offer the potential for safe, cost-effective storage with long cycle life.
- NaS (NGK) and Na-$NiCl_2$ (FIAMM) batteries are currently being manufactured and deployed globally for grid-scale applications.
  - ✓ On-Grid
  - ✓ Off-Grid
  - ✓ Microgrid
  - ✓ Grid regulation
  - ✓ Renewables integration
- Current research into safe, new sodium battery chemistries is expected to lead to reduced cost and increased utility.

- Inherent Safety
- Long Cycle Life
- Functional Energy Density (voltage, capacity)
- Low to Intermediate Temperature Operation
- Low Cost and Scalable

Sodium-based batteries *are* viable and promising candidates for grid-scale energy storage!

Acknowledgements

Thank you!

Work at Sandia National Laboratories is supported by Dr. Imre Gyuk through the Department of Energy Office of Electricity Delivery and Energy Reliability.

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Backup Information

Table 13 Typical performance characteristics of various energy storage systems and technologies[431]

	Power rating (MW)	Discharge time	Cycles or lifetime	Self-discharge (%)	Energy density (W h l^{-1})	Power density (W l^{-1})	Efficiency (%)	Response time
Pumped-hydro	100–2500	4–16 h	30–60 year	~0	0.2–2	0.1–0.2	70–85	10 s–min
Compressed air	100–1000	2–30 h	20–40 year	~0	2–6	0.2–0.6	40–70	Min
Flywheel	0.001–20	s–min	20 000–100 000	1.3–100	20–80	5000	70–95	<s
Li-Ion battery	0.05–100	1 min–8 h		0.1–0.3	200–400	1300–10 000	85–95	<s
Lead–acid battery	0.001–100	1 min–8 h	6–40 year	0.1–0.3	50–80	90–700	80–90	<s
Na–S battery	10–100	1 min–8 h	2500–4500	0.05–20	150–300	120–160	70–90	<s
Flow battery	0.1–100	Hours	12 000–14 000	0.2	20–70	0.5–2	60–85	<s
Supercon. magnet	0.1–1	ms–s	100 000	10–15	~6	~2600	80–95	<s
Super-capacitor	0.01–1	ms–min	10 000–100 000	20–40	10–20	40 000–120 000	80–95	<s
Hydrogen	0.01–100	Min–week	5–30 year	0–4	600 (200 bar)	0.2–20	25–45	s–min
Synthetic natural gas	1–100	Hour–week	30 year	~0	1800 (200 bar)	0.2–2	25–50	s–min
Molten salt (latent thermal)	1–150	Hours	30 year	N/A	70–210	N/A	80–90	min

NaSICON Tube Sizing

Cite this: *Energy Environ. Sci.*, 2018, 11, 2696

Backup Information

***FY18**: Demonstrated 40% improvement in energy density for low-cost N-$FeCl_2$ battery enabling complete usage of available material capacity.*