Sandia National Laboratories

Introduction to Energy Storage Technologies

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Vermont PUC Webinar Series: Workshop #1
November 2nd, 2023

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Erik Spoerke's work at Sandia National Laboratories is supported through the U.S. Department of Energy's Office of Electricity, including the Energy Storage Program, managed by Dr. Imre Gyuk

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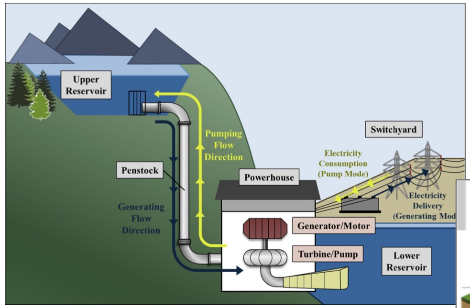
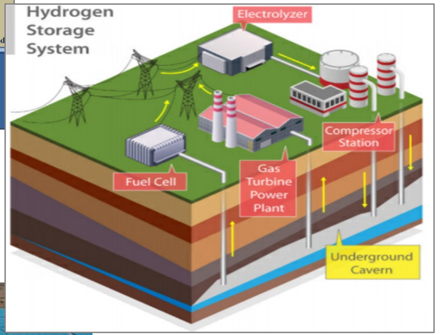
SAND No.: SAND2023-13120PE

What Are Our Technology Options for LDES?

- Gravity-Based/Mechanical Storage
- Chemical and Hydrogen Storage
- Thermal Storage
- Electrochemical (Batteries) Storage





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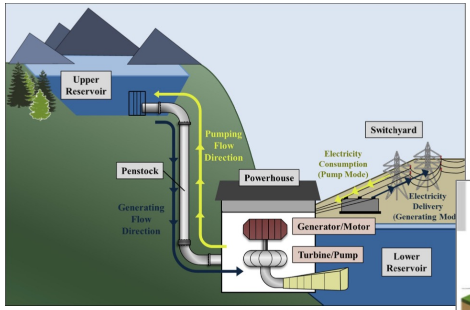
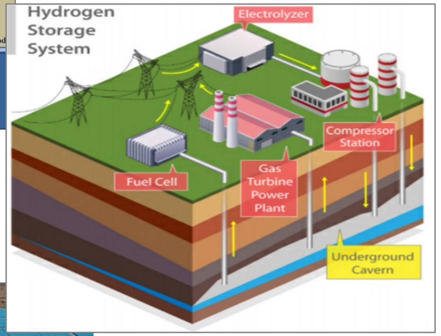
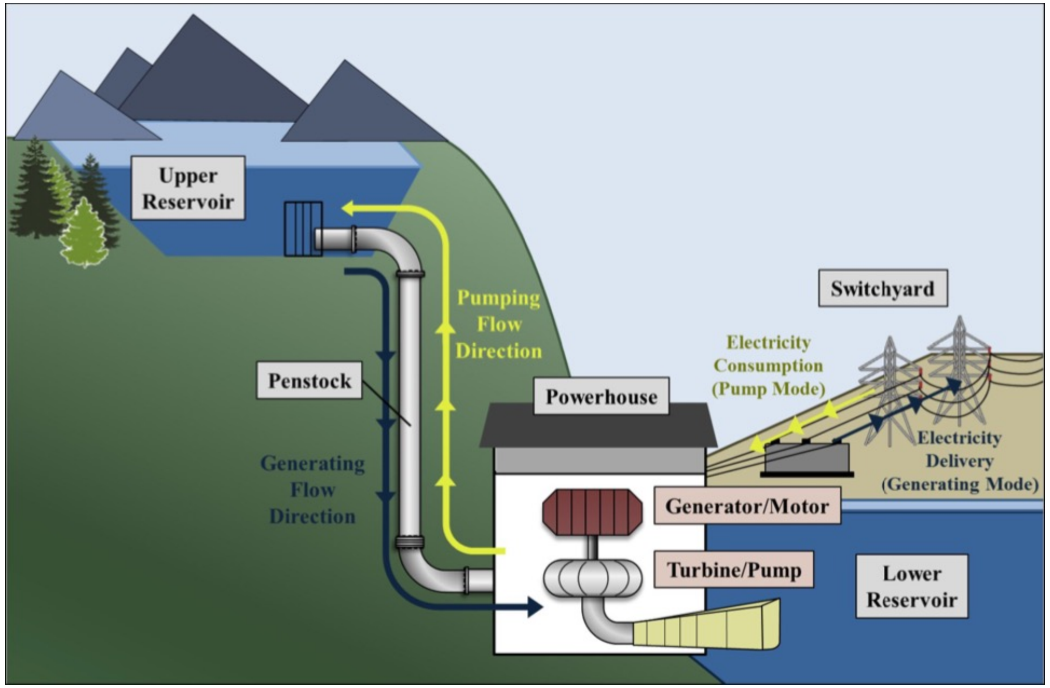
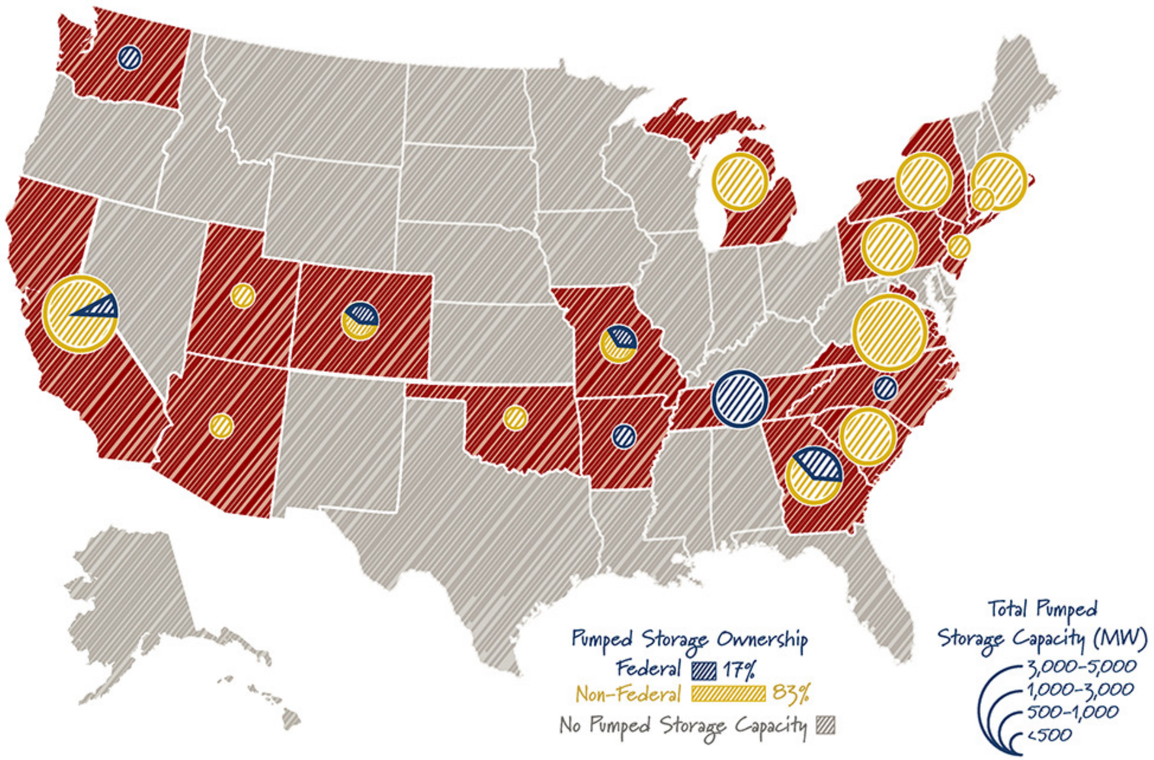




Pumped Hydro Storage: King on the Hill



~23,000 MW of pumped storage, ~95% of U.S. Storage

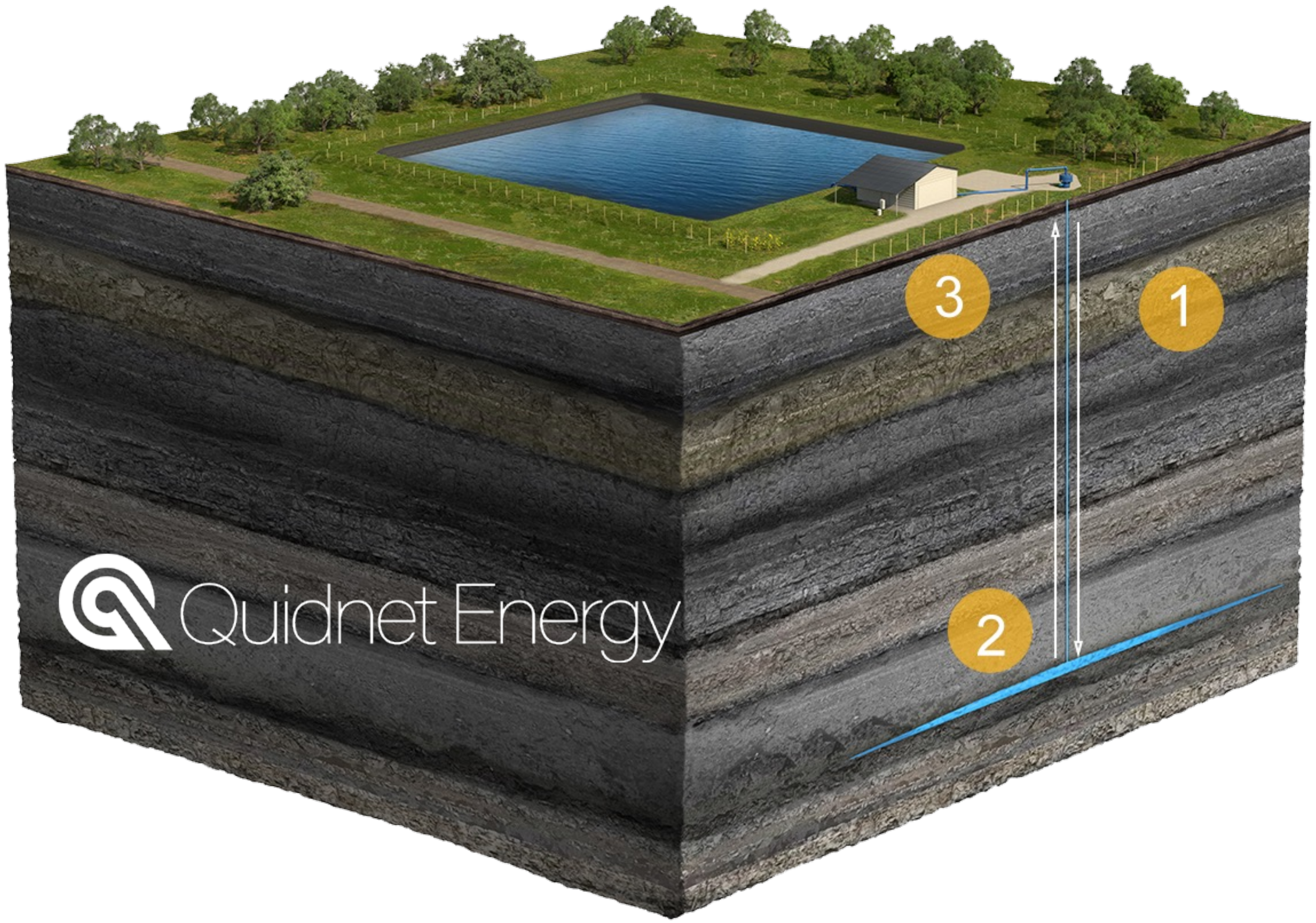


Substantially "mature" and long lifetime
- Most large-scale systems built in 1970s…

- 4-20 hour discharge duration
- ~ 80% efficient
- Largest system in Bath County, Virginia
  - 3GW / 24GWh

https://clearpath.org/tech-101/americas-energy-storage-workhorse-pumped-hydro-at-the-races-once-again/

Quidnet Energy – Subsurface Pumped Hydro



Storage Process

1. Pump water from a pond down a well and into a body of rock.

2. The well is closed, keeping the energy stored under pressure between rock layers for as long as needed.

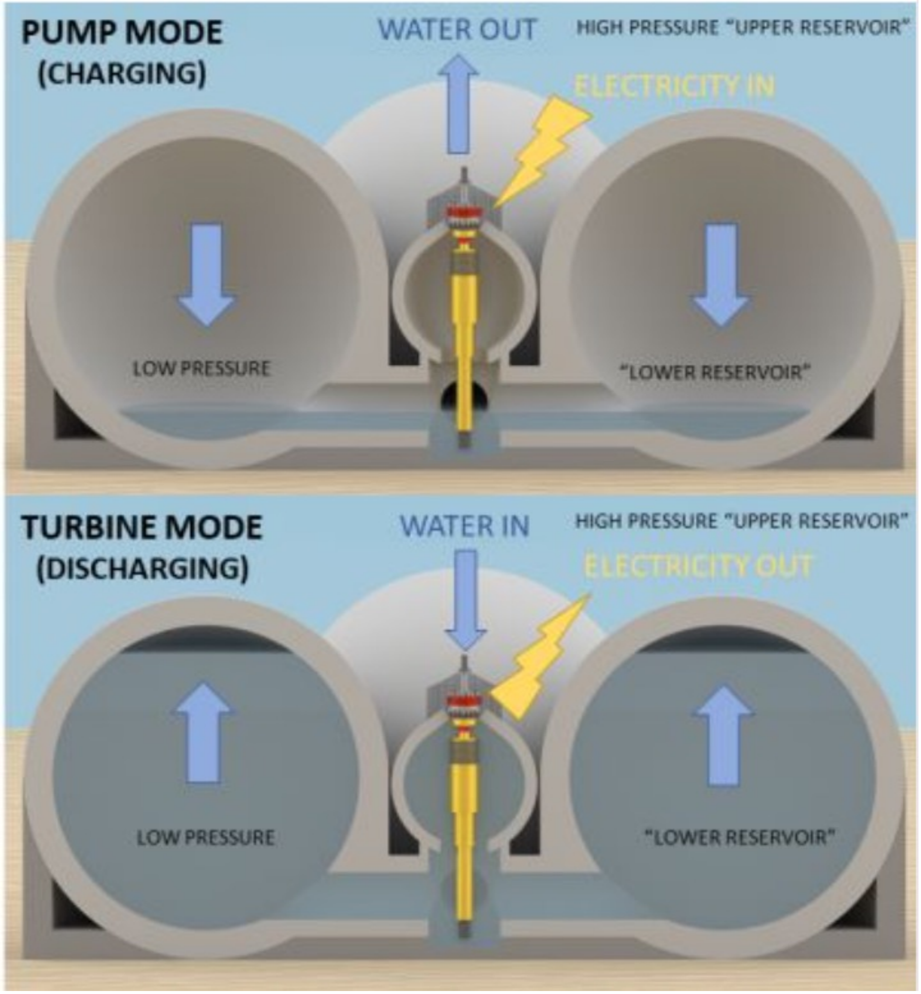
3. When electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity, and return to the pond ready for the next cycle.

1-10 MW systems,
10+ hour modules

Underwater Pumped Hydro (e.g., RCAM)

Subsea storage solution integrates with offshore wind to provide firm, steady power

100-2000m

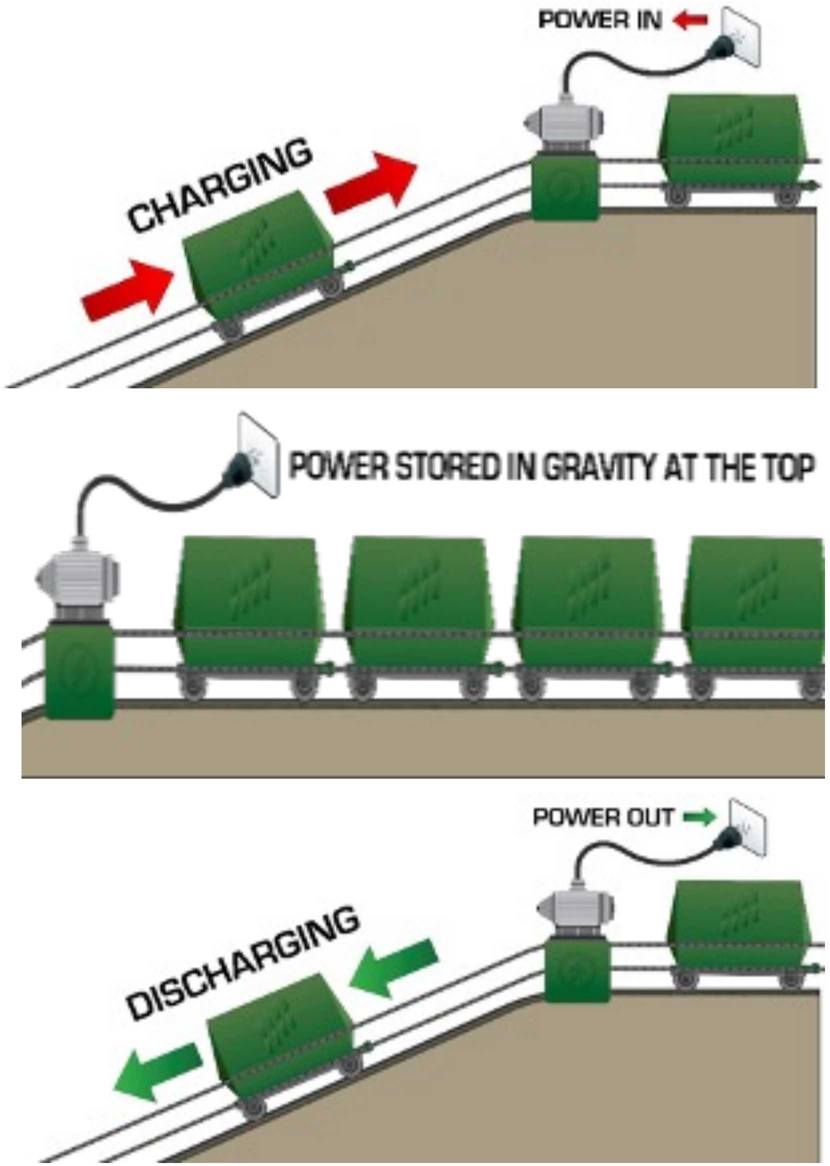


Nominally, three 30-m diameter spheres installed in 700-m water and a 5-MW pump/turbine module has a storage capacity of 60 MWh (12 hours). Increasing the spheres to 8 per pump/turbine provides 32 hours or 160 MWh of energy storage.

Gravity/Mechanical Storage: Gravity Rail Storage

Advanced Rail Energy Storage (ARES)

Scalability	5MW – 1GW
Storage Duration	15 mins–10 hours
Time to Max Output Discharge (optimal)	3 seconds
Time to Max Output Consumption (optimal)	3 seconds
Round-Trip Efficiency	90%+
System Life	40+ years
Flammability	Non-flammable



ares

*50MW GravityLine™ system in Pahrump Valley, NV is under construction

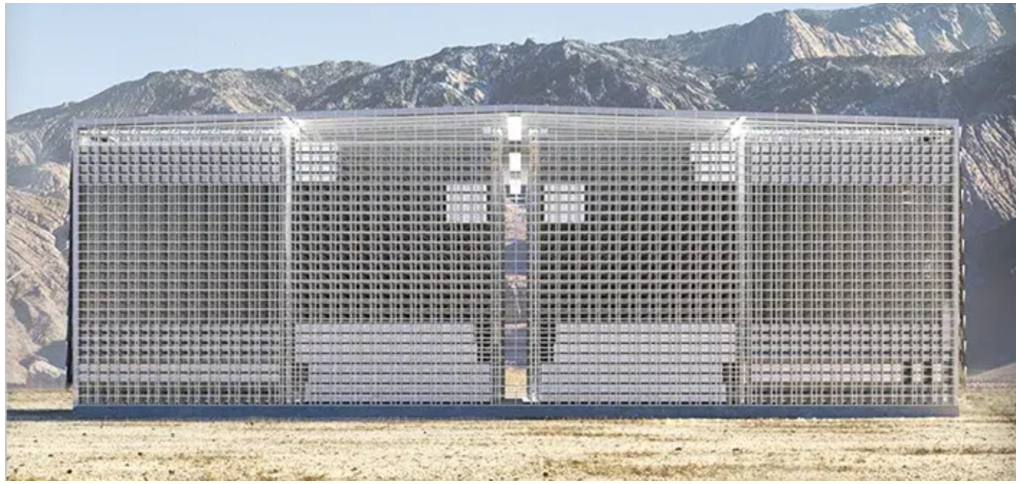
Gravity/Mechanical Storage: Stacked Block

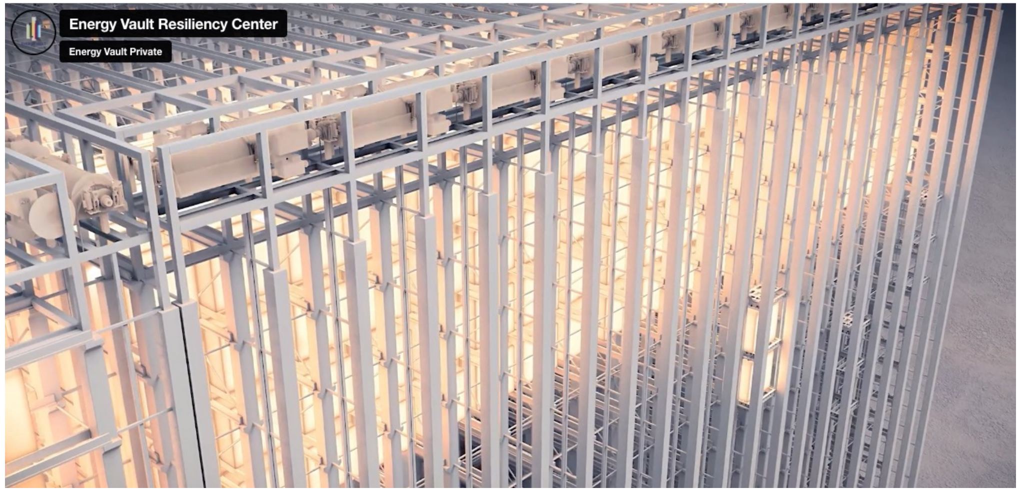
Prototype completed in July 2021 in Ticino, Switzerland

- Scalable in 10MWh increments
- 2-4 hour and 4-12+ hour duration
- Emphasizes local, sustainable sourcing of materials

ENERGY VAULT
Enabling a Renewable World

Gravity/Mechanical Storage: Stacked Block





ENERGY VAULT
Enabling a Renewable World

- Energy Vault® EVx™ system raises/lowers 30 ton bricks
- Scalable in 10MWh modules
- China Tianying Group (CNTY) is installing a 25 MW/100MWh system in Rudong, China (near Shanghai)

Compressed Air Energy Storage (CAES)

Examples of Current conventional CAES systems:

- Uniper Kraftwerke GmbH (Huntorf, Germany) 290 MW, 2 hour discharge time operational 1978
- Power South Energy Coop (McIntosh, Alabama) 110 MW, 26 hour discharge time (2.86GWh), operational 1991

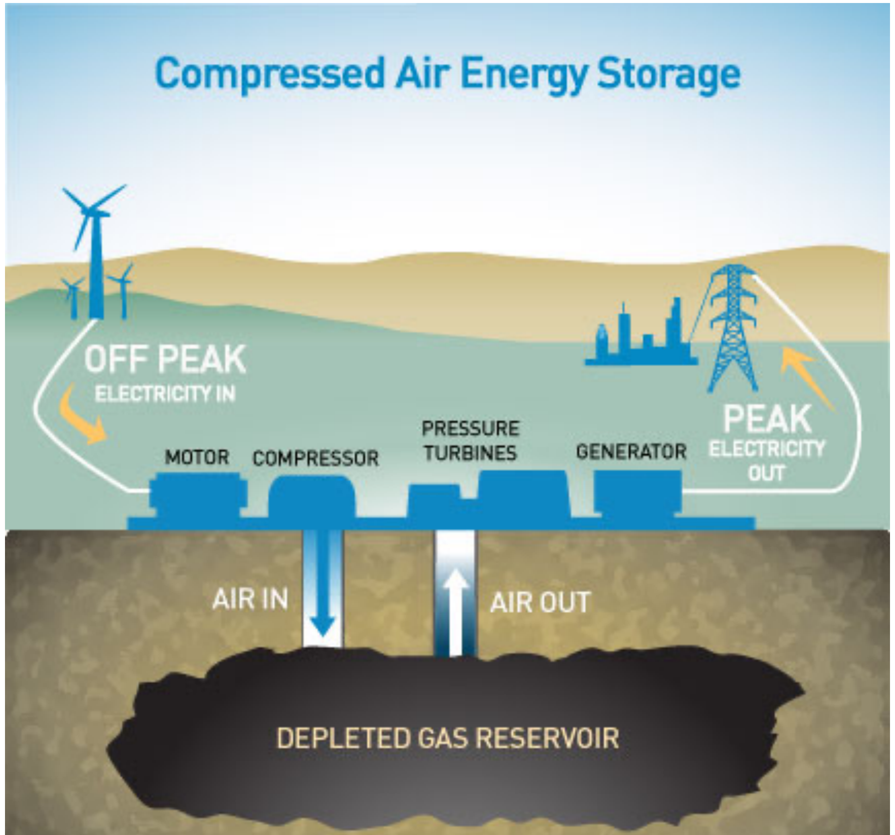


Image from pge.com

https://newatlas.com/energy/hydrostor-compressed-air-energy-storage/

Proposed Hydrostar plant, planned to provide 500 MW, 4GWh (Rosamond, CA)

Compressed Air Storage: Recent Developments

Project Name	Location	CAES Technology	Project Purpose	Project Status	Years Active	Power [MW]	Capacity [MWh]	Efficiency [%]	Air Storage Pressure [bar]	Storage Method
Norton CAES plant	Norton, Ohio, USA	Conventional diabatic, gas fuelled	Commercial	Not realised	2001–2013	800–2700	–	–	55–110	Repurposed limestone mine
GAELECTRIC Northern Ireland	Islandmagee, Co Antrim, UK	Conventional diabatic, gas fuelled	Commercial	Not realised	2008–2019	200 (charge) 330 (discharge)	1980	–	–	Solution mined salt cavern
Seneca CAES Project	Reading, New York, USA	Conventional diabatic, gas fuelled	Demonstration	Not realised	2010–2012	130–210	2000	–	–	Solution mined salt cavern
SustainX Smart Grid Programme	Seabrook, New Hampshire, USA	Isothermal, innovative water-foam mixture employed to ensure constant heat transfer during compression and expansion	Demonstration	Discontinued	2013–2015	2.2 (charge) 1.65 (discharge)	1	54	12–207	Above ground pressure vessels
ADELE project	Staβfurt, Germany	Adiabatic, sensible heat store	Commercial	Discontinued	2010–2016	200	1000	70	100	Solution mined salt caverns
PG&E Advanced Underground CAES	San Joaquin County, California, USA	Conventional diabatic, gas fuelled	Commercial	Not realised	2010–2018	300	–	–	–	Depleted natural gas store
TICC-500	Tsinghua University, China	Adiabatic, sensible heat store	Demonstration	Active	2014 – present	0.5	0.5	33	30–110	Overground storage tank
Chinese Academy of Sciences, CAES demonstration plant	Bijie City, Guizhou, China	Adiabatic, sensible heat store	Demonstration	Active	2017 – present	2.8 (charge) 10 (discharge)	40	62.3	70	Overground storage tanks
Pilot scale demonstration of AA-CAES	Gotthard base tunnel, Biasca, Switzerland	Adiabatic, sensible heat/combined sensible-latent heat store	Demonstration	Active	2017 – present	0.7	–	63–74	8	Previously excavated unlined rock cavern
Zhongyan Jintan CAES	Jintan, Jiangsu, China	Adiabatic, sensible heat store	Commercial	Commissioned	2017 – present	50–60	200–300	–	–	Solution mined salt cavern
Goderich A-CAES facility	Goderich, Ontario, Canada	Adiabatic, cavern flooded and hydrostatic pressure used for isobaric storage	Commercial	Active	2019 – present	2.2 (charge) 1.75 (discharge)	7	>60	–	Specifically mined cavern
Apex CAES Bethel Energy Centre	Tennessee Colony, Texas, USA	Conventional diabatic, gas fuelled	Commercial	Commissioned	2019 – present	324–487	16000	–	–	Solution mined salt cavern
Feicheng A-CAES	Feicheng, Shandong, China	Adiabatic, sensible heat store	Commercial	Active	2019 – present	50–1250 (expected)	7500	67	–	Solution mined salt cavern
Angas A-CAES facility	Strathalbyn, South Australia, Australia	Adiabatic, cavern flooded and hydrostatic pressure used for isobaric storage	Commercial	Commissioned	2022 (expected)	5	10	>60	–	Repurposed zinc mine

M. King, et al. Renewable and Sustainable Energy Reviews (2021) **140** 110760.

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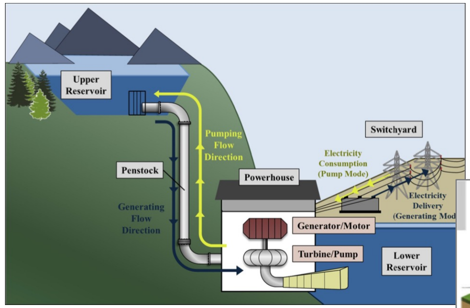
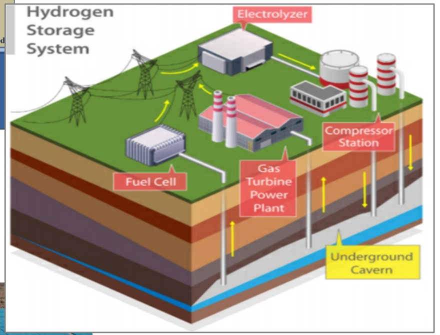
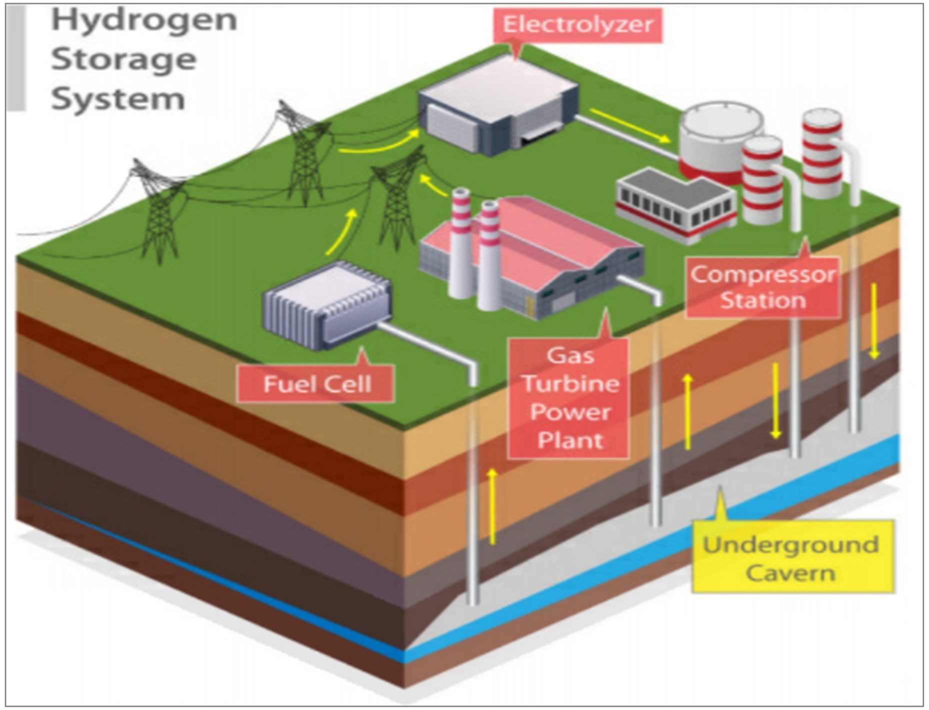




Hydrogen Energy Storage



- Smaller quantities of H_2 can be stored in pressurized vessels (MWh scale)

- Larger amounts of H_2 can be stored in underground salt caverns at high pressure (e.g., 500,000 cubic meters at 2,900 psi would afford ~100GWh of stored electricity). nearly 3,000 psi).

- Hydrogen electrolysis is ~70-80% efficient (R&D is improving this value…)
- Re-electrifying hydrogen in fuel cells is ~50% efficient; burning in combined cycle gas power plants ~60%.

American Clean Power - https://energystorage.org/why-energy-storage/technologies/hydrogen-energy-storage/

Hydrogen energy storage involves
1) an electrolyzer (or other H2 generator)
2) bulk storage (e.g. cavern or vessel)
3) fuel cell or turbine.

Management of hydrogen losses during storage/transport must be addressed for effective large-scale adoption.

Image source: "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System." 2021. NREL. https://www.nrel.gov/docs/fy21osti/77480.pdf

Slide Content from Neha Rustagi (HFTO)

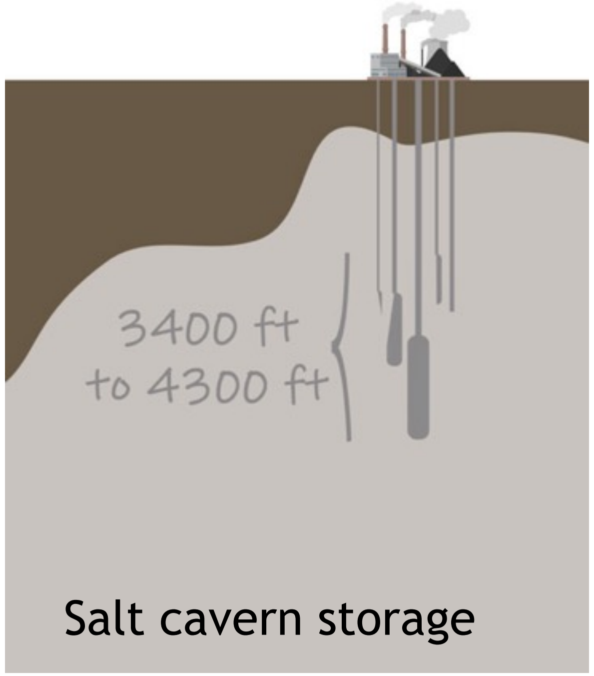
Large-Scale Hydrogen Storage

IPP-Renewed

- **Intermountain Power Project (IPP)** provides regional power, including to Southern California, through the Southern Transmission System

“Renewed” will ‘update’ IPP for increased transmission of renewables and base load generation via hydrogen

- Gas turbines (840 MW): 30% H_2+NG starting in 2025, 100% H_2 by 2045
- Salt caverns will provide long-term storage (up to 500M kg H_2)



Salt cavern storage

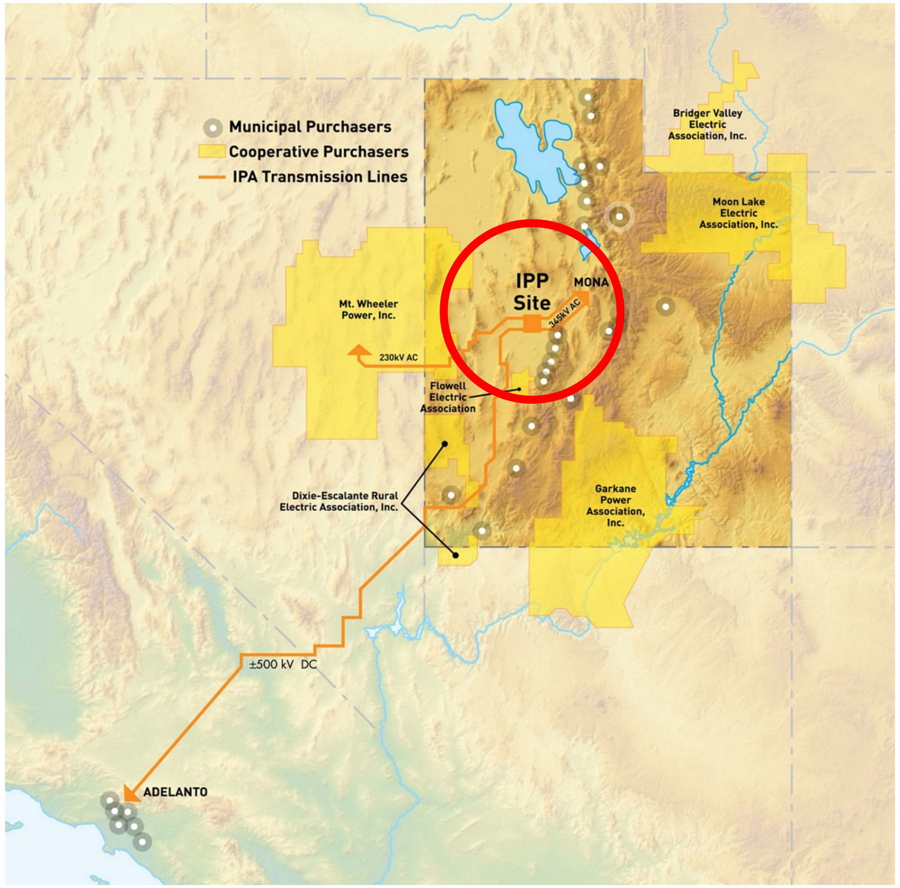
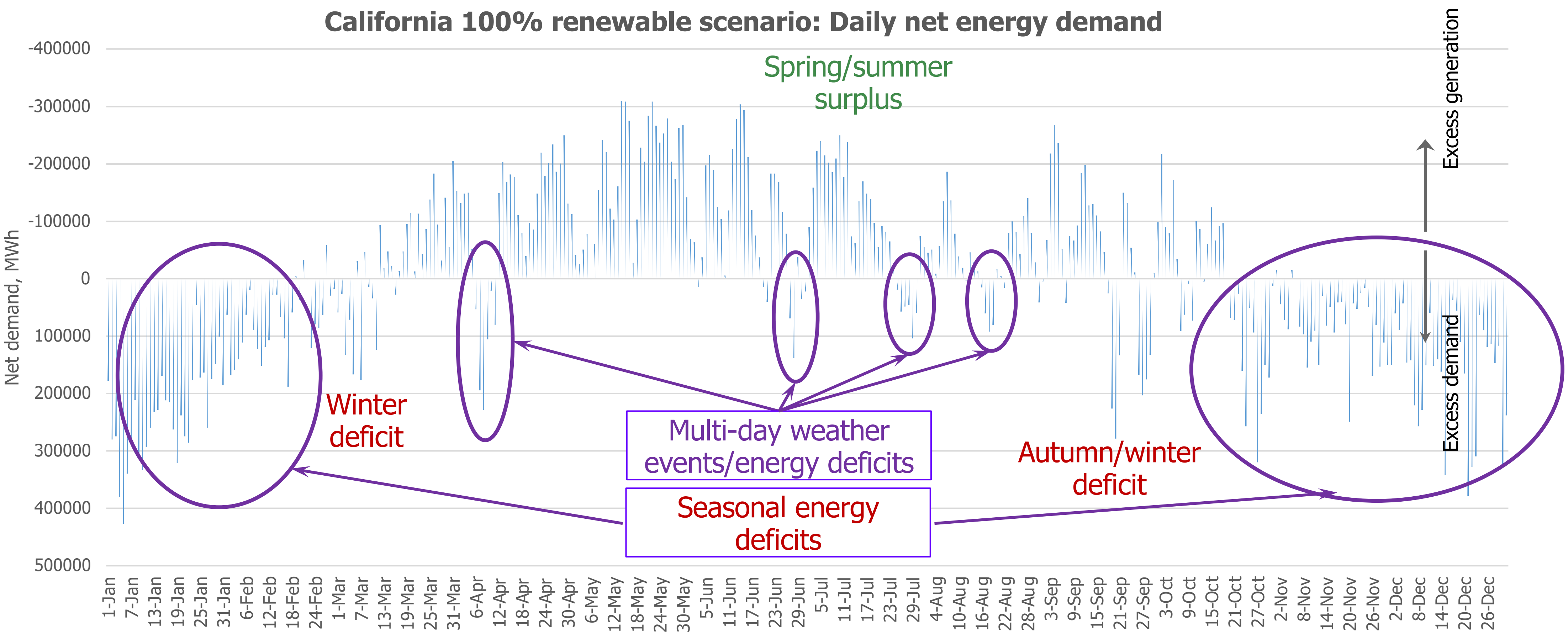


Image from: https://www.ipautah.com/ipp-renewed/

Need for Multi-Day and Seasonal Energy Storage



Source: CAISO and Strategen Analysis

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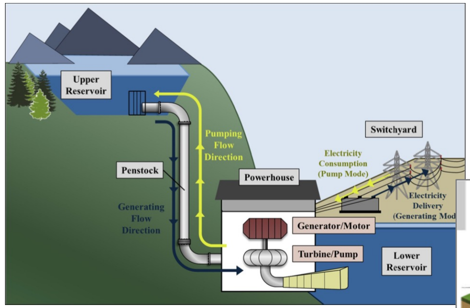
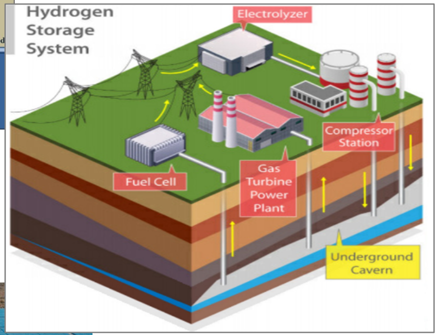




Molten Salt Thermal Storage

- Molten salts (e.g., nitrate salts) are the primary storage medium for concentrated solar power plants (Nearly 30 GWh_e of CSP thermal energy storage!)
- Salts are heated to high temperatures (e.g., 385C or 565C)
- Stored energy in salt is then used to heat a medium, such as water to generate steam.
- Nitrate salts are inexpensive (~$1/kg), but need to be maintained at ~200-300C to keep from freezing.

Solana Parabolic Trough Solar Project
1.5 GWh_e storage in 6 pairs of hot and cold tanks.

Example Use Cases

Solana Parabolic Trough Solar Project (Arizona)
280MWhe with 6 hour storage (~1.5GWh_e)

Noor I Parabolic Trough Solar Project (Morocco)
160MWh_e with 3 hours of storage (480MWh_e)

Noor III Central Receiver Solar Project (Morocco)
150MWh_e with 7 hours of storage (1GWh_e)

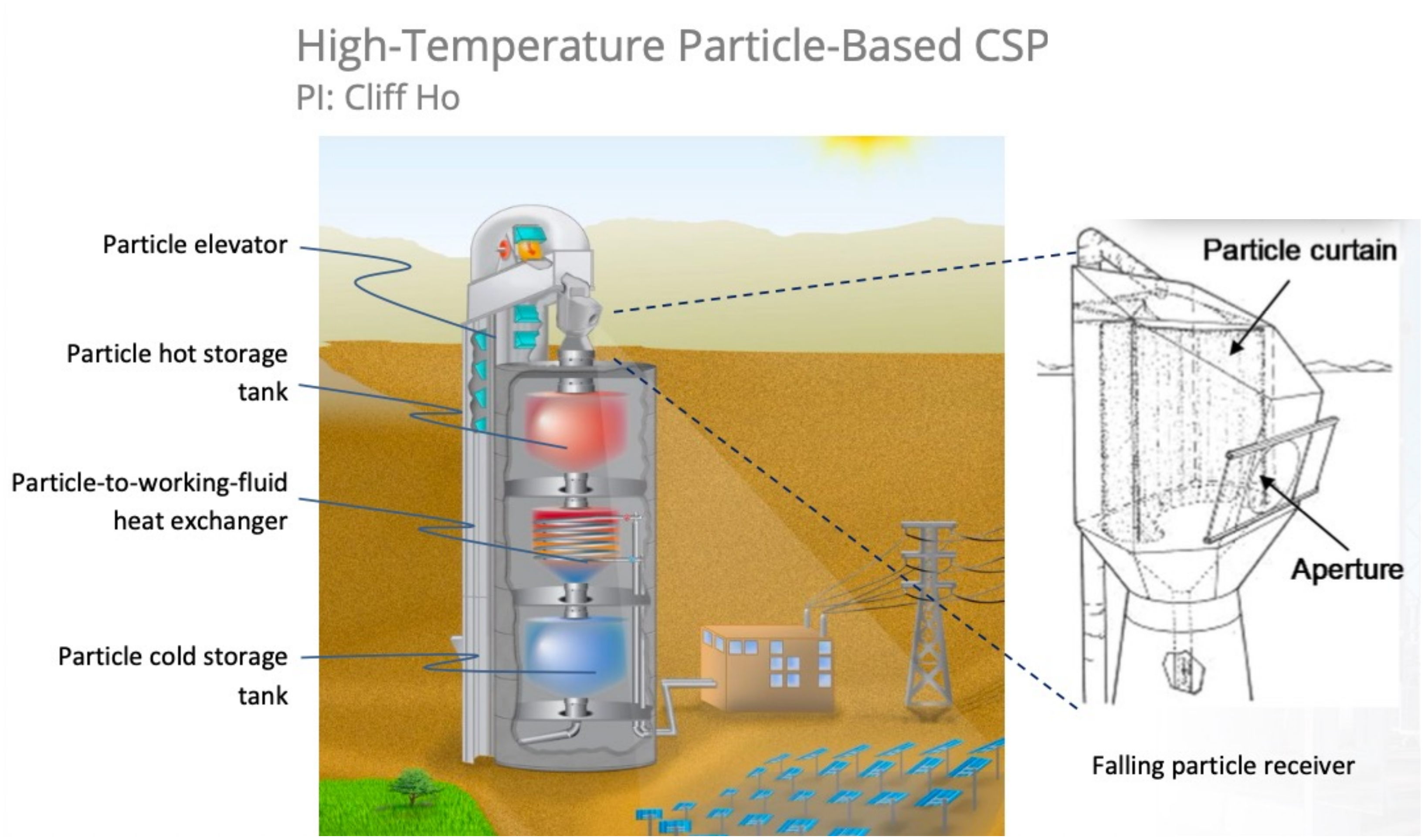
Crescent Dunes Central Receiver Solar Project (Nevada)
125 MWh_e with 10 hours of storage (1.250GWh_e)

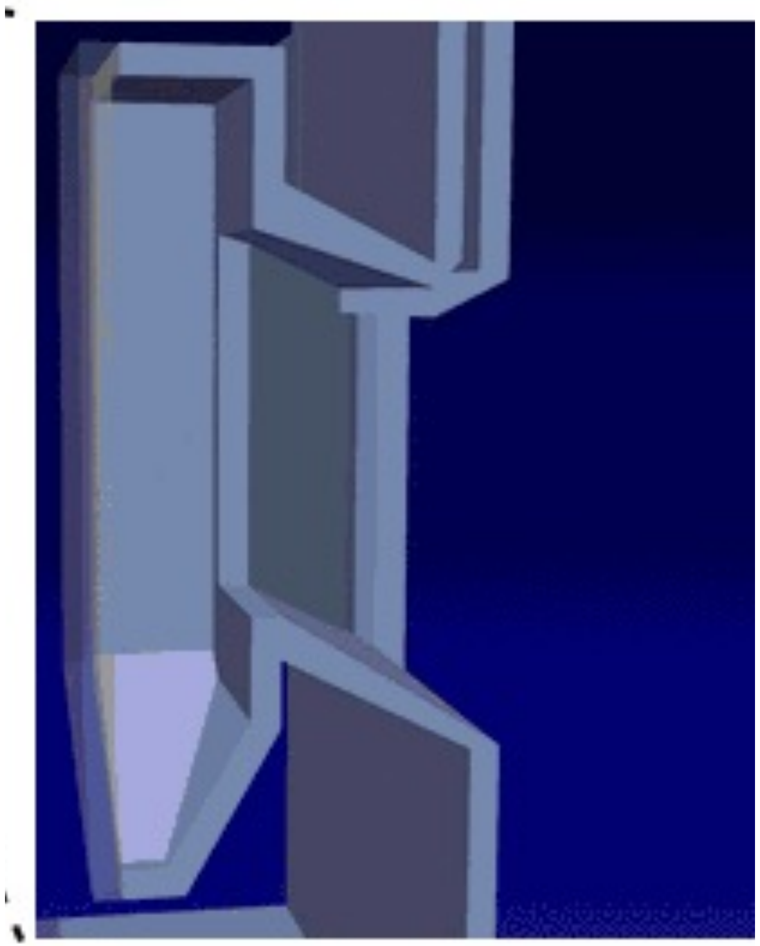
National Solar Thermal Test Facility (NSTTF)

Contact: Margaret Gordon, SNL/NSTTF
megord@sandi.gov

https://energy.sandia.gov/programs/renewable-energy/csp/nsttf/

Storage in Solid Media with a Falling Particle Receiver



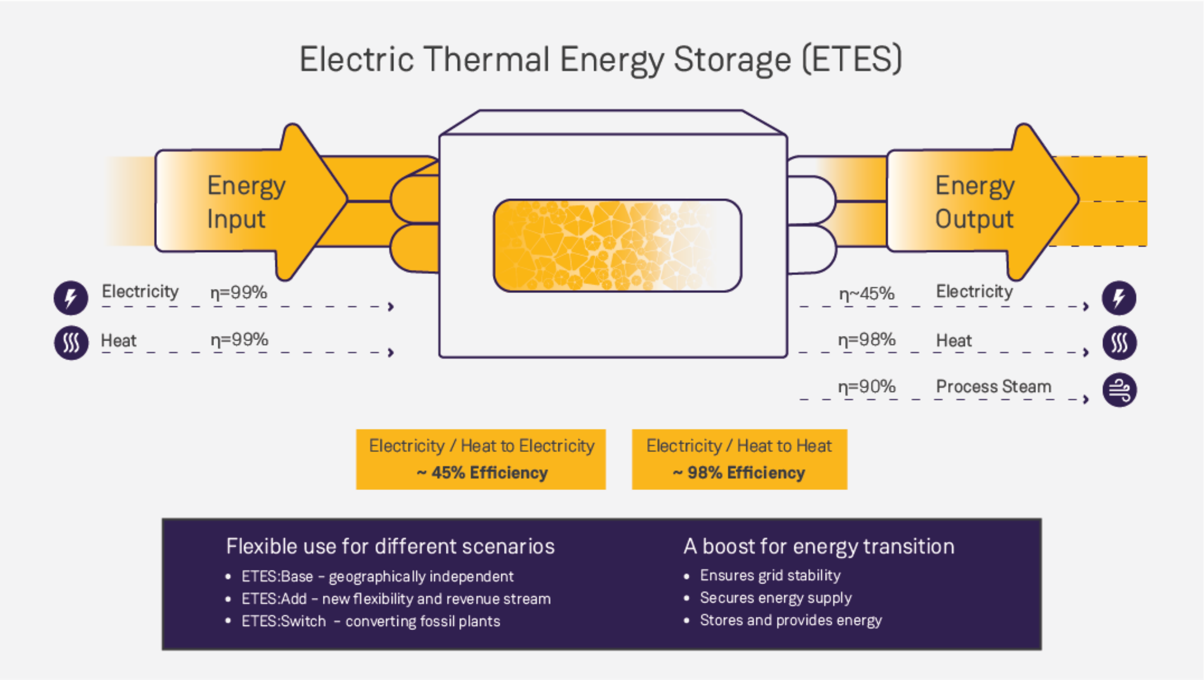


Information provided by Margaret Gordon, SNL/NSTTF

https://energy.sandia.gov/programs/renewable-energy/csp/current-research-projects/gen-3-particle-pilot-plant-g3p3/

Fixed Rock-Bed Thermal Storage

Range from MW to GW scale
Nominal Power: >30MW
Capacity > 130MWh
Storage for discharge up to 24 hours

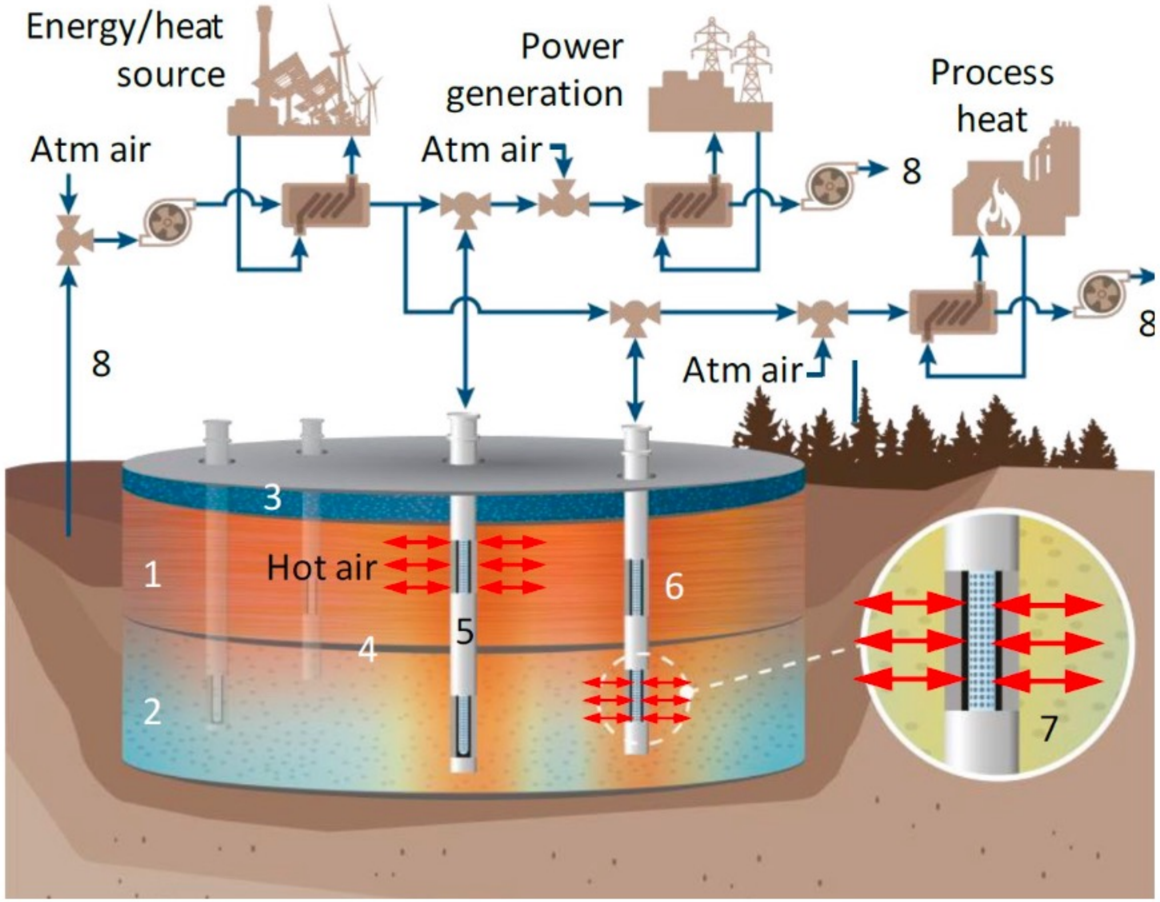


Hamburg, Germany
1000 tons of rock at 750°C
Using steam turbine, generator will produce
24 hour storage at 1.5MW

Siemens-Gamesa

Terrestrial Heat Repository for Months of Storage (THERMS)

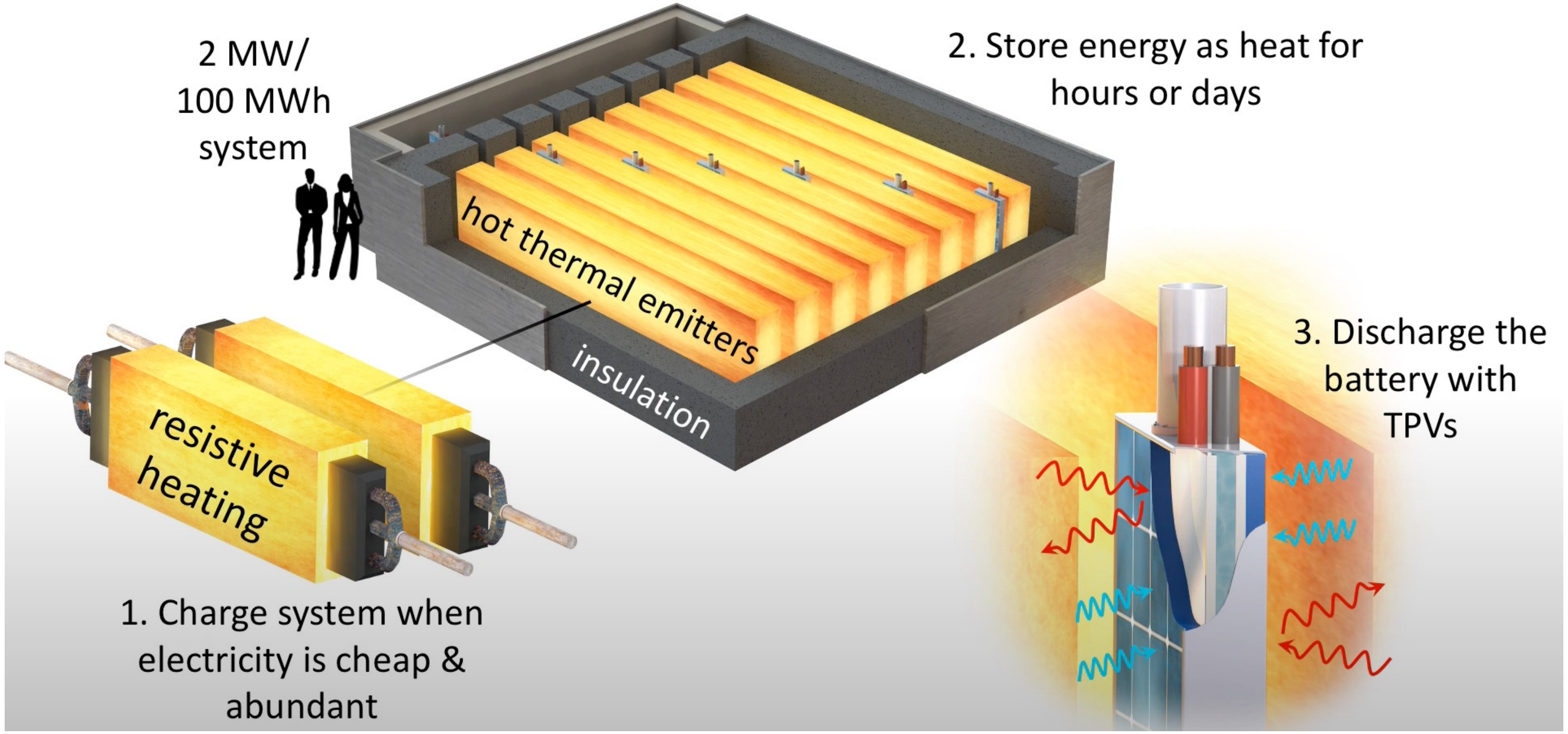
- Radial Packed Bed capable of storing heat for weeks to months
- Separated regions can be used for various storage durations
- Usage:
  - Electricity Generation (from storage)
  - Process Heat
  - District Heating



Source: Cliff Ho, Sandia National Labs

Heated Brick+

Antora Energy is developing TPV for thermal energy storage applications for emitter temperatures > 1000 °C



Solid carbon is free of supply chain constraints, environmental justice issues, and toxicity concerns.

Projected 30 year lifetime
No thermal runaway
MW building block modules

ANTORA

Azelio (Sweden)

- Electrically-generated heat stored in a recycled aluminium phase change alloy at the melting point of 600°C
- Heat transferred to stirling engine to provide power
- Residual heat available (55-65C)
- Each unit has 13kW power for 13 hours
- 0.1MW to 100MW

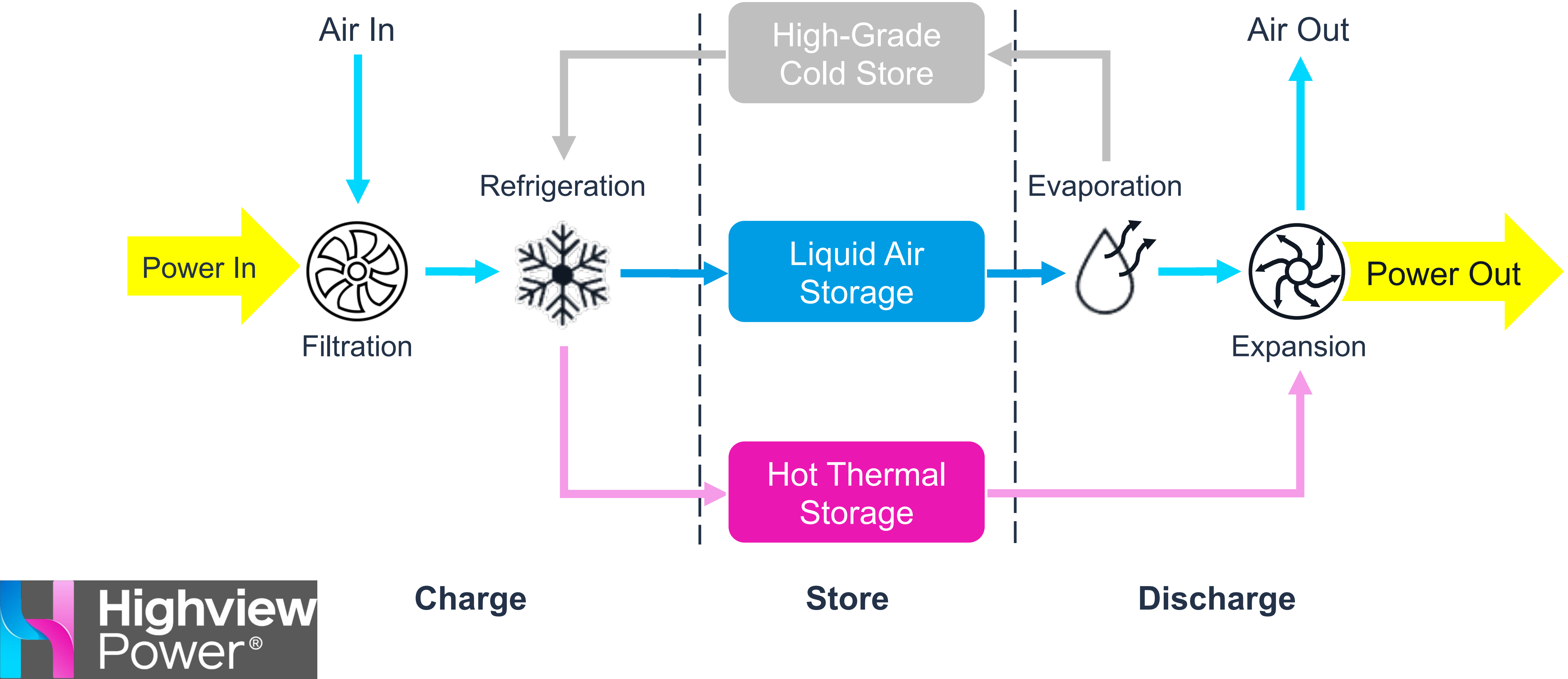
Demonstration projects, typically supporting renewable integration, in Sweden, Morocco, and UAE

AZELIO

Liquid Air Energy Storage

Charge: Store energy through condensation of refrigerated air.

Discharge: Gaseous air generated during reheating turns a turbine to generate power.



Emerging Liquid Air Energy Storage

50 MW Facility (400 MWh shown)

Beginning construction in Europe, Late-stage development in the U.S.

Construction start **2020**

Planned COD **2022**

Pilot

350 kW / 2.5 MWh

Heathrow, UK

Commissioned in **2011**

Demonstration

5MW / 15 MWh

Manchester, UK

Commissioned in **2018**

CRYOBattery One

50MW / 250 MWh

Manchester, UK

Constr. start Nov. 2020

Highview Power®

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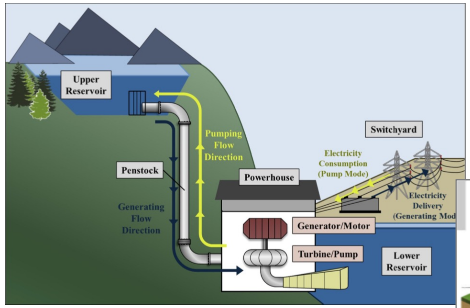
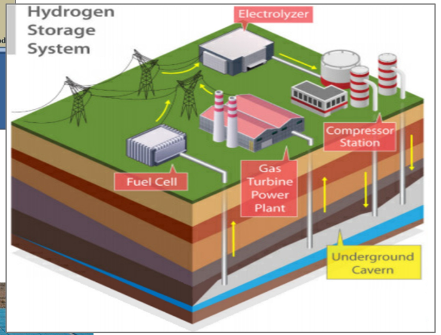
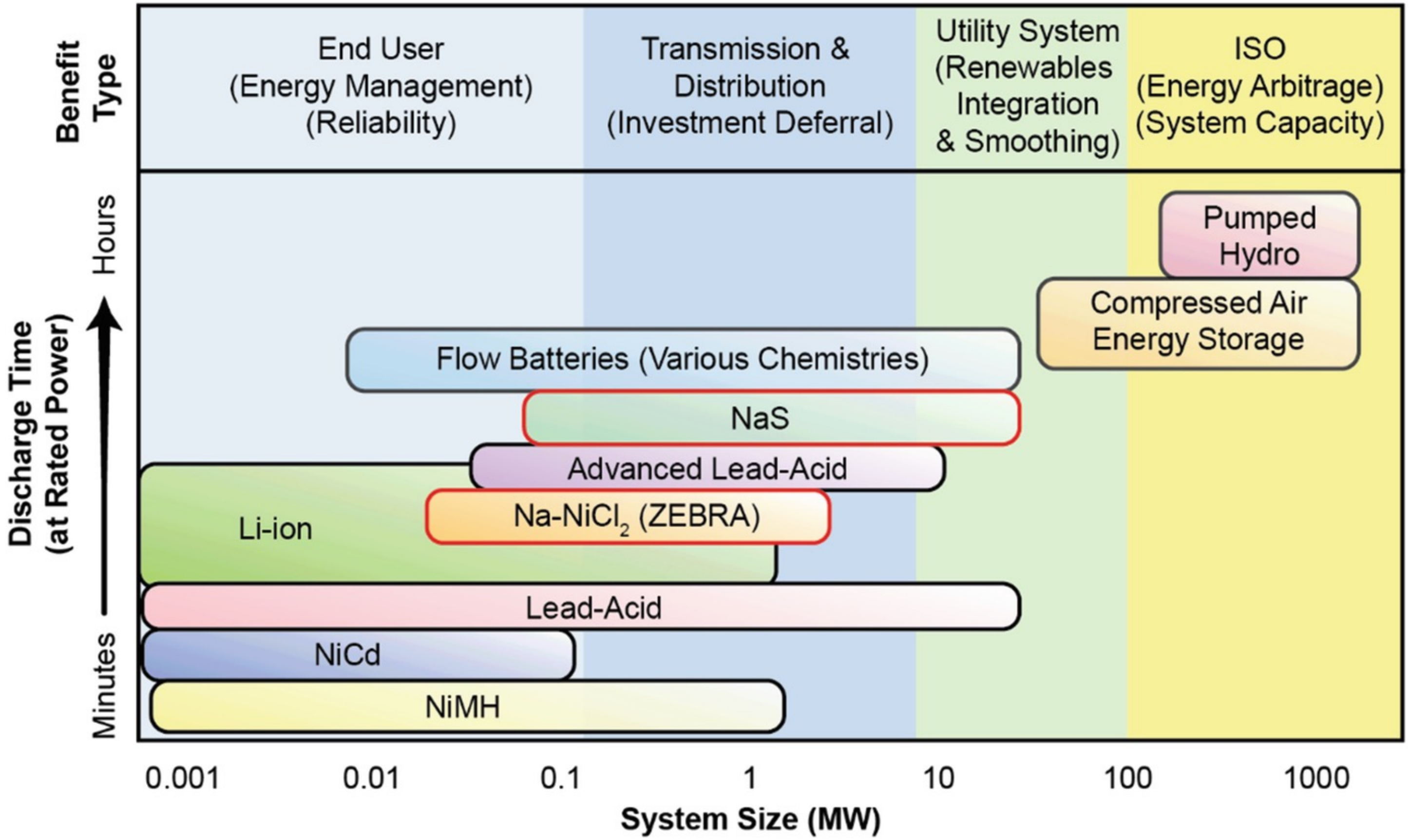




Batteries for Long-Duration Energy Storage?

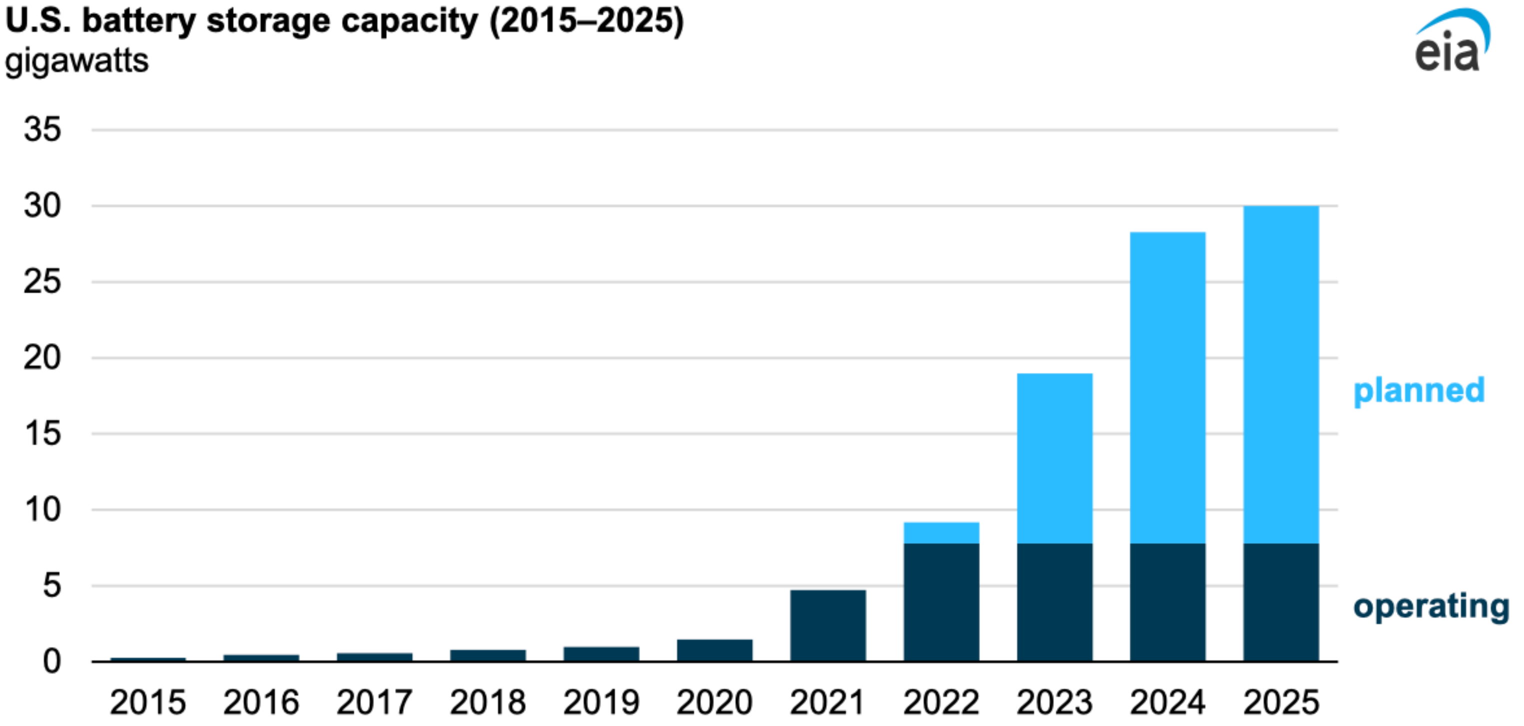
- Lithium-Ion Batteries
- Pb-Acid
- Sodium-Ion Batteries
- Molten Sodium Batteries
- Zn-Based Batteries
- Metal-Air Batteries
- Flow Batteries
- Molten Metal Batteries



Where Are We?

DECEMBER 8, 2022

U.S. battery storage capacity will increase significantly by 2025



Data source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*, October 2022

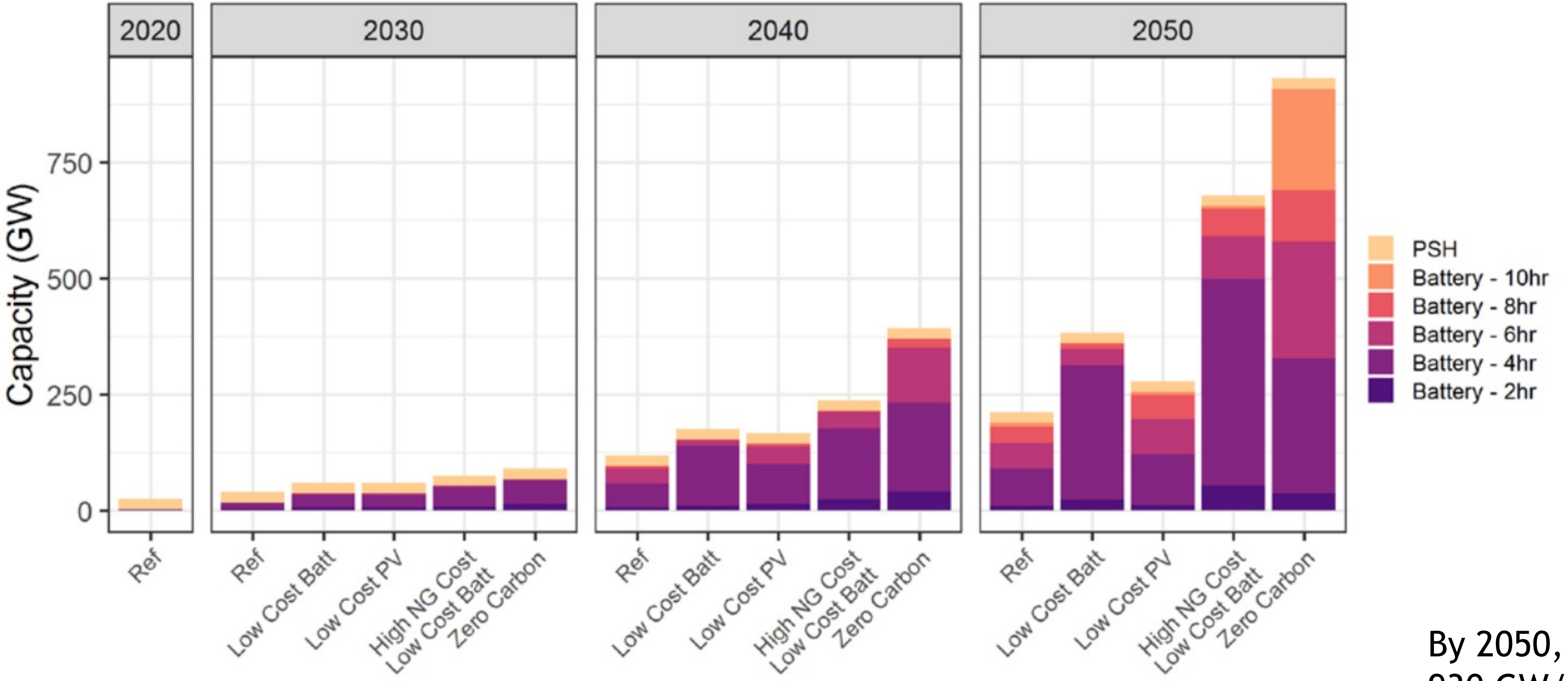
At the end of 2022, U.S. had 9GW/25GWh of installed battery storage.

By Q2 of 2023, U.S. had reached 11 GW/31GWh installed.

Almost All U.S. Battery Storage is in Li-ion (more than 90%).

U.S. Still maintains about 22GW/550GWh of Pumped Storage Hydro.

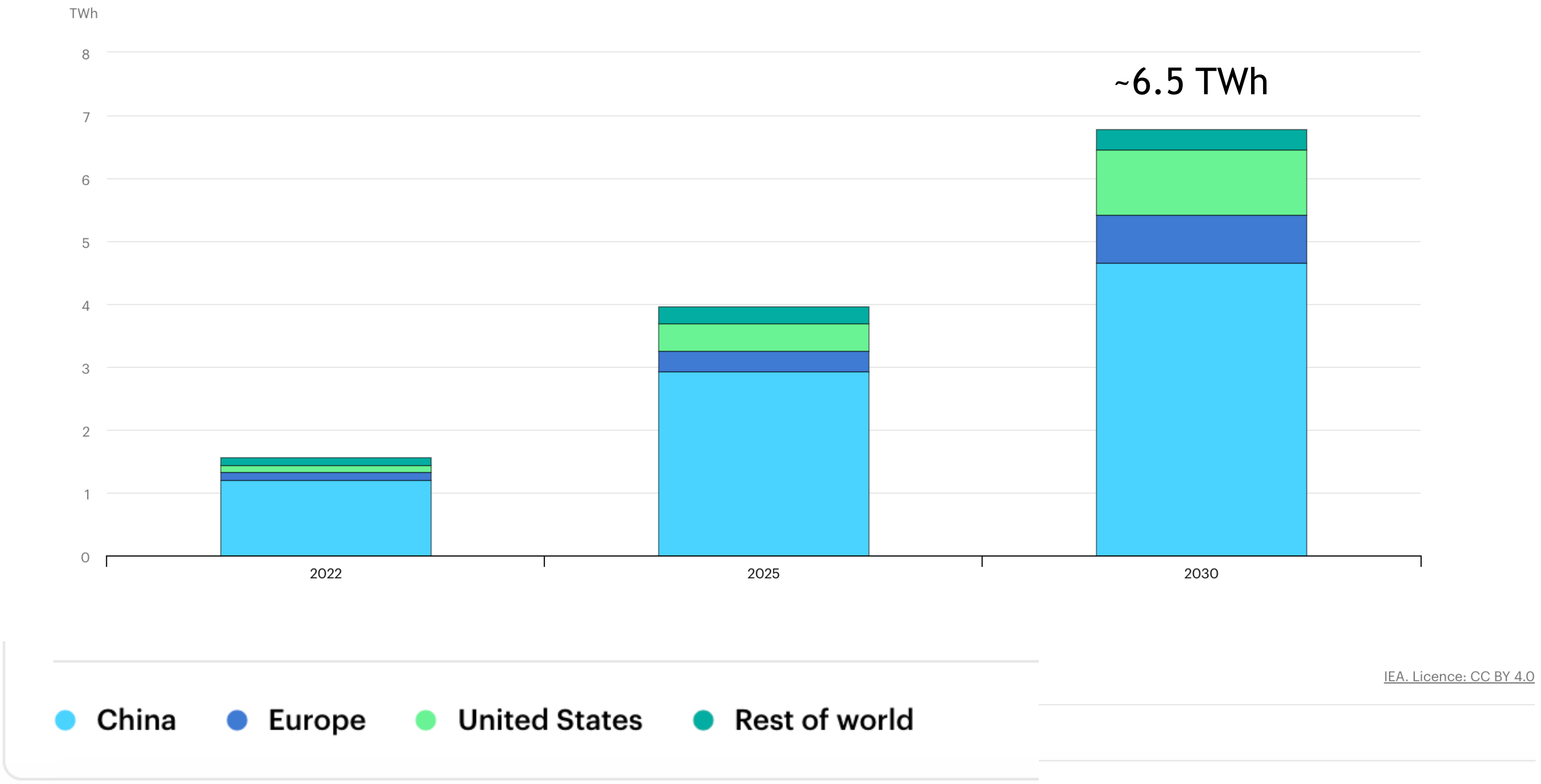
Where Do We Need To Go?



By 2050, U.S. will need 930 GW/6TWh of storage. (85X Increase over today) to hit 94% renewables targets.

2023 NREL Report: “Storage Futures Study Grid Operational Impacts of Widespread Storage Deployment”
https://www.nrel.gov/docs/fy22osti/80688.pdf

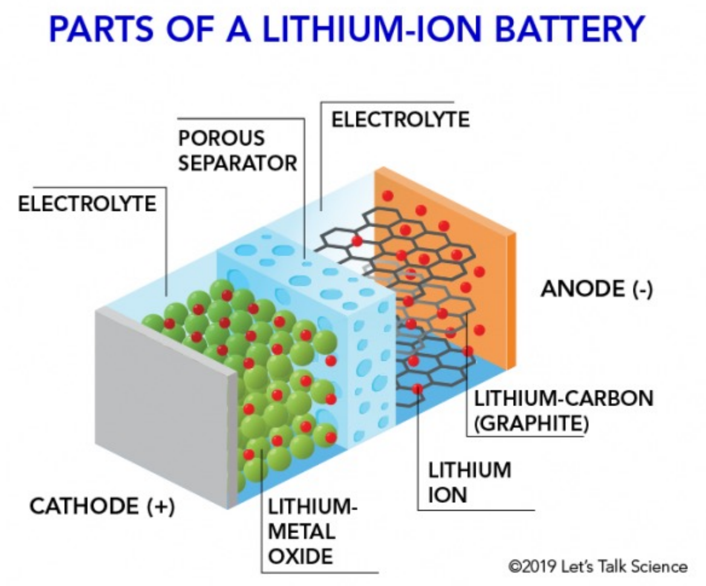
Can we Make Enough Batteries?



EV Battery emand by 2030 is expected to be 4.5TWh!

(McKinsey & Co.)

Li-ion Batteries are Moving the Field Forward



Saft 6 MW / 4.2 MWh ESS
Kauai - Grid Stability

AES 30 MW / 120 MWh ESS, Escondido, CA
Peaker replacement

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

Vistra Energy, Moss Landing, Monterey, CA - 300 MW / 1200 MWh – Peaker Replacement, Grid Reliability

GWh size BESS Plants no longer at the conceptual stage!

Slide adapted from Babu Chalamala
Images: Company websites and Wikipedia

But Challenges Remain!

Aerial picture of the 2021 fire incident at Victorian Big Battery, which was thought to be the first incident of its type involving Tesla Megapacks. Image: Country Fire Authority.

One of 40 Tesla Megapacks caught fire at the 50MW/100MWh grid-scale battery storage project in Queensland, Australia. (Sept, 2023)

https://www.energy-storage.news/tesla-megapack-on-fire-in-minor-incident-at-battery-storage-site-in-australia/

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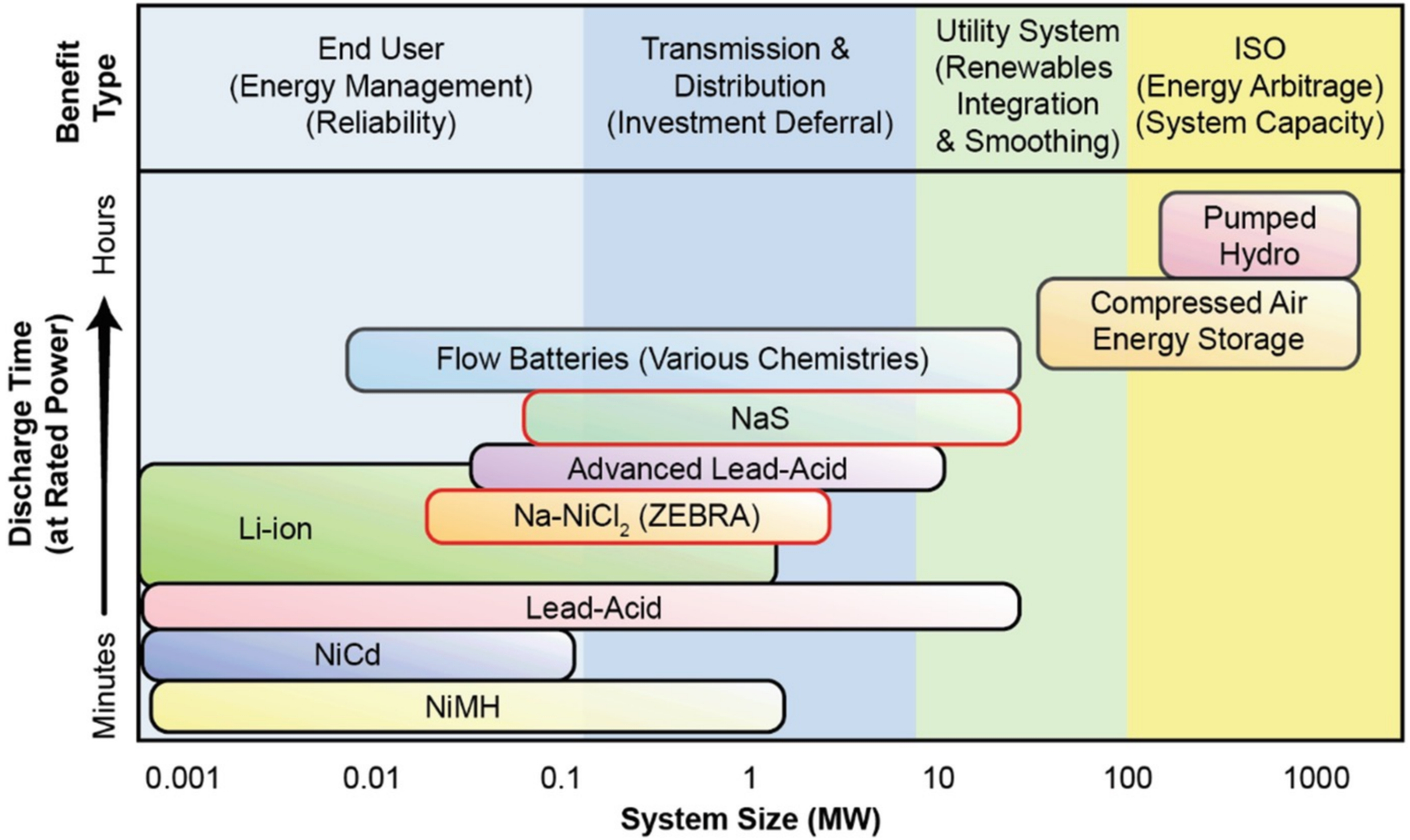
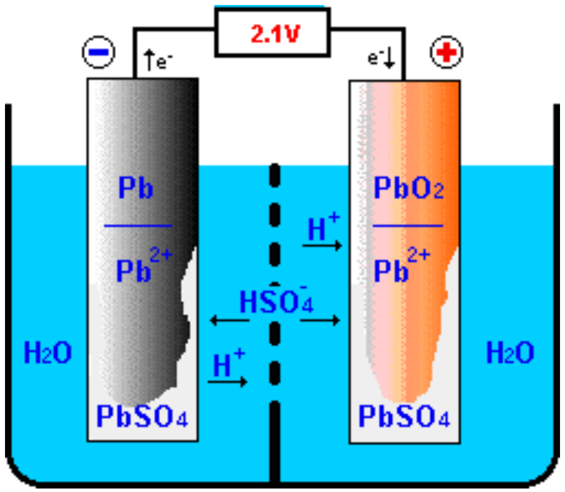


Lead Acid Batteries

- Invented in 1859 by Gaston Planté
- Energy Density ~30-50 Wh/kg
- Typically hundreds of cycles

- The 2020 global market for PbA batteries was ~500 GWh (70% of global energy storage) and $40 billion*

- Automotive/mobile applications
- Off-grid use (e.g., traffic signal and lighting, railroad communications, uninterruptable power supply (UPS), and telecommunications)
- Grid-integrated applications (e.g., renewable integration, load smoothing, time-shifting, etc.)



S.R. Salkuti, DOI:10.11591/ijece.v11i3.pp1849-1856

Battery Operation
- Anode: Pb
- Cathode: PbO_2
- Electrolyte: H_2SO_4

- During discharge, oxidation and reduction reactions at each electrode produce $PbSO_4$.

*DOE SI 2030 Technology Assessment on Pb-Acid Batteries (Sue Babinec)

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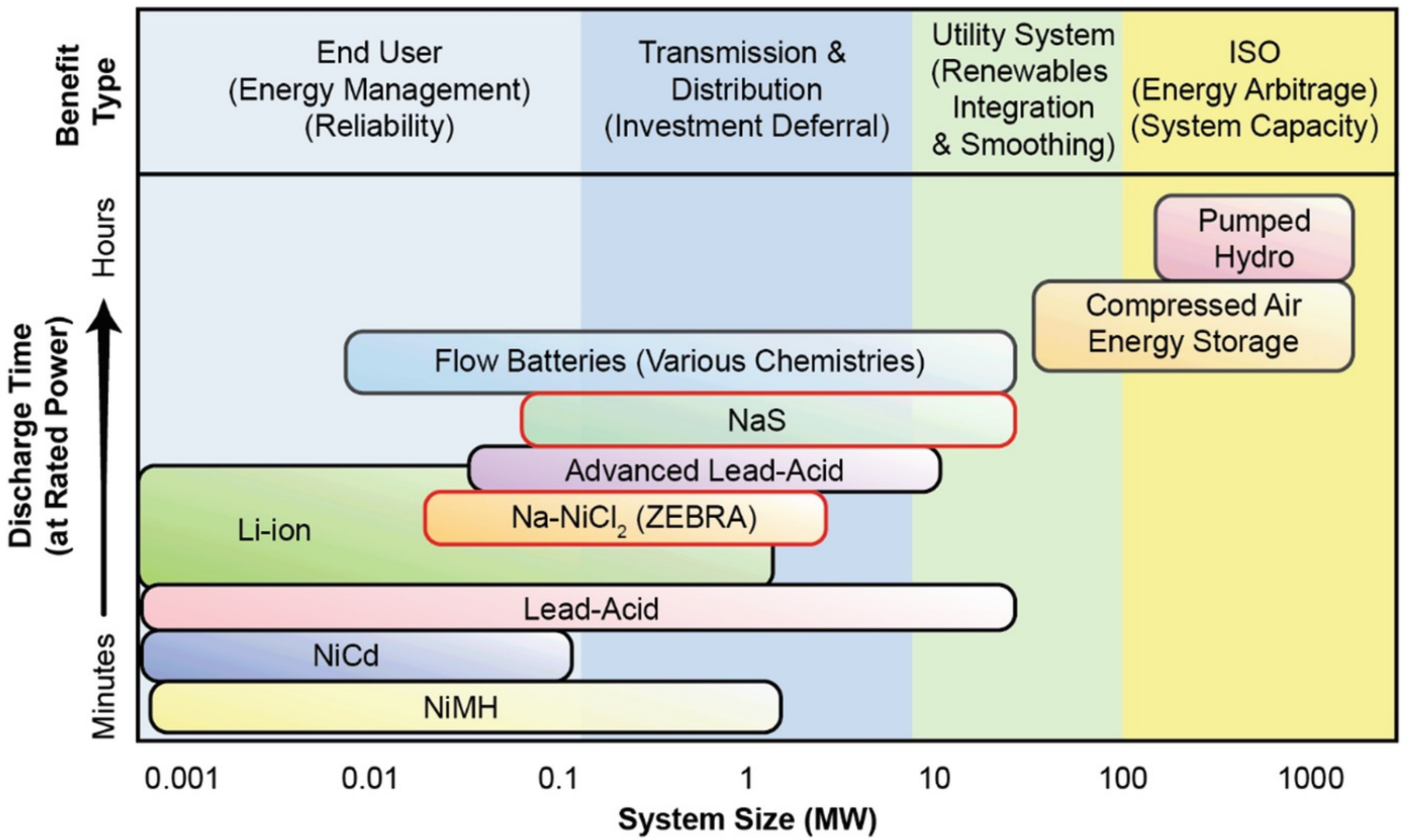
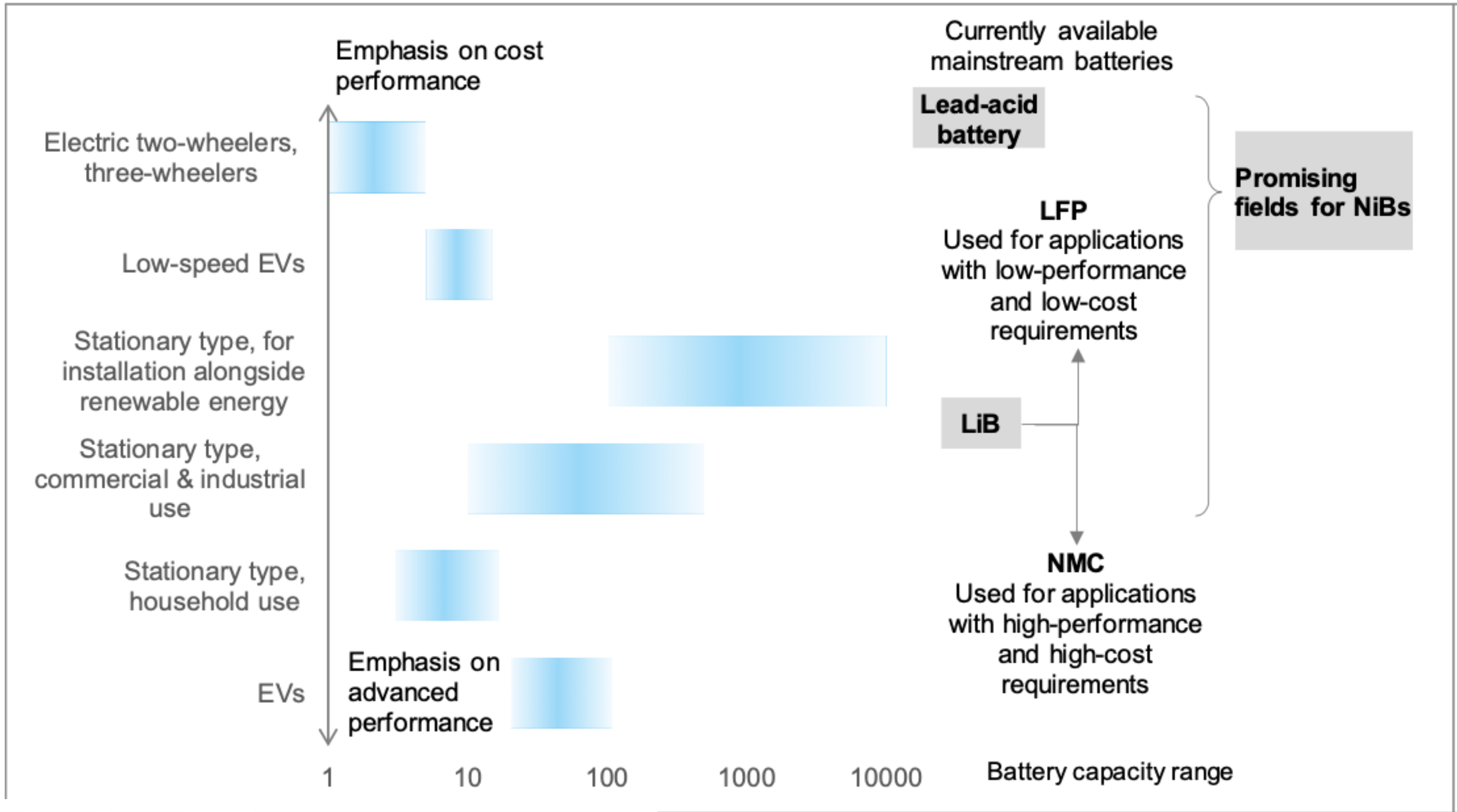
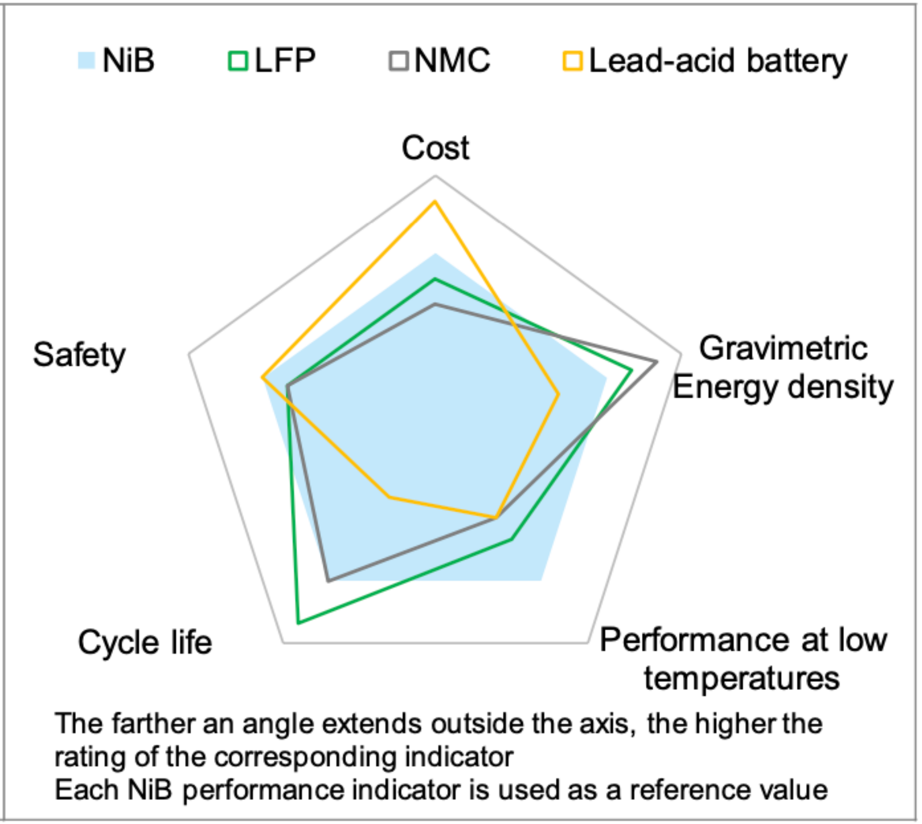
- Metal-Air Batteries
- Flow Batteries
- Molten Metal Batteries



Na-Ion Battery (NaIB, NIB, NiB) Opportunity Space





Mitsui & Co., June 2022

Application of NIBs

Wind power/
Solar power station
Household energy storage
Large-Scale Energy Storage

Electric cars
Electric ship
Delivery vehicles
Agricultural vehicles
Low-Speed Vehicles

- Projected lower cost, simplified cell architectures, and improved safety are benefits of NaIBs.
- While NaIBs are unlikely to replace LiBs for high power (e.g., EV) applications, low-speed vehicles and stationary storage is likely to be a growing market.
- Woods Mackenzie anticipates growth of 40GWh of NaIBs alone by 2030, but up to an additional 100GWh of manufacturing capacity is projected if the market is successful by 2025

Woods Mackenzie. “Sodium-ion update: A make-or-break year for the battery market disruptor.” Jan., 2023

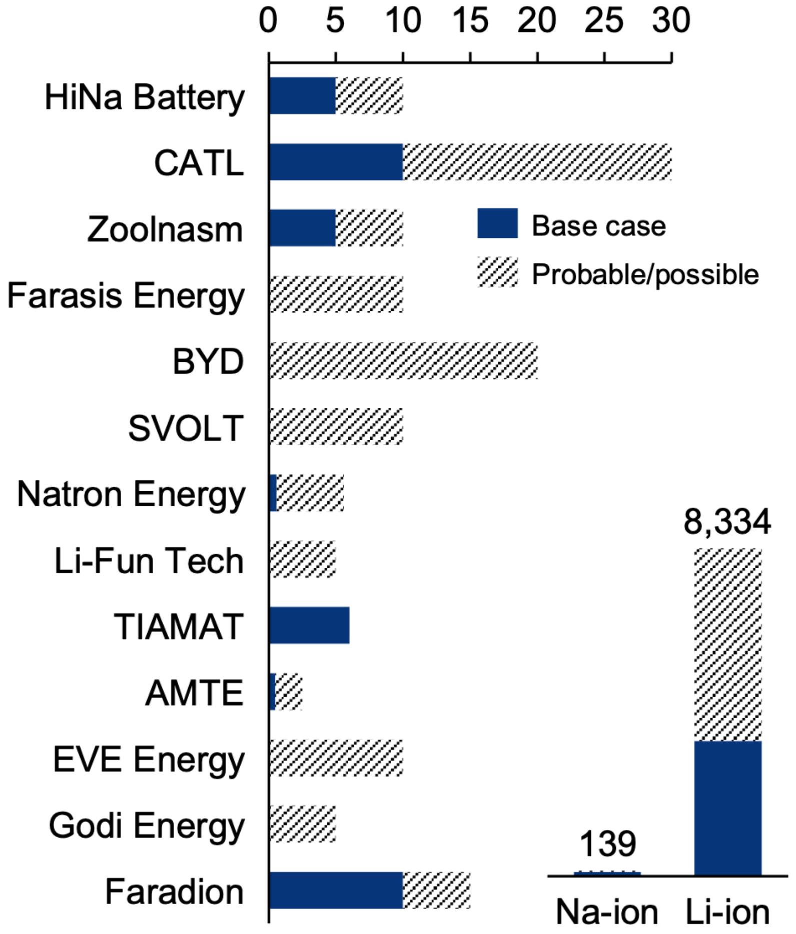
Emerging/Evolving Sodium Ion Batteries

Na-ion cell producers

Year	GWh	Producer	Production details
2022	1-5	中科海钠 HiNa BATTERY	First Na-ion production at GWh scale last year
2023	>10	CATL	Planned GWh-scale production this year
2023	5	ZOOLNASM	Building a factory in Jiangsu, China
2023	-	FARASIS	Partnered with the **JMEV** to develop Na-ion EVs
2023	-	BYD	May launch a Na-ion-based EV this year
2023	-	SVOLT	Expects to develop Na-ion cells this year
2023	0.6	Natron Energy	**Clarios** will manufacture cells this year
2023	-	LiFUN 立方新能源	Planned production in 2023
2020s	6	TIAMAT	**Neogy** will mass produce Na-ion cells
2020s	0.5	amte	Building a factory in Scotland, UK
2020s	-	EVE	Developing cells further before production
2020s	-	GODI	Planning a 5 GWh Li-ion factory before Na-ion
2020s	>10	faradion	Planning double-digit production under **Reliance**

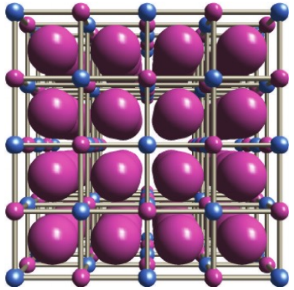
Source: Wood Mackenzie

Pipeline capacity



Significant NaIB manufacturing capacity is projected to 40-100 GWh by 2030.

Alternative Sodium Ion Batteries



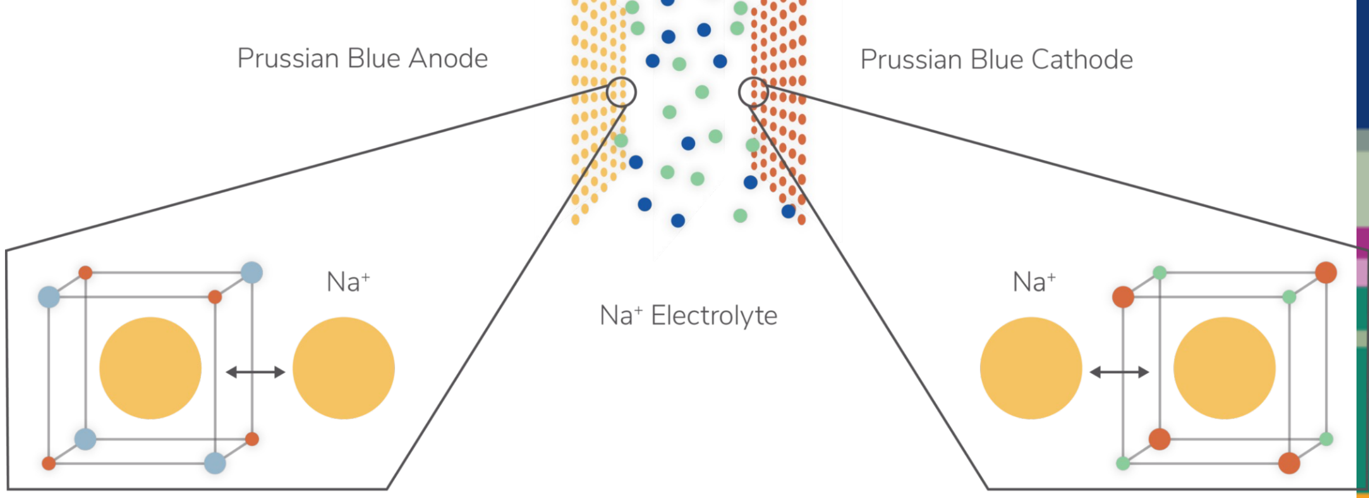
Y. Moritomo, *Adv. Cond. Matt. Phys.* (2013) 539620.

Prussian Blue Analogs (PBAs)

- Utilize ferric ferrocyanide salts as electroactive materials

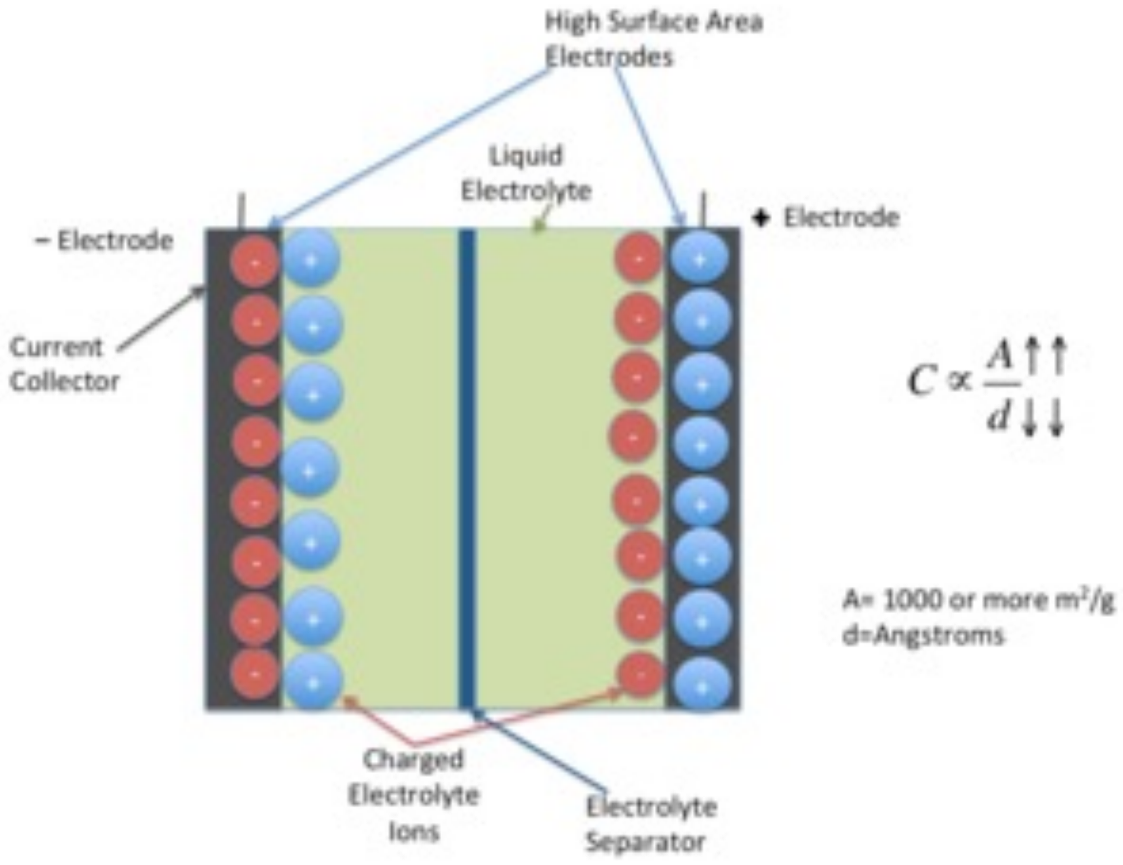
- **Natron Energy** is developing PBA-NaIBs (with Clarios in Michigan)
  - Aiming for 600MW annually starting in 2023.
  - Focus on High Power
    - 25kW, 48V module, scalable to 812V with full charging in 15 minutes.
    - 4kW at 48V for 2 mins with a 6kW peak power rating and 8-minute recharge time.
  - As many as 100,000 cycles projected!
  - -20C to +45C Operation

- **Altris** (Sweden) (Focus on sustainable materials)
  - Prussian White (Fully Reduced and sodiated PB)
  (Pilot Line underway)



*For Supercapacitors Technology Assessment:https://www.energy.gov/oe/storage-innovations-2030

SuperCapacitors



- Critical infrastructure: provide ride-through power (e.g. during generator start up).
- Industrial and manufacturing: ensure constant voltage in variable-frequency drives that operate critical manufacturing; provide quick peaking power (e.g., for seaport cranes).
- Microgrids: used along with battery energy storage in microgrids and off-grid remote facilities to buffer current during equipment start-up and during line faults.
- Bulk power systems: used in a flexible alternating current transmission system (FACTS) and in high-voltage direct current transmission to alter the impedance of the line in order to regulate power factor and transmission capabilities by injecting or absorbing reactive power; used in renewable systems integration for improving power quality.

*For Supercapacitors Technology Assessment:https://www.energy.gov/oe/storage-innovations-2030

Batteries for Long-Duration Energy Storage?

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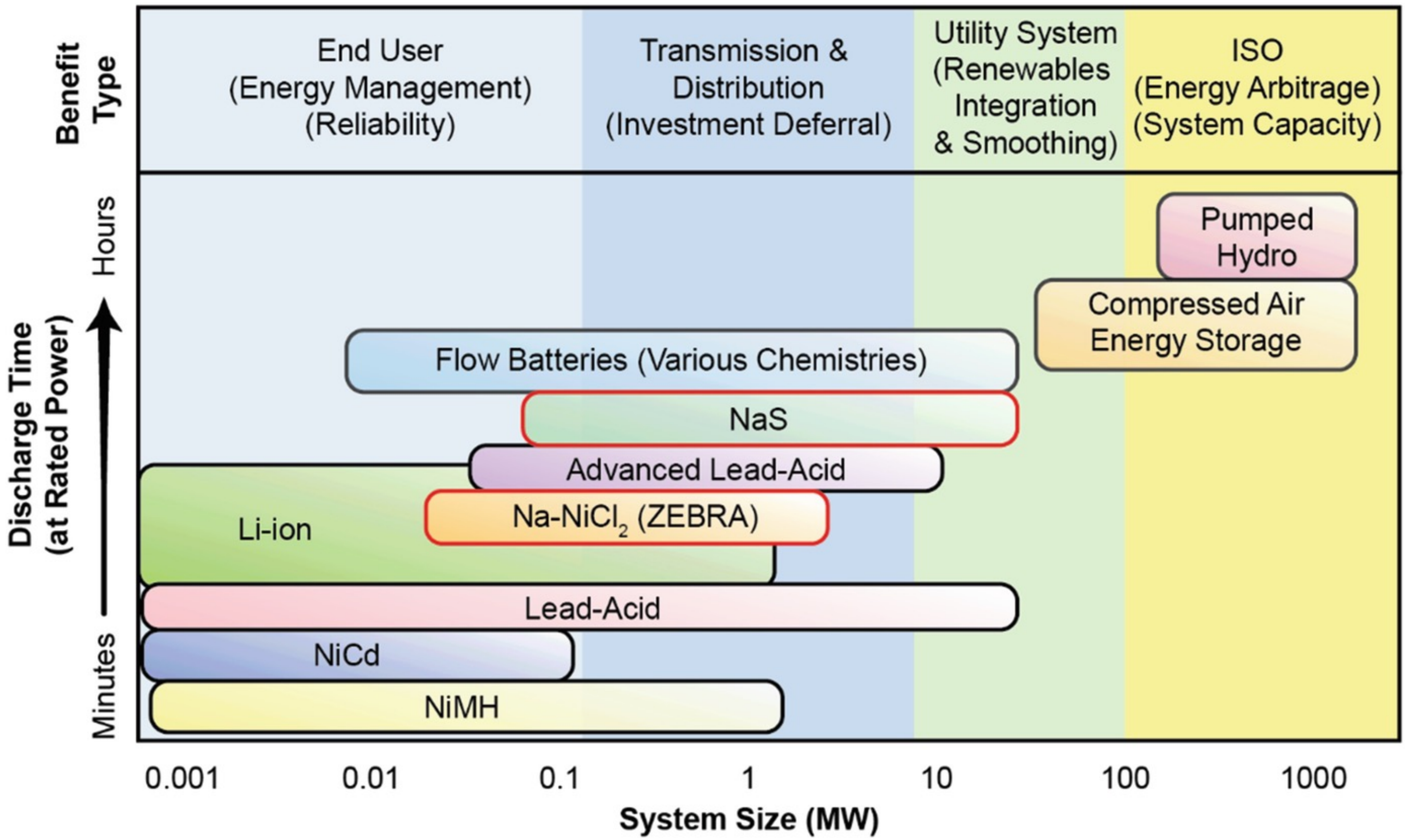
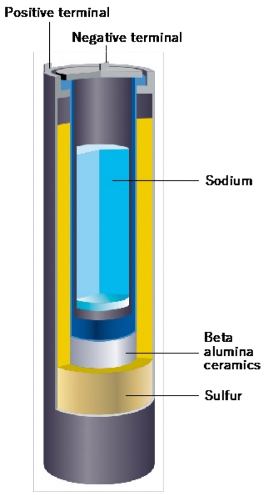
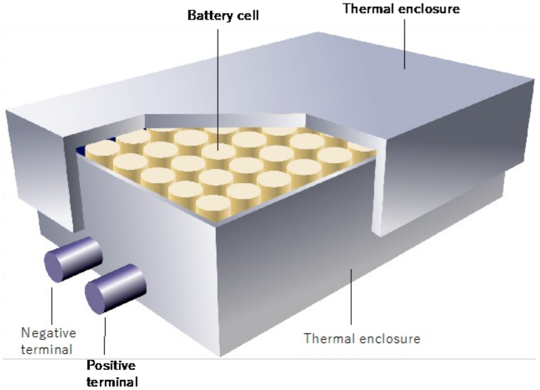


Molten Sodium Batteries





	Practical Energy Density (Wh/L)	Expected Cycle Life (cycles at 80% DOD)	Expected Lifetime (years)	Operating Temperature (°C)	Suitable Ambient Temperature (°C)	Discharge Duration (at rated power)	Round Trip Efficiency
NaS	300-400	7,300	15	300-350	-20 to + 40	6-7 hours	80%
$Na\text{-}NiCl_2$	150-190	>4500	20	270-300	-20 to +60	2-4 hours	80-85%

NaS and $Na\text{-}NiCl_2$ batteries are used today for Renewables Integration, Grid Services, Consumer Applications, and Microgrids

Na-S

NGK INSULATORS

BASF We create chemistry

$xS + 2Na \leftrightarrow Na_2S_x$ ($3 \le x \le 5$) E_{cell} ~2.08 V at 350°C

- ✓ 700 MW/4.9 GWh of deployed storage in over 200 cites globally
- ✓ Recent 108 MW, 648MWh system in Abu Dhabi

$Na\text{-}NiCl_2$

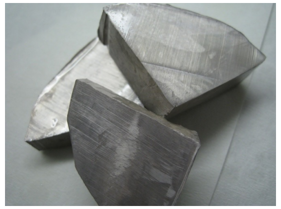
FZSoNick

$NiCl_2$ (s) + 2Na (l) $\leftrightarrow$ 2NaCl + Ni (s) E_{cell} ~2.58 V at 300°C

- ✓ Extensive global deployments for grid-based and BTM use.
- ✓ Recyclable
- ✓ UL1973, UL9540A, other safety certifications

- Na-S takes advantage of low cost materials, but introduces some safety concerns.
- $Na\text{-}NiCl_2$ is a safer, greener chemistry, but high, variable cost of Ni is a challenge.

Sodium Batteries Overview



Sodium (Na) is >1000X more abundant than Lithium – just in the Earth's crust

- 6th most abundant element in Earth's crust and 4th most abundant in the oceans
  - 93% of soda ash (Na_2CO_3) reserves are in the U.S. (Hirsh, et al. Adv. Energy. Mater., 2020, 10(32), 202001274.

Sodium Metal Anode (e.g., Molten Sodium)

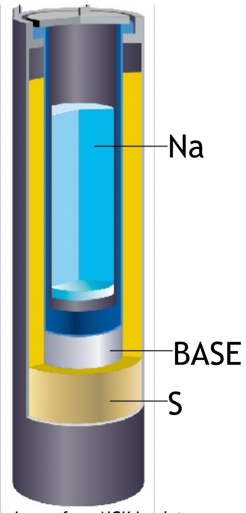


Image from NGK Insulators

"Mature" High-Temperature NaS and Na-$NiCl_2$ deployments support:

- Renewables Integration
- Grid Services
- Microgrids
- Behind-the-Meter Applications
- Select Mobility

BASF We create chemistry

NGK INSULATORS

FZSoNick

Emerging systems show promise

- Low-temperature molten salt
- Molten Na flow batteries
- Solid State Na batteries

INLYTE ENERGY

ENLIGHTEN®

ADENA POWER

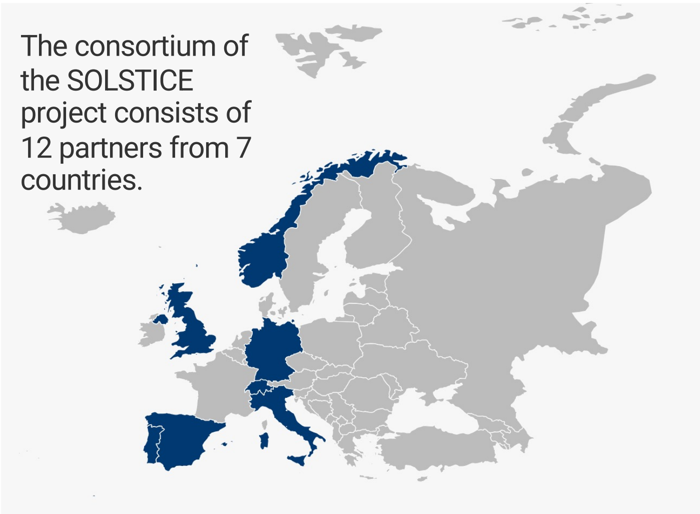
SOLSTICE

Sodium-Zinc molten salt batteries for low-cost stationary storage

SOLSTICE

(Na-Zn) high temperature batteries (molten and ZEBRA

LiNa Energy



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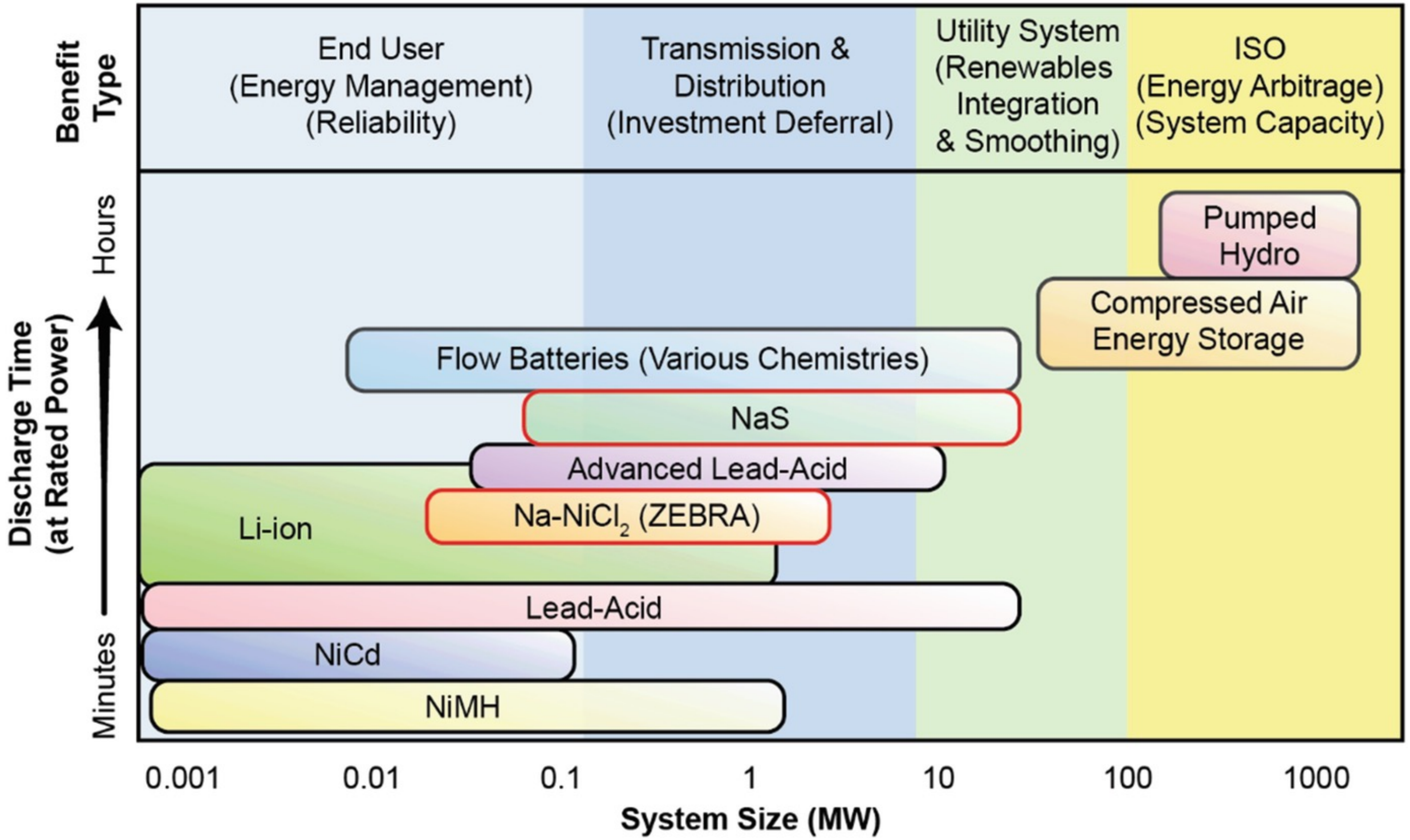


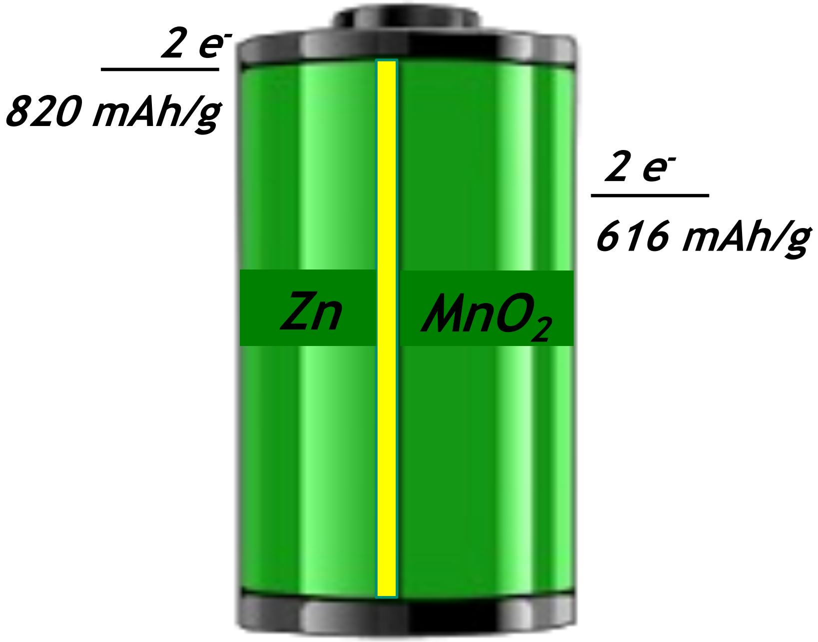
Rechargeable Alkaline Zn-MnO_2 Batteries

Promising large-scale storage candidate

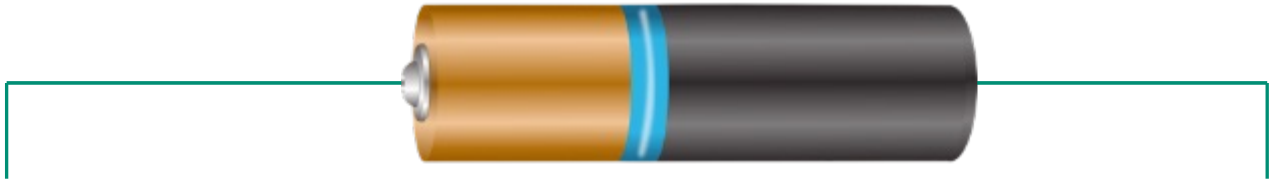
- Low cost: traditional primary batteries @ $18/kWh
- Long shelf life, lowest cost of materials, lowest manufacturing expenses, established supply chain
- Can be scaled to large form factors
- Limited thermal management required compared to Pb or Li
- Safer, environmentally friendly (EPA certified for landfill disposal, non flammable)

Challenge: Re-chargeability = Battery Lifetime & Cost

Energy density of up to 400 Wh/L or 150 Wh/kg: comparable to Li-ion



Zn-MnO_2



MnO_2

- ~ $1-2 per lb
- Mn, 12th most abundant
- 16,000,000 tons (2012)
- Safe

KOH

- Potash ~ $260 per ton
- Abundant
- Aqueous
- > Safety than Li-organics

Zn

- ~ $1 per lb
- 25th most abundant
- 13,000,000 tons (2012)
- Safe

SNL Principal Investigator: Dr. Tim Lambert (tnlambe@sandia.gov)

Rechargeable Zn-based Batteries

- Low-cost, high energy density, safety, and global availability have made Zn-based batteries attractive for more than 220 years!
- *Diverse* Zn-batteries offer a range of properties to meet growing demand across varied applications:

✓ Renewables integration (including microgrids)

✓ Backup power (assurance for data centers, telecom, etc.)

✓ Grid stability and resilience

✓ Behind-the-meter applications for residential and commercial applications (Lower energy cost, power quality, etc.)

Zn-MnO_2

URBAN ELECTRIC POWER

1 MWh UEP alkaline battery backup system for the San Diego Supercomputer Center (CA).

ZELOS

Zn-Ni

ZincFive

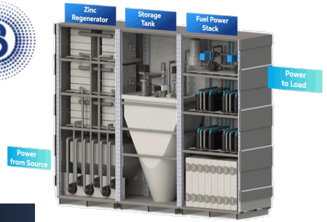
ZAF Energy Systems

Æsir Technologies, Inc.

ENZINC

Zn-Air

ZINC8

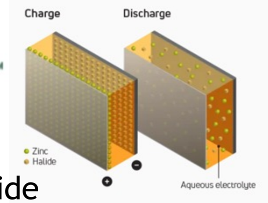


ZAF Energy Systems

e-zinc

Zn-Br

eos



35 MWh EOS Zn-Br system planned to provide 10 hour storage for solar-plus-storage microgrid with Indian Energy (CA).

redflow

Zn-Br flow battery installation

Zn-ion

SALIENT ENERGY

enerpoly

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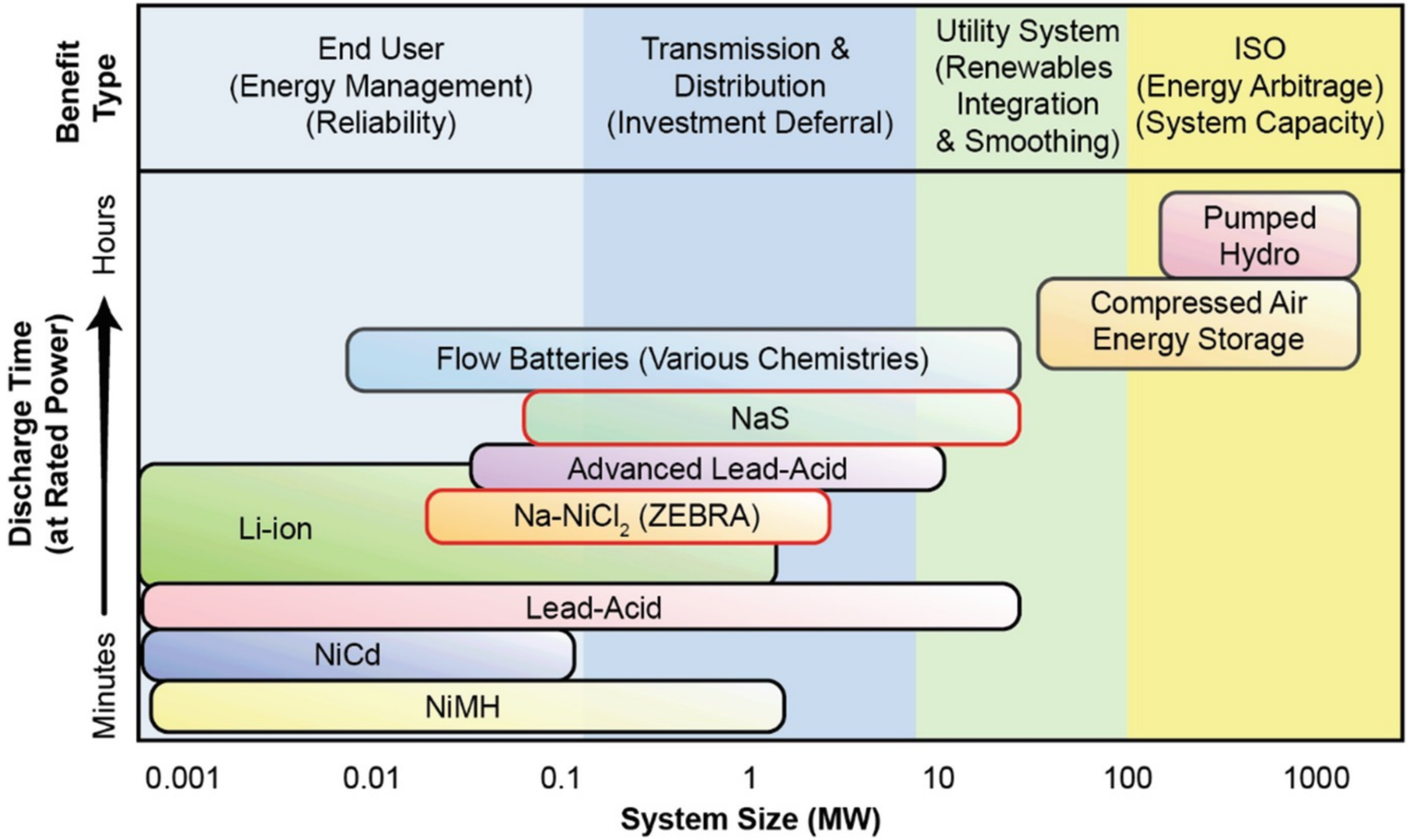
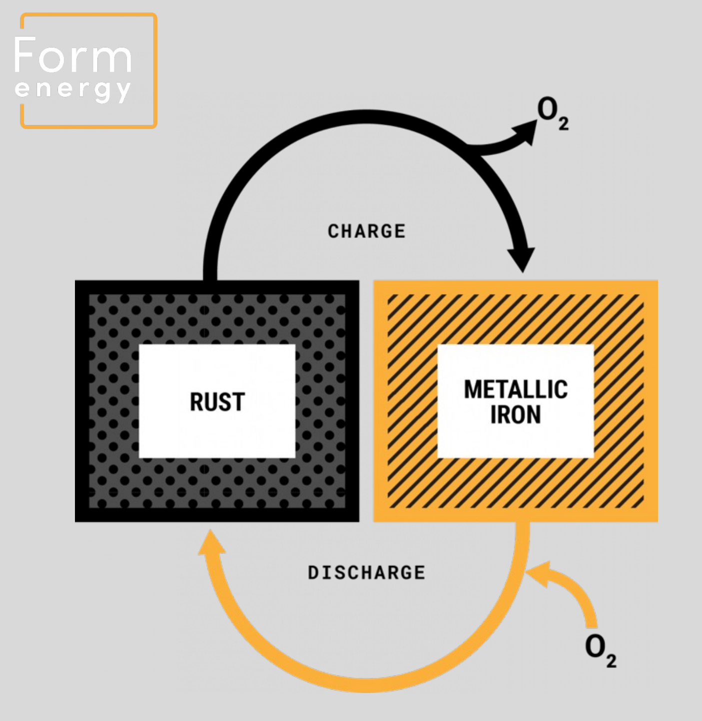


Air-Based Batteries

- Utilize air-based cathode and earth-abundant metal anode.
- Challenges around reversible, fast kinetics of oxygen evolution reaction (OER) or oxygen reduction reaction at cathode(s).
- Air-breathing cathodes also must address side reactions with variable atmospheric conditions.

Zn-Air Batteries targeting scalable storage up to 24 hours.

Fe-Air: Targeting 100 hour storage



Form Energy's large-scale manufacturing facility in Weirton, WV

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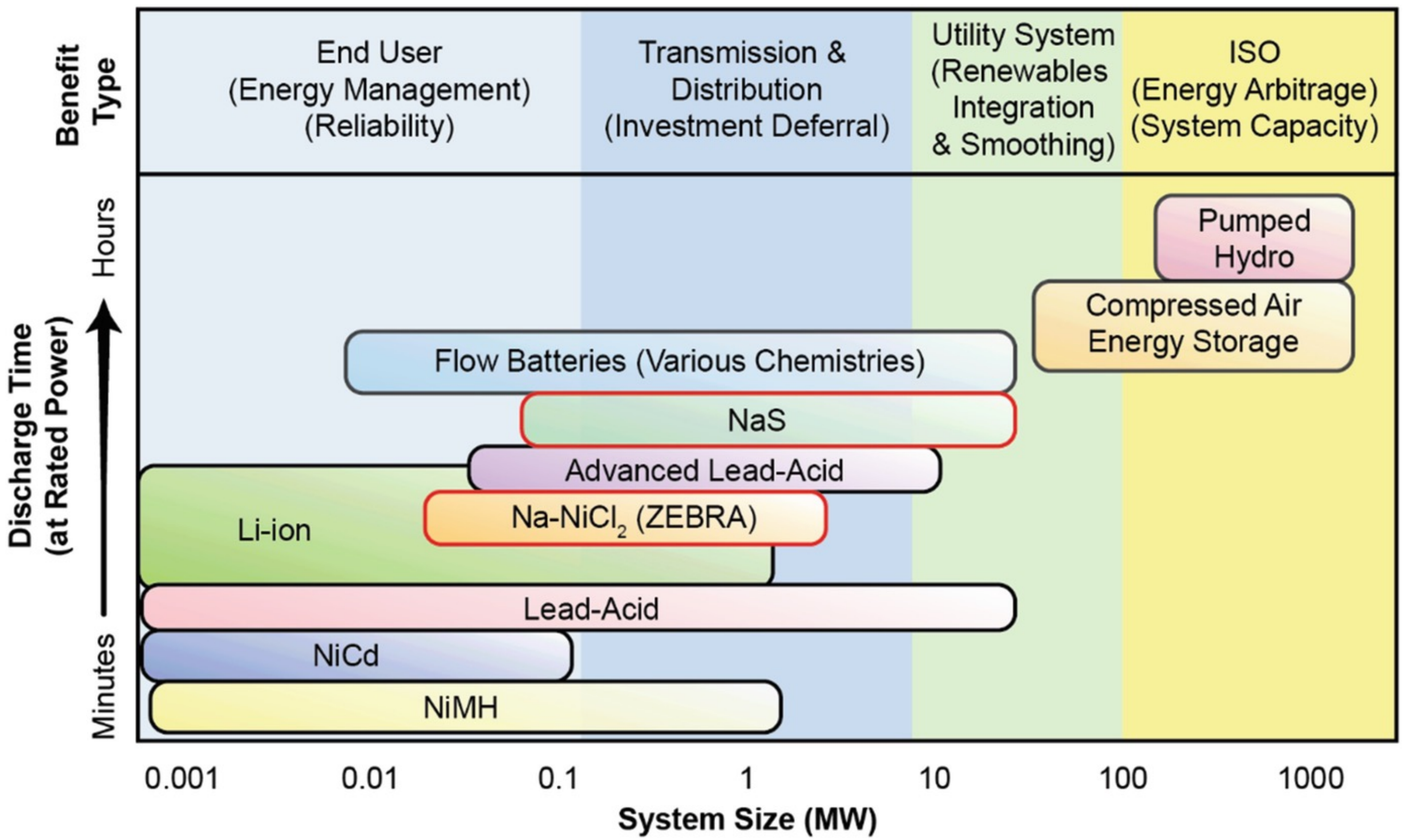
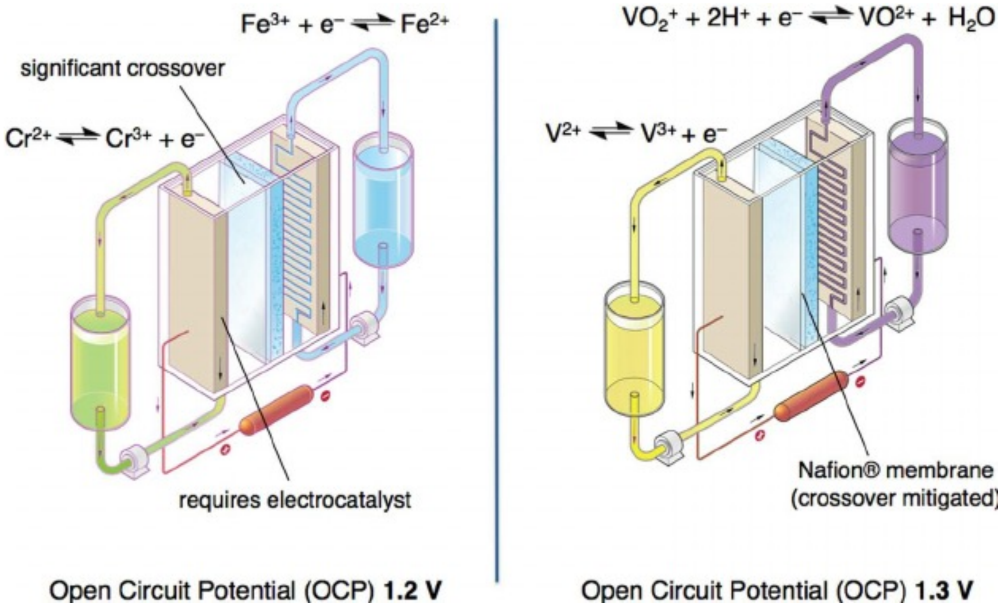


Redox Flow Batteries

- Widely commercialized (>100 companies)
  - **Vanadium** (Largest: 100MW / 400MWh (Dalian, China))
  - Zn-Br (~500kW/2MWh) – RedFlow
    - 2,959 MWh stored energy
    - 285 active deployments
  - Fe-Cr (~250kW / 1MWh)
  - Fe-Flow (ESS, Inc.)
  - Transition Metal-Chelate Chemistry
  - Non-aqueous RFBs?
    - Higher voltages possible, but more expensive



- Independently tunable power and energy
- Challenges
  - Energy Density
  - Cost
  - Reliability

redflow

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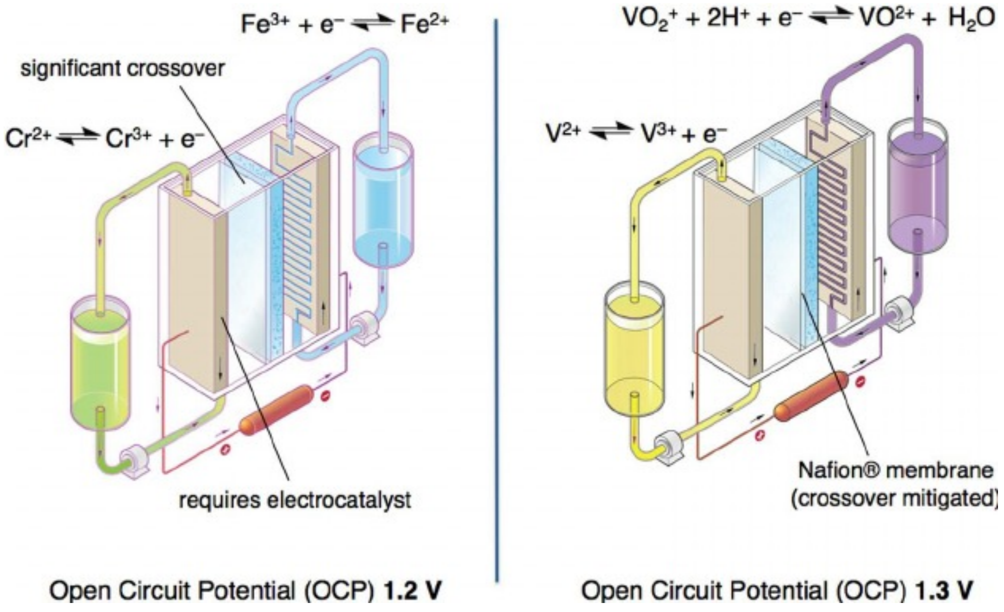

- Independently tunable power and energy
- Challenges
  - Energy Density
  - Cost
  - Reliability

- Dalian Flow Battery Energy Storage Peak-shaving Power Station
- Power up to 200,000 residents per day

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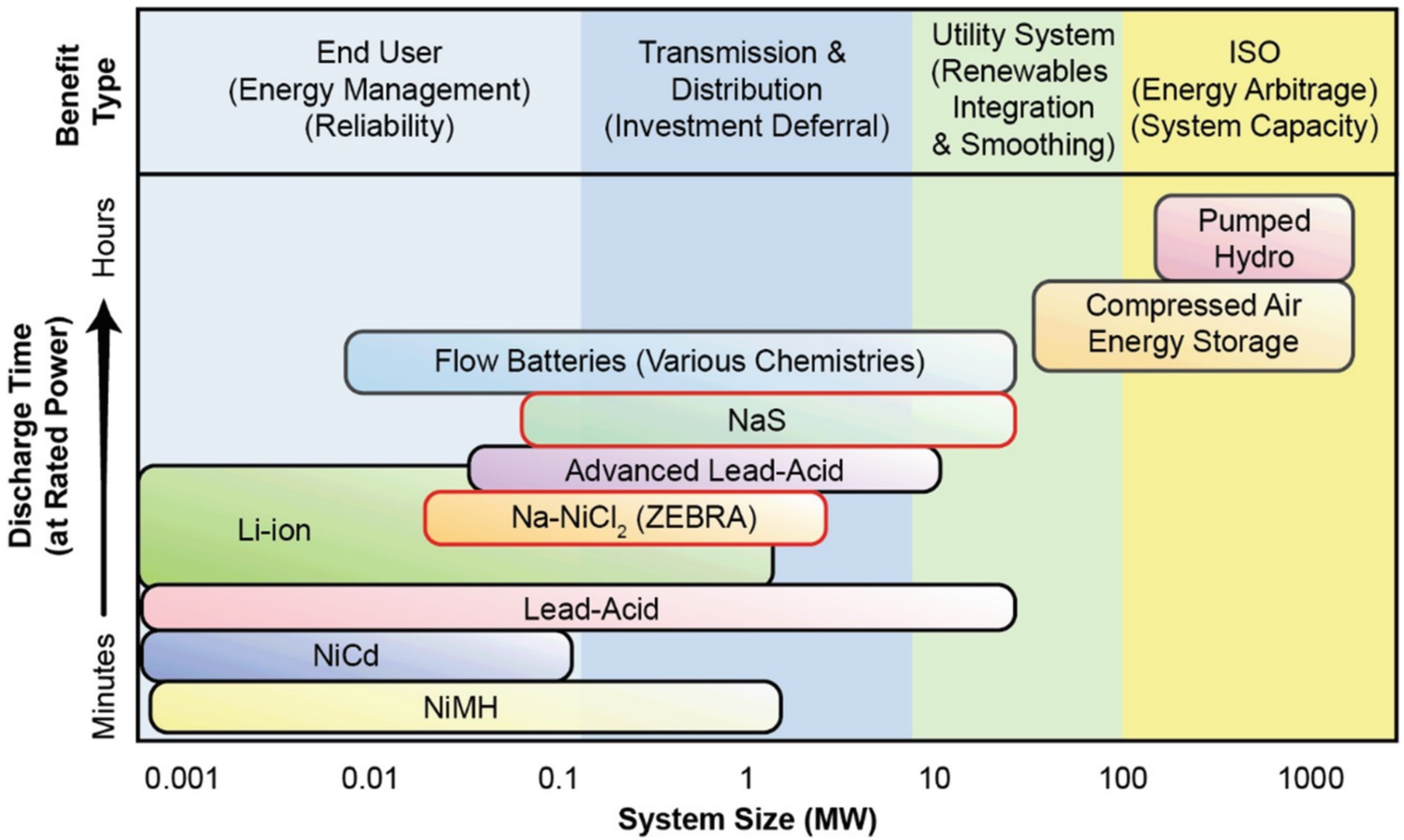
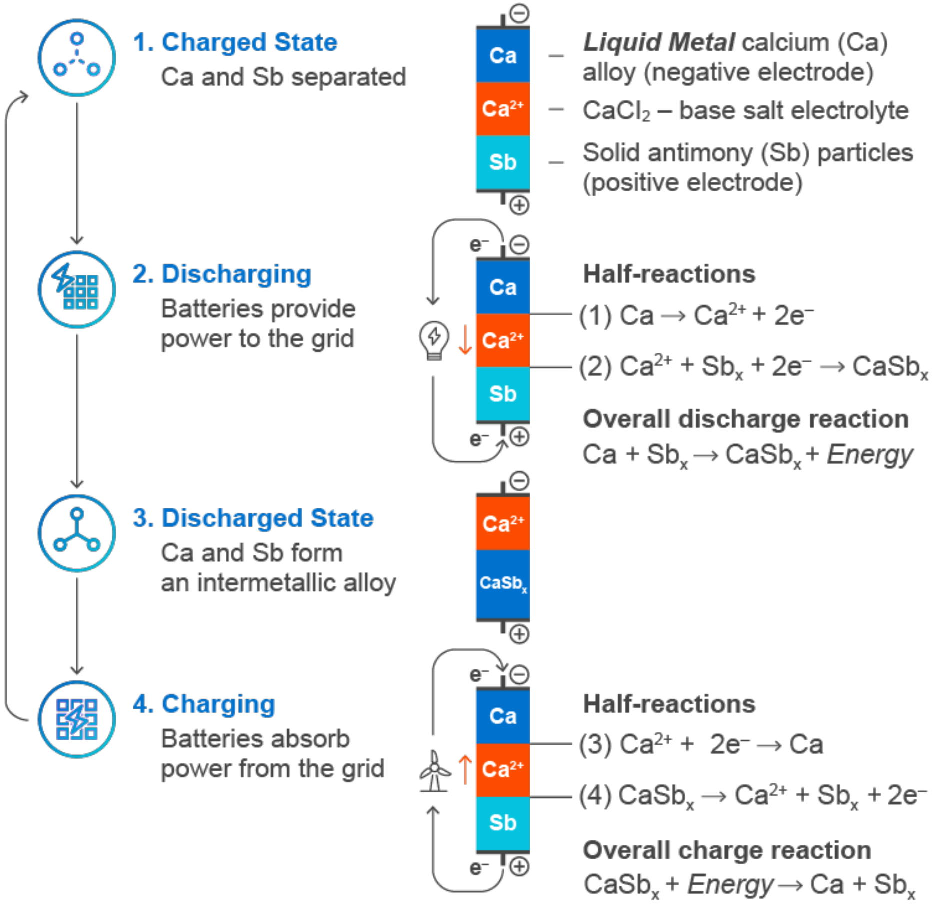


Liquid Metal Batteries



Ambri-based system

Insulated container with outer wall at ambient temperature

Projected System Specifications

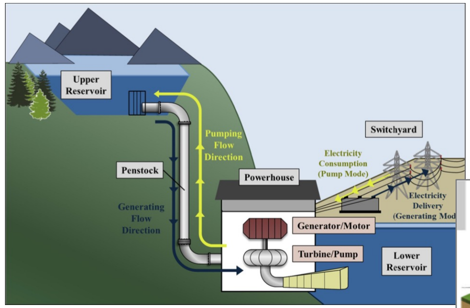
Power at rated energy	250 kW
Energy at Cp/4	1 MWh
Voltage	550 - 1150 VDC
External temperature range	-50°C to 100°C
DC-DC Efficiency	80% to 90% from C/4 to C/12
Internal operating temperature	485-525°C
Response time	Instantaneous
Dimensions	10' x 10' x 8' container
Design life	20 years

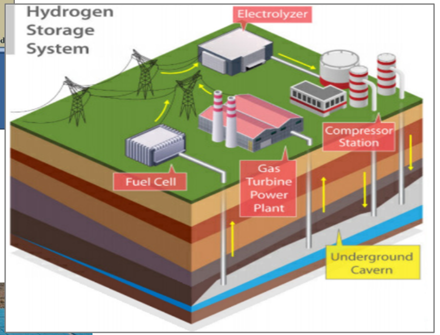
Currently supporting datacenters (e.g., Microsoft), and renewable energy demonstrations by Xcel energy (CO). A 300MW, 1.2GWh system that will be installed to support wind and solar renewables integration South Africa beginning in 2024.

Ambri

We Have a Growing Number of Current and Emerging Storage Options!

- Gravity-Based/Mechanical Storage
- Chemical and Hydrogen Storage
- Thermal Storage
- Electrochemical (Batteries) Storage





Thanks!

Erik Spoerke's work at Sandia National Laboratories is supported through the U.S. Department of Energy's Office of Electricity, including the Energy Storage Program, managed by Dr. Imre Gyuk.

Contact: Erik Spoerke (edspoer@sandia.gov)

https://events.naatbatt.org/

https://naatbatt.org/join-a-committee/

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Backup Slides

Considerations in Na-Ion Battery Development

Resource

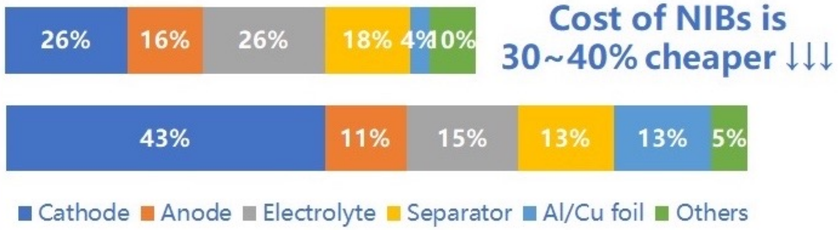
	Crustal Abundance	Distribution	Price US$/kg
Na	2.75%	Everywhere	0.3 (Na_2CO_3)
Li	0.0065%	75% in Americas	20 (Li_2CO_3)

Current Collector

NIBs: Al foil (cheap) for both positive and negative electrodes

LIBs: Cu foil (expensive) for negative and Al foil for positive

Cost of NIBs vs. Cost of LIBs



Cost of NIBs is 30~40% cheaper ↓↓↓

Tips: NaCuFeMnO and Soft-Carbon are used in NIBs; $LiFePO_4$ and Graphite are used in LIBs.

NIBs can be fully discharged for shipping, LIBs must be maintained at 30% SOC.

	LABs	<	SIBs	<	LIBs
Energy Density	30~50 Wh/kg		100~150 Wh/kg		150~250 Wh/kg
Voltage	~2.1 V		2.8~3.5 V		3.0~4.5 V
Life	~300 cycles		2000+ cycles		3000+ cycles

Tips: The above parameters of different materials varies.

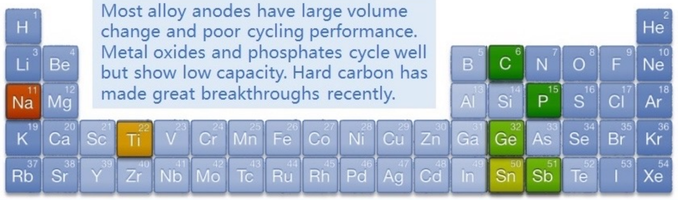
Anode Materials for NIBs

Transition Metals Are Dispensable for Anodes.

100+ Anode materials have been reported:

- Carbon (e.g. hard/soft carbon)
- Alloy (e.g. Sn, Sb, SnSb)
- Transition Metal Oxides (e.g. $Na_{0.66}Li_{0.22}Ti_{0.78}O_2$)
- Transition Metal Phosphates (e.g. $NaTiOPO_4$)

Longer Cycling Life
Lower Cost
Faster Charge/Discharge



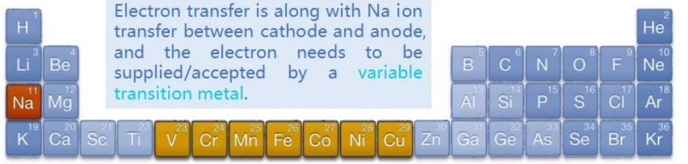
Cathode Materials for NIBs

Different Structure, Indispensable Transition Metals

100+ cathode materials have been reported:

- Transition Metal Oxides (e.g. $NaMnO_2$)
- Transition Metal Phosphates (e.g. $Na_3V_2(PO_4)_3$, $Na_2MnP_2O_7$)
- Transition Metal Sulfates (e.g. $Na_2Fe_2(SO_4)_3$)
- Transition Metal Cyanates (e.g. $Na_2FeFe(CN)_6$)

Higher Energy Density
Longer Cycling Life
Lower Cost



Application of NIBs

Wind power/
Solar power station
Household energy storage

Large-Scale Energy Storage

Electric cars
Electric ship
Delivery vehicles
Agricultural vehicles

Low-Speed Vehicles

- Global sodium-ion batteries market has been estimated to reach USD 1.01 billion in 2021.
- Projected to grow at a CAGR of 19.3% during the forecast period from 2021-2030.

Quince Market Insights, 2021

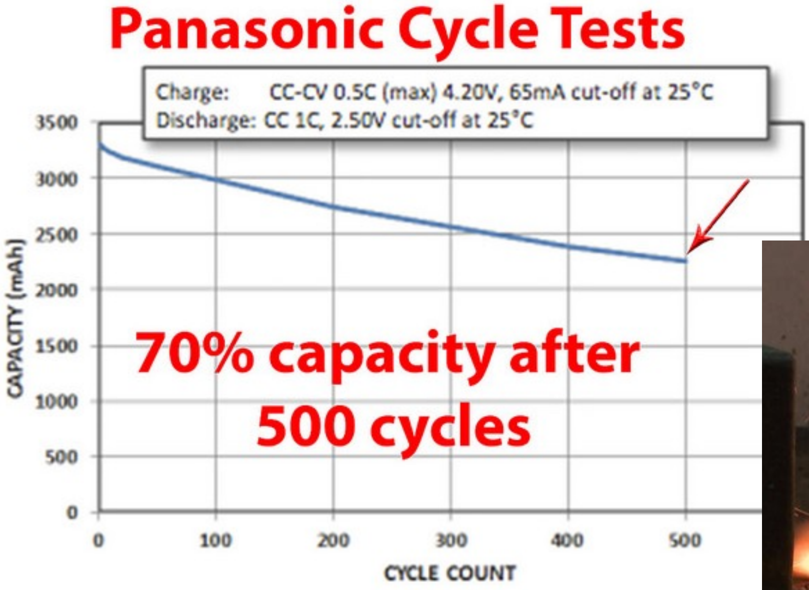
Slide data from https://www.hinabattery.com/en/index.php?catid=12

Li-Ion Batteries: Widely Successful, but Some Vulnerability

Li-ion (E_{cell} ~ 3.6V)

$LiC_6 + CoO_2 \leftarrow\rightarrow C_6 + LiCoO_2$ (example)

- Geopolitical material sourcing
- Safety (flammable organic electrolytes, thermal runaway)
- Cycle lifetime limited
- Cost?



Some longer-duration applications being pursued, but…

Despite a predominantly successful large scale deployment, a few notable "mishaps" reveal a vulnerability of Li-ion.

- Moss Landing (300 MW, California) Shut down in Sept, 2021. No fire, but system offline.
- Victorian Big Battery (300MW, Australia) Fire, August 2021.
- Carnegie Road (20MW, Liverpool, UK) fire in Sept, 2020.
- Approximately 30 large scale fires in South Korea from 2017-2019.
- McMicken (2 MW, Arizona) fire destroyed facility, hospitalized firefighters in April 2019.

Batteries Are Playing a Growing Role in Large-Scale Storage!

- Lithium-Ion Batteries
- Sodium-Ion Batteries
- Pb-Acid
- Zn-Based Batteries
- Metal-Air Batteries
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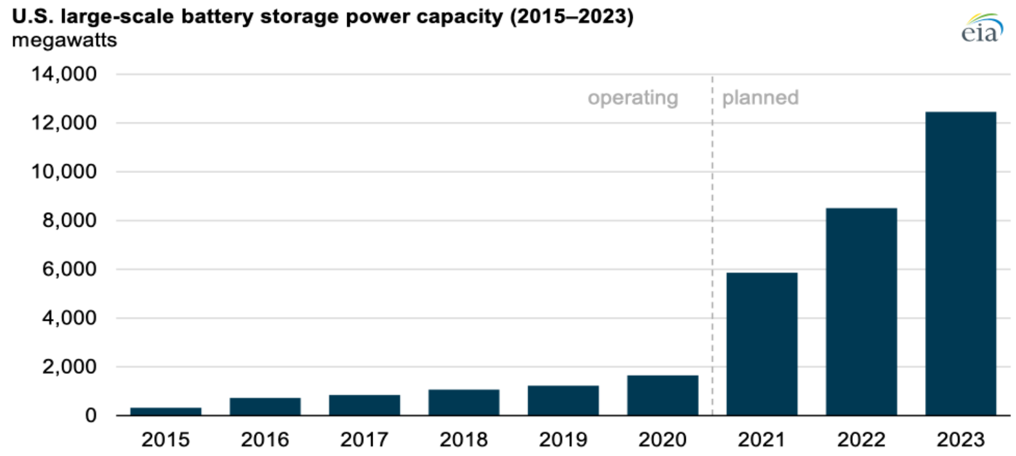
- Molten Metal Batteries

AUGUST 20, 2021

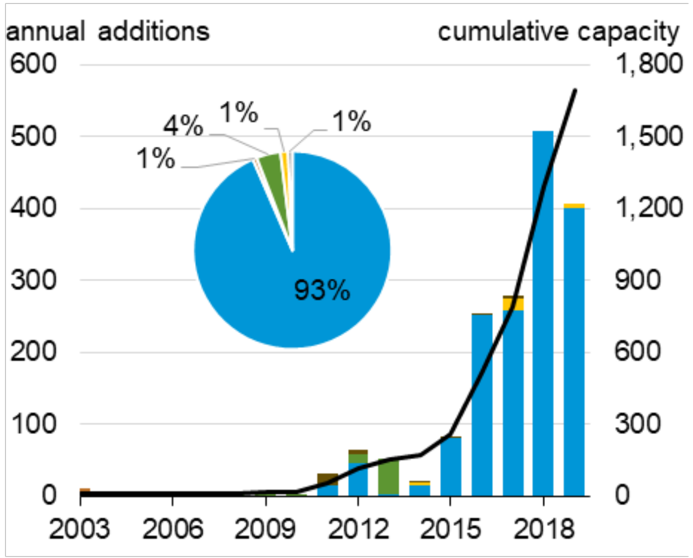
U.S. large-scale battery storage capacity up 35% in 2020, rapid growth set to continue



Source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*, December 2020

energy capacity (MWh)

lithium-ion
nickel-based
sodium-based
flow
other



Source: U.S. Energy Information Administration, 2019 Form EIA-860, *Annual Electric Generator Report*