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Advances in Energy Storage Technologies

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Sandia National Laboratories

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Energy Storage - Technology and Market Drivers

Rechargeable Battery Technologies

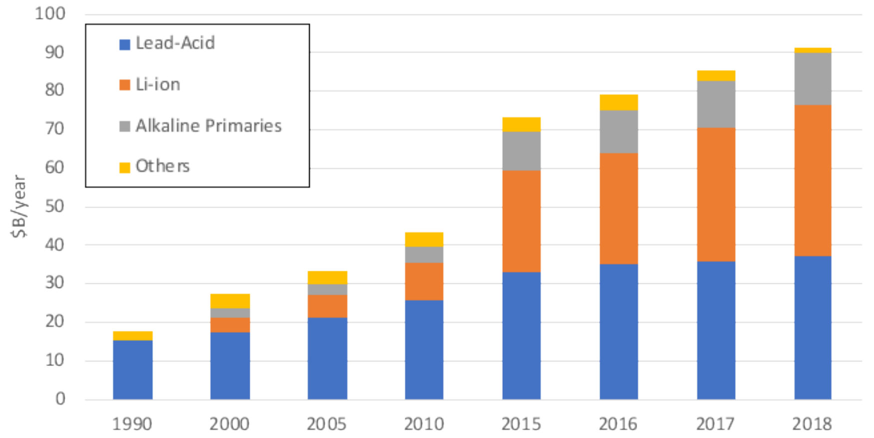
- Traditional batteries: Lead-acid, Zn-Ni, Ni-MH
- Lithium batteries: Li-ion, Li-S, Li-metal
- Emerging technologies such as solid state batteries, Na-ion batteries, flow batteries

Market Drivers

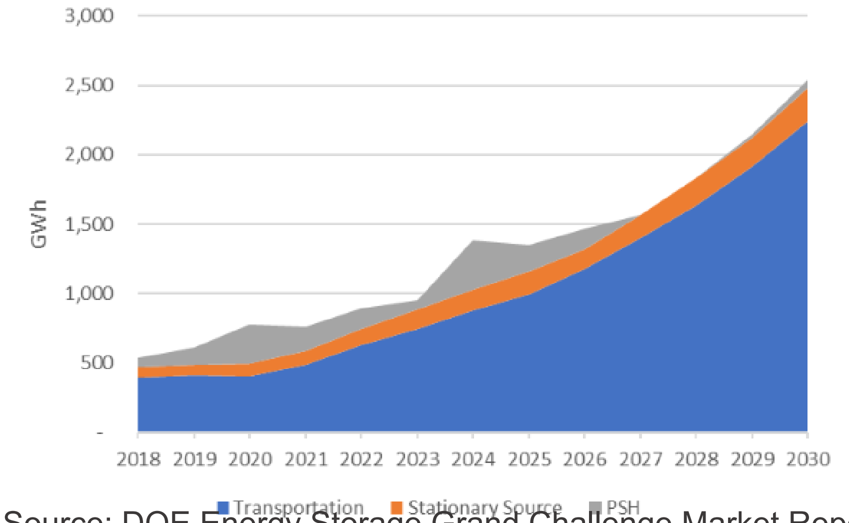
- Consumer Electronics: Rechargeable batteries key component for all things mobile
- Electric Vehicles: Rapid growth and the largest growth market
- Stationary Energy Storage: Grid energy storage emerging area

Demand driven by growth in the transportation sector

- Specific magnitude of growth in each sector depends on who you ask and when you ask them



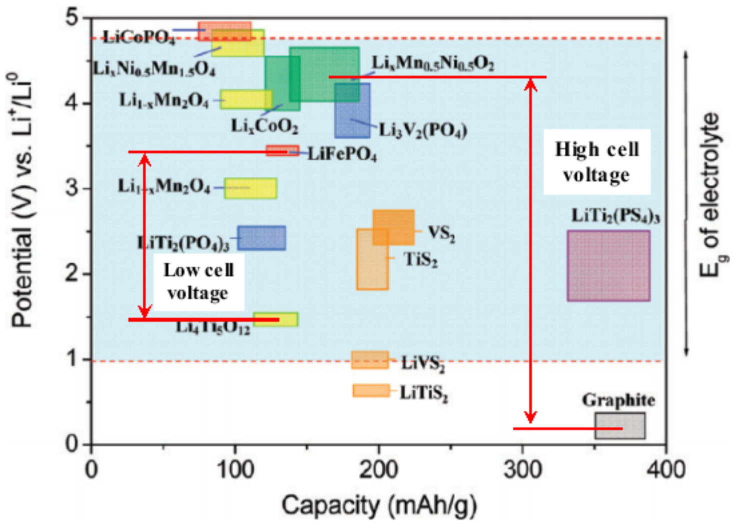
Source: Avicenne Energy, 2020

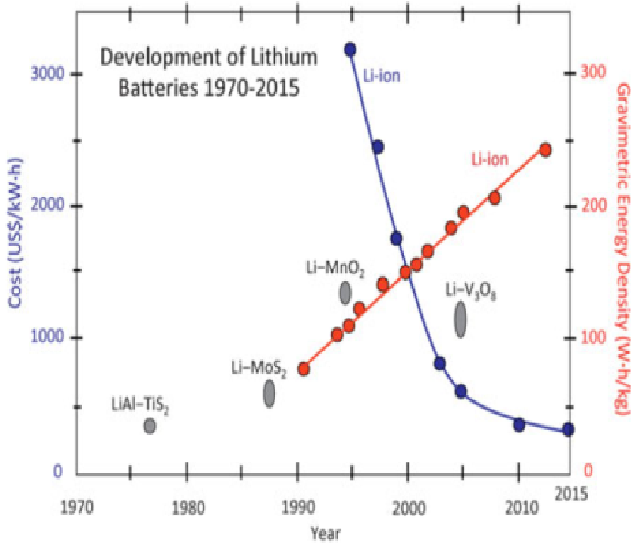


Source: DOE Energy Storage Grand Challenge Market Report, Dec. 2020

Li-ion Batteries

- Family of electrochemical systems
- Positive electrode
  - Metal-oxides (e.g. LCO, NMC, NCA)
  - Phosphates (e.g. LFP)
- Negative electrode
  - Graphite and other carbons
  - Silicon anodes (blended)
  - Lithium titanate
- SOA EV batteries - Specific energies near 250 Wh/kg
- 330-350 Wh/kg possible near term with composite anodes
  (Si-based anodes)
- 500 Wh/kg as a longer term goal based on significant improvements in electrode design and composition (e.g., lithium anodes), electrolyte formulations, and separator innovations
- Safety continue to be a significant concern



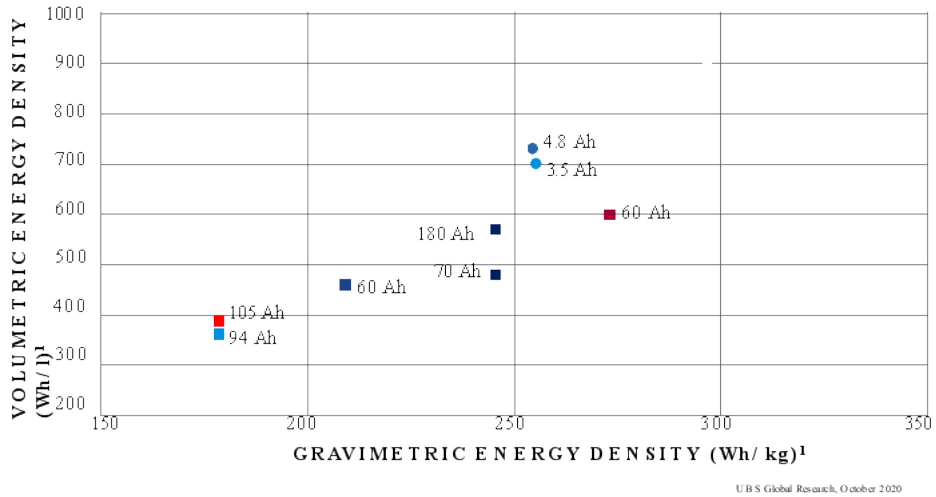


Source: Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015

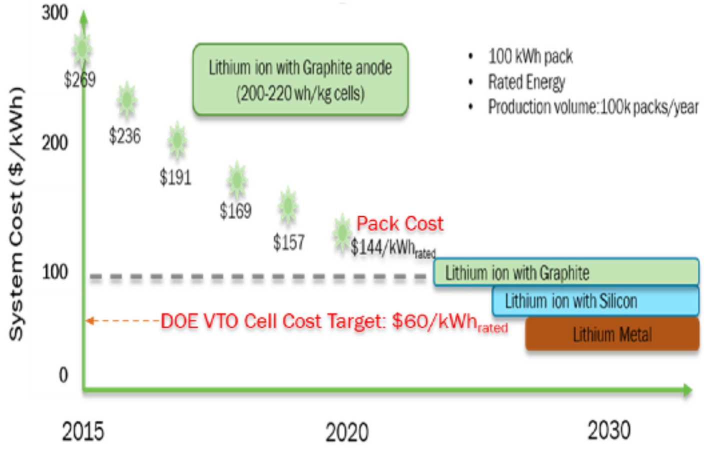
Trends in Li-ion Batteries: Materials Innovation

Current: Range of Li-ion cathodes for different applications

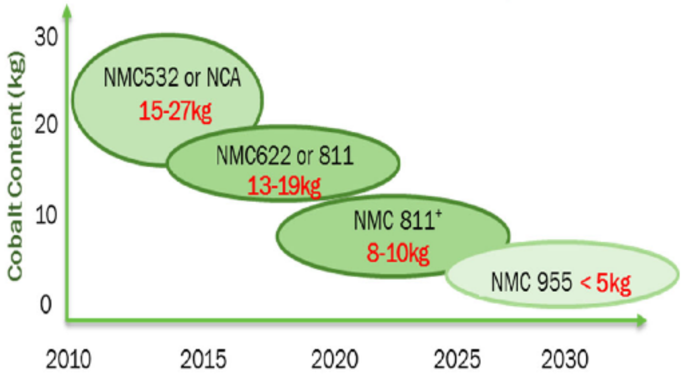
- EVs, NCA nickel-based for high energy density/long range, LFP by some
  - Reduce Co cobalt content, Introduce Si anodes
- LFP for buses, e-bike, stationary
- LCO for mobile, consumer electronics



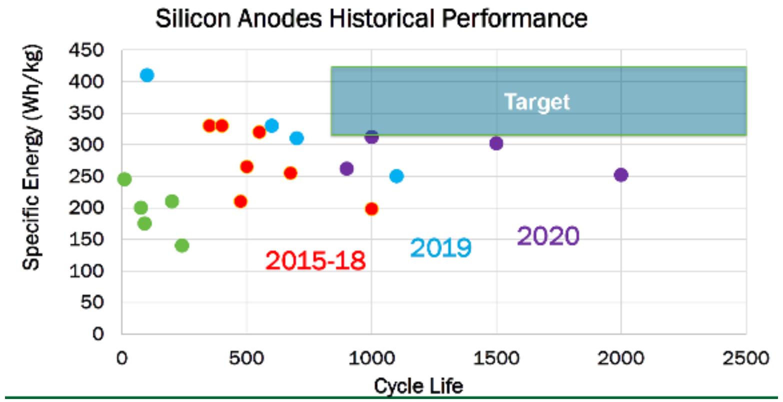
Energy density of commercial Li-ion cells (Sources: UBS and other industry data, 2020)



DOE VTO Li-ion cost roadmap



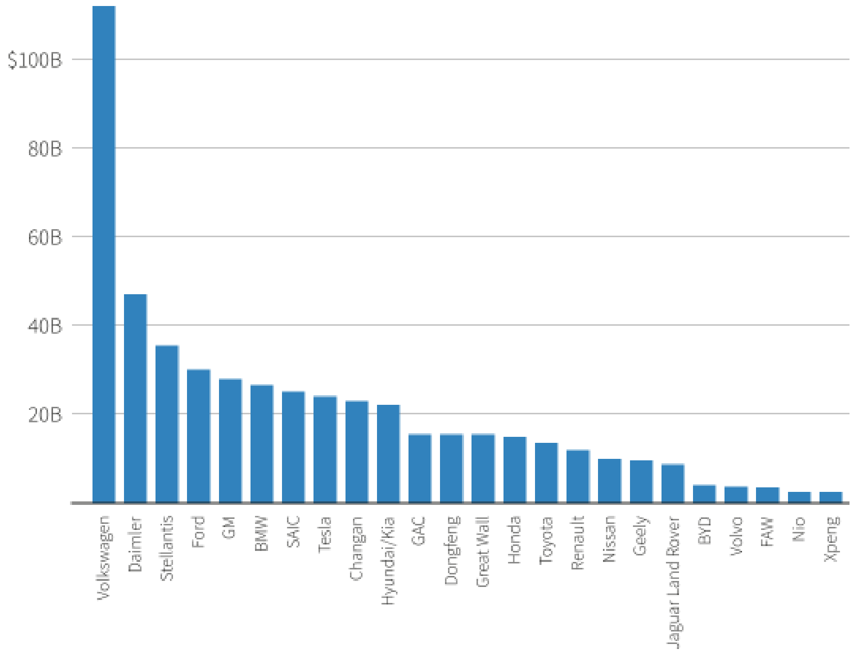
Reducing cobalt content is critical



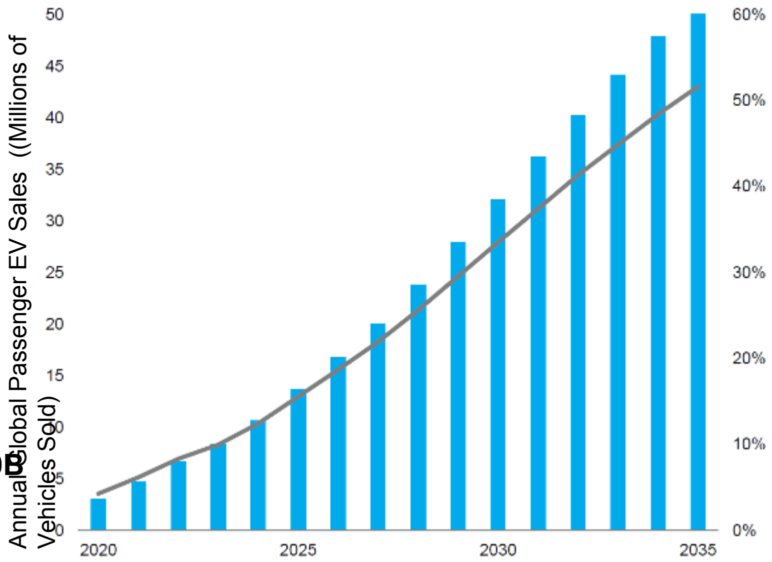
Advancements in silicon anodes

Source: D. Howell, DOE VTO , 2021

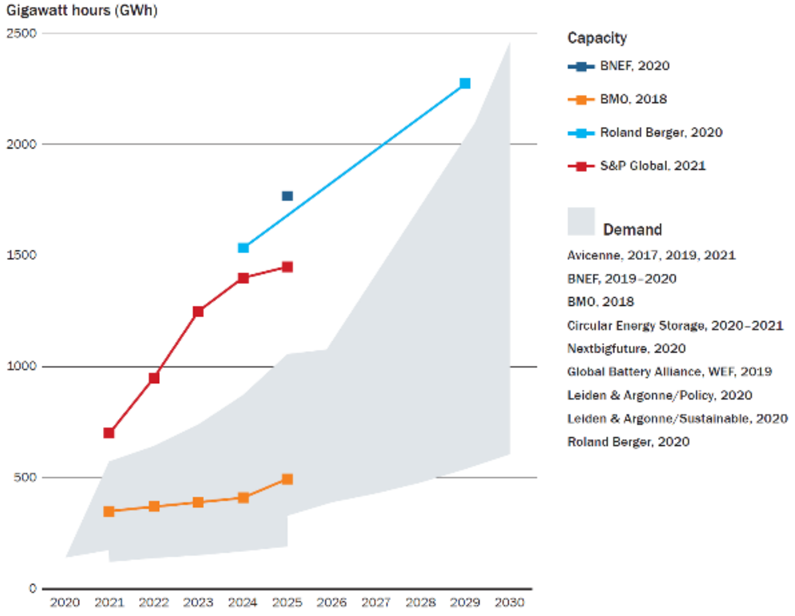
Trends in Li-ion Batteries: EVs Driving Manufacturing Growth



EV investment announcements by global automajors >$500B
Source: Reuters analysis, 2019 | 2021 update

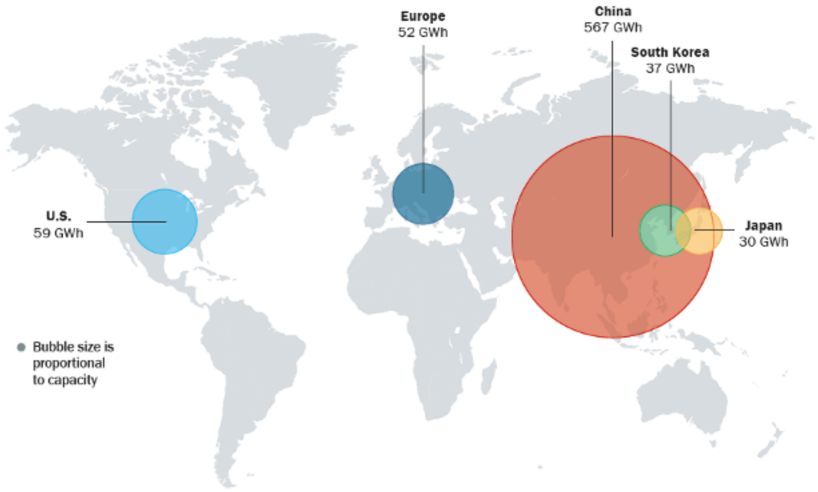


Annual Sales of Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles
Source: Bloomberg New Energy Finance BNEF, 2021



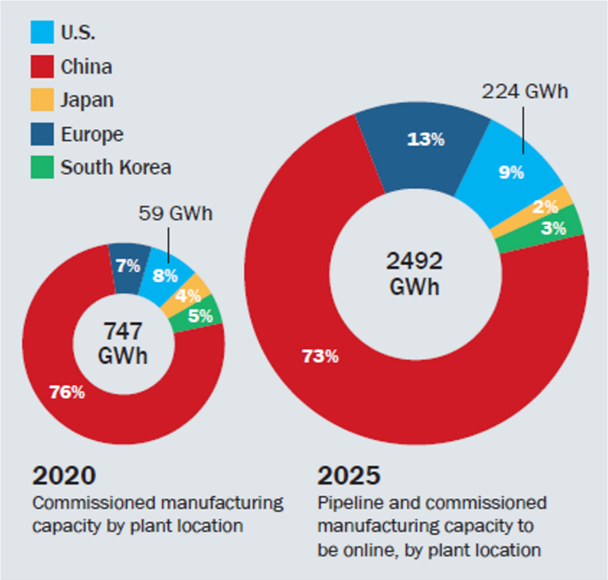
Global Lithium-ion EV Battery Demand Projections
(Source: Y. Zhou Y, D. Gohlke, L. Rush, J. Kelly, Q. Dai, *Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States: 2010–2020*. Argonne National Laboratory. 2021; ANL/ESD-21/3.

Trends in Li-ion Batteries: Global Growth



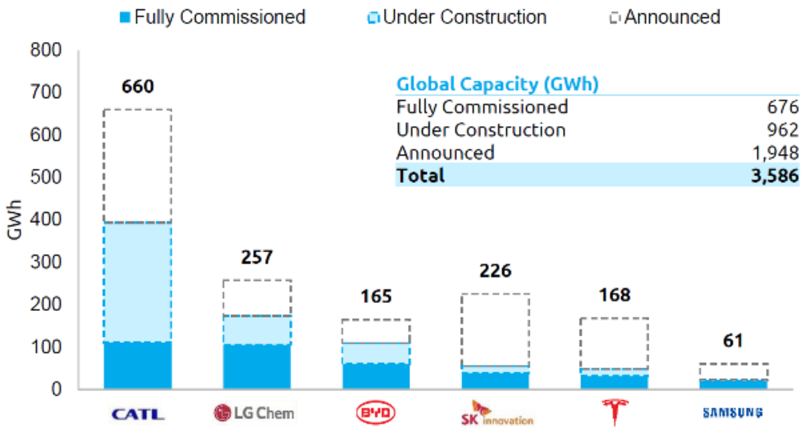
(Source: *Lithium-Ion Battery Megafactory Assessment*, Benchmark Mineral Intelligence, March 2021)

Cell Manufacturing Capacity by Country/Region in 2021



(Source: "Lithium-Ion Battery Megafactory Assessment"
Benchmark Mineral Intelligence, March 2021).

Current and projected cell Manufacturing Capacities by Countries and Regions

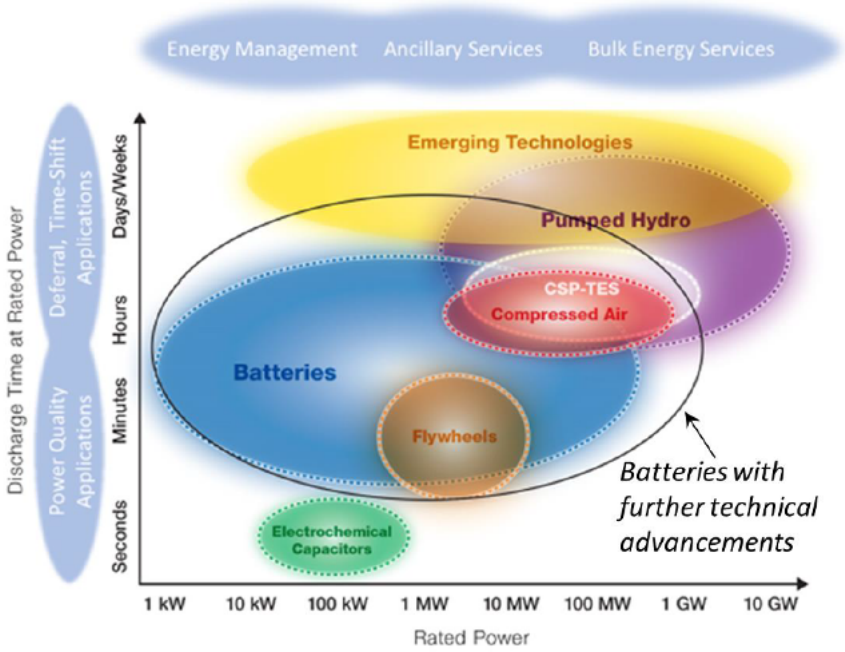


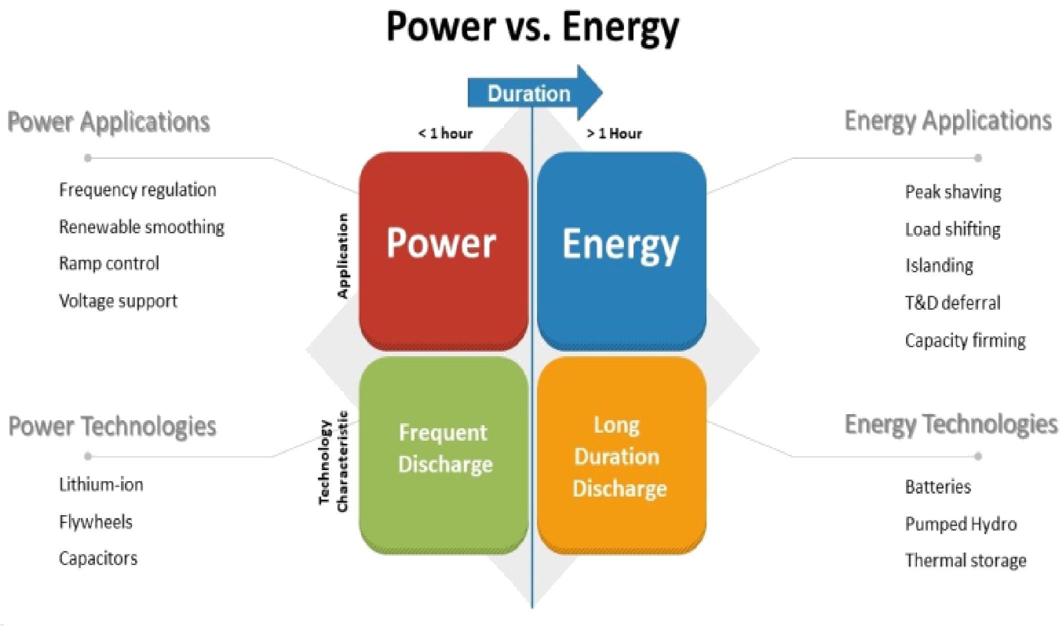
Cell Production Capacity By Manufacturer (Source: Bloomberg NEF, 2021)

Grid Energy Storage: Range of Technologies and Applications

- Range of battery technologies for short duration energy storage, seconds to days
  - Pumped hydro and CAES for hours-to-day long energy storage
  - No ready solutions for real long-duration and seasonal storage needs

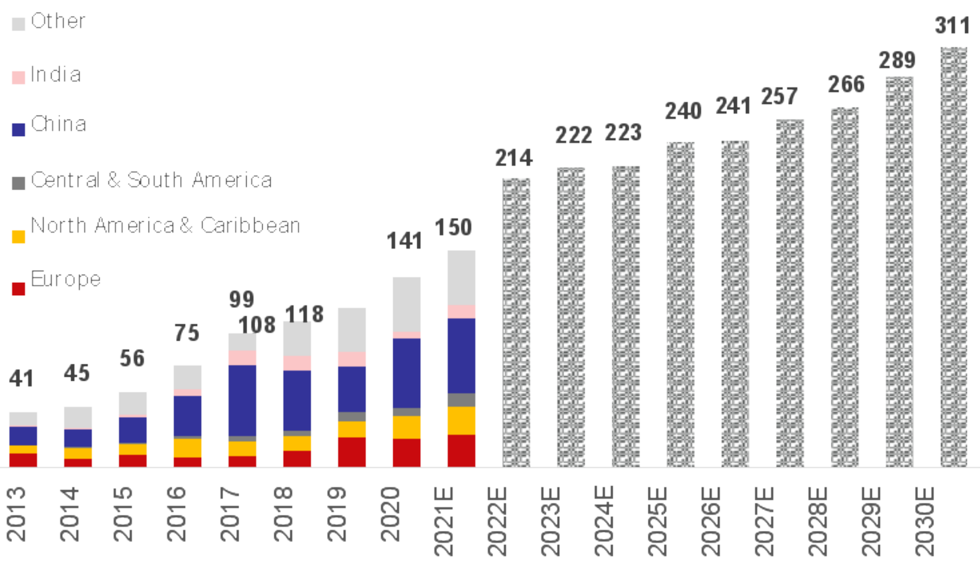
- Applications of energy storage systems
  - "Energy" applications: slower time scale, large amounts of energy
  - "Power" applications: faster time scale, real-time control of the electric grid





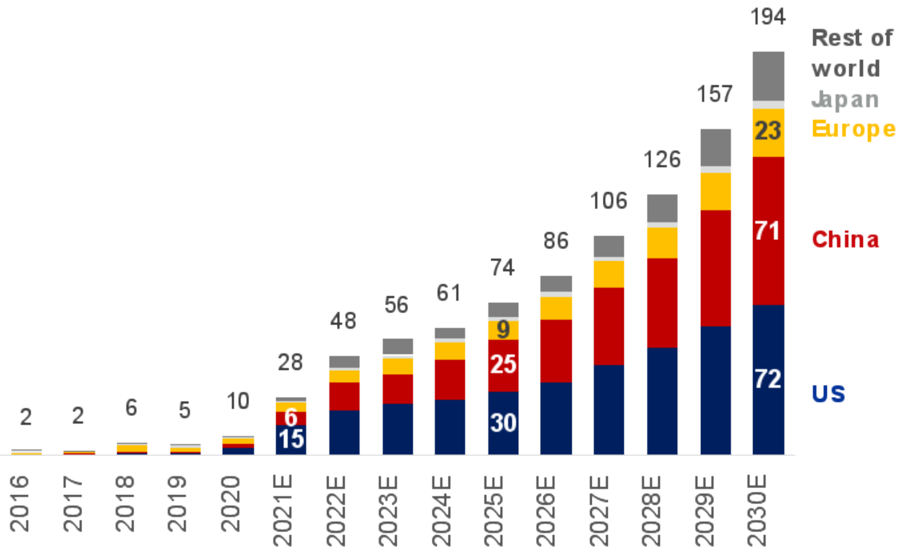
Sources: Potential Benefits of High-Power High-Capacity Batteries, DOE Report, Jan 2020, Energy Storage Primer, IEEE Power and Energy Society, 2020

Grid Energy Storage: Tied to Renewables and Grid Modernization



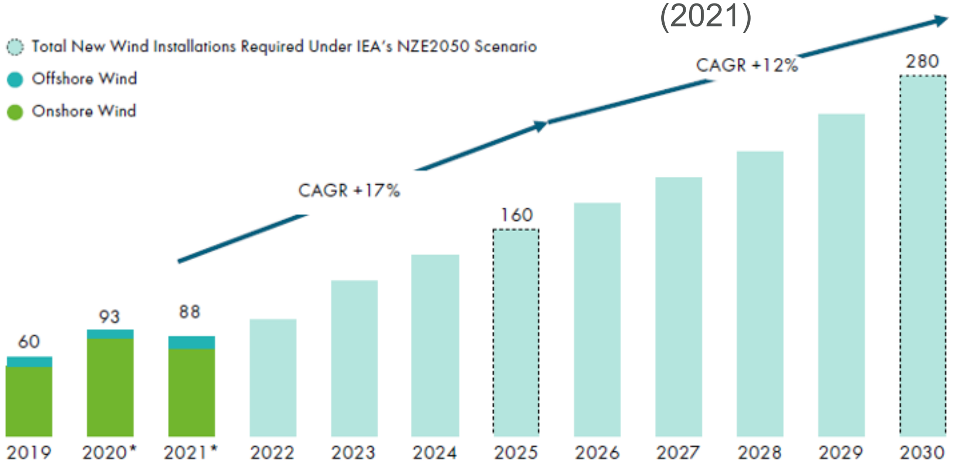
Global Solar PV Annual Installations, GW

Source: BNEF, Wood Mackenzie estimates (2021)



Projections for Energy Storage Annual Capacity Additions, GWh

Source: BNEF, Wood Mackenzie estimates (2021)



Global Wind Energy Report 2021
Source: Global Wind Energy Council (GWEC, 2021)

Solar PV installed capacity reaching 1 TW in 2022, projection of 3 TW of installed capacity 2030. Similar growth in on-shore and offshore wind.

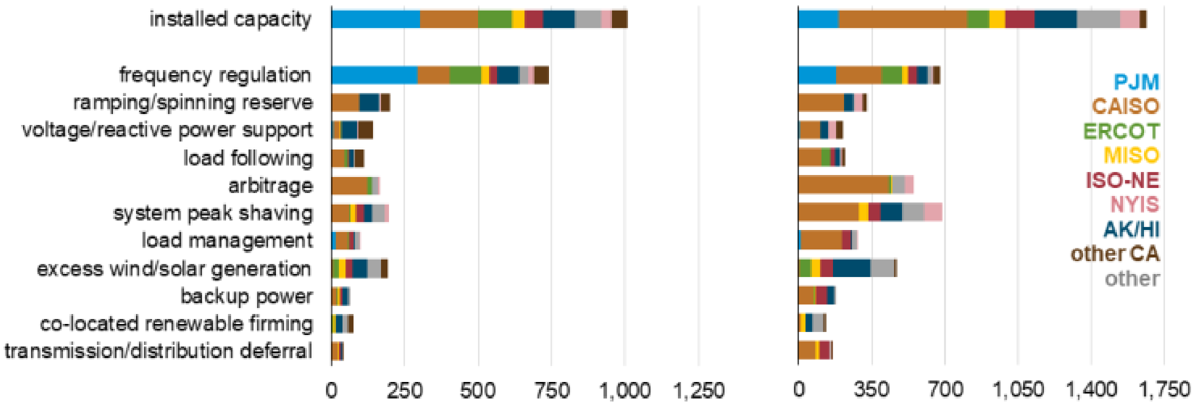
Battery energy storage installed capacity reaching 100 GWh in 2022, projections installed capacity of 1 TWh by 2030.

Pace of deployments of energy storage picking up

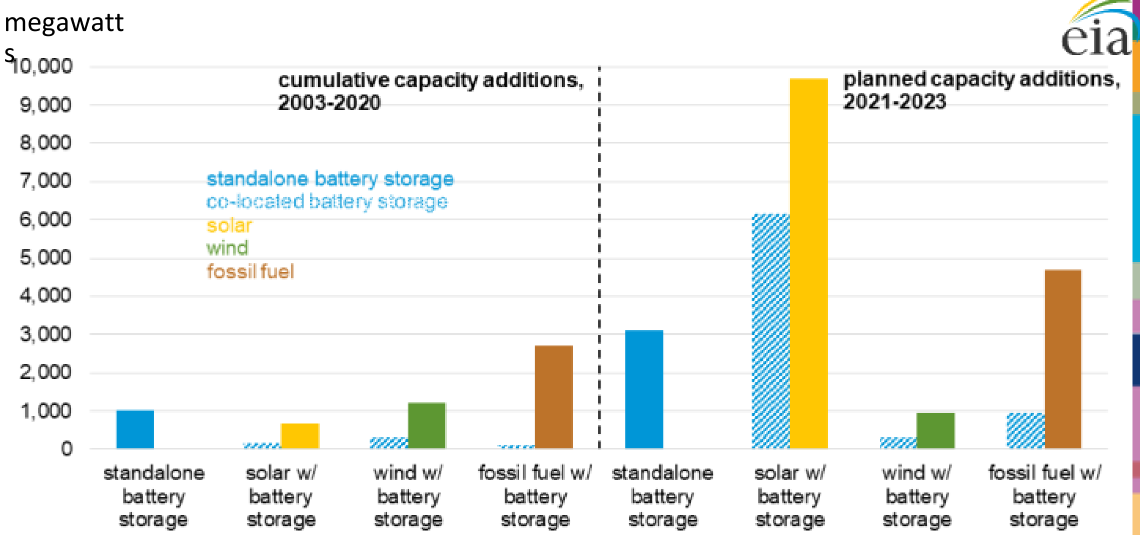
- Grid reliability, solar + storage, resiliency applications

Long term growth driven by competitive economics

Where is Battery Energy Storage Getting Deployed?



Applications served by large-scale battery storage in the US (2019)



U.S. large-scale battery storage power capacity additions, standalone & co-located

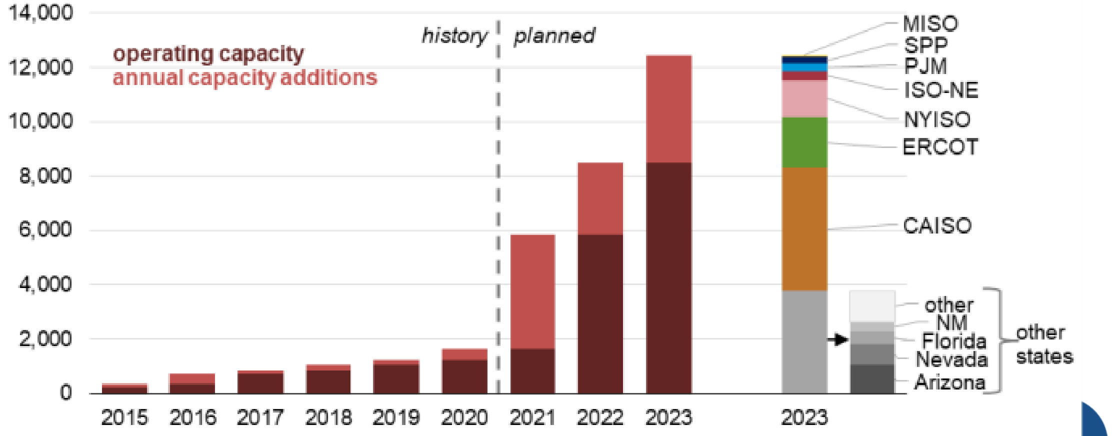
Early deployments are all power applications

Planned new capacity in the pipeline is hybrids either with solar, wind or NG in selected markets

Energy markets beginning to open, energy storage is still expensive for many energy applications including bulk grid

Battery energy storage systems are mostly using Li batteries

Source: U.S. Energy Information Administration, Dec 2020 Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*



Large-scale battery storage cumulative power capacity in the US, 2015–2023

Li-ion BESS Driving Large Commercial Projects

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

Deployment of large BESS plants becoming routine

GWh size plants no longer at the conceptual stage

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

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

Images: Company websites and Wikipedia

Trends in Li-ion Batteries: Solid State Batteries

Big push on solid-state batteries, SSBs (Li metal anode + solid electrolyte)

- Li-metal anode, higher energy densities
- Replacement of flammable liquid electrolyte, improved safety

Key Differences

- Liquid to solid electrolyte
  - Non-flammable solid
- No anion movement
  - High transference number
- Enabling of Li-metal anode
  - High energy density

Most major OEMs have investments in SSB start-ups

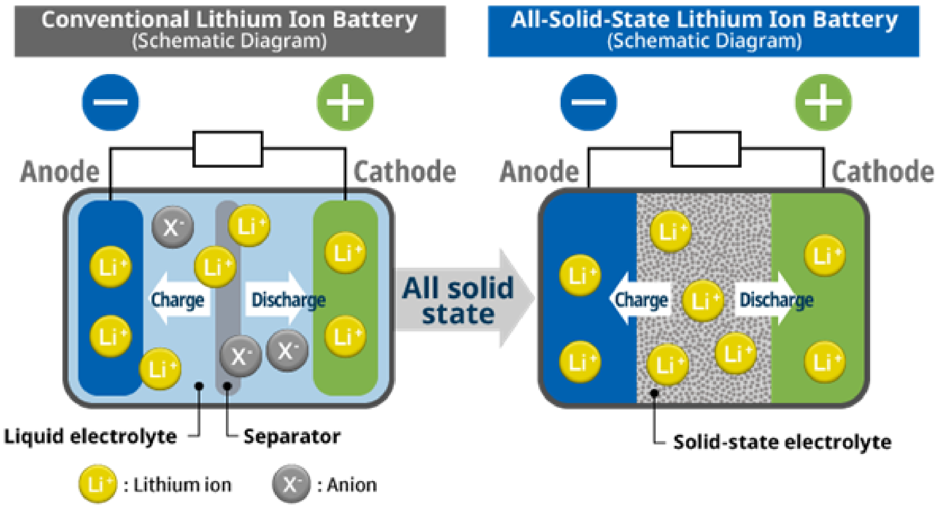
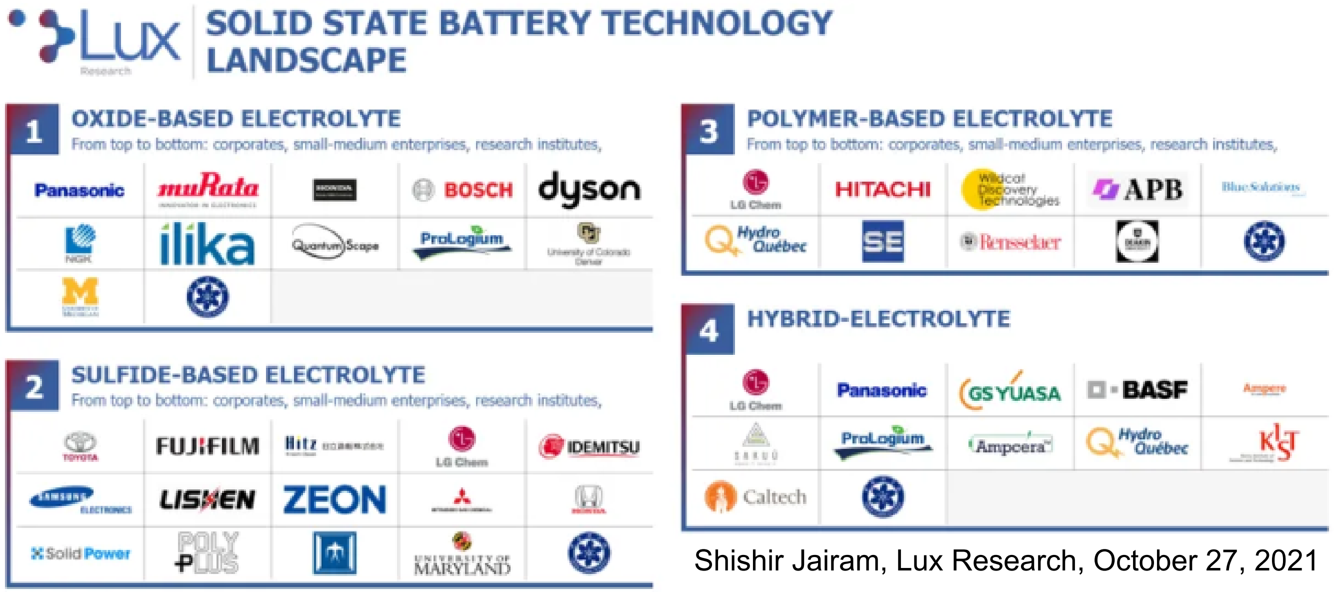


Image courtesy: Prof. Xiaoqing Pan, UC Irvine
https://sites.uci.edu/pangroup2/solid-oxide-electrolytes/



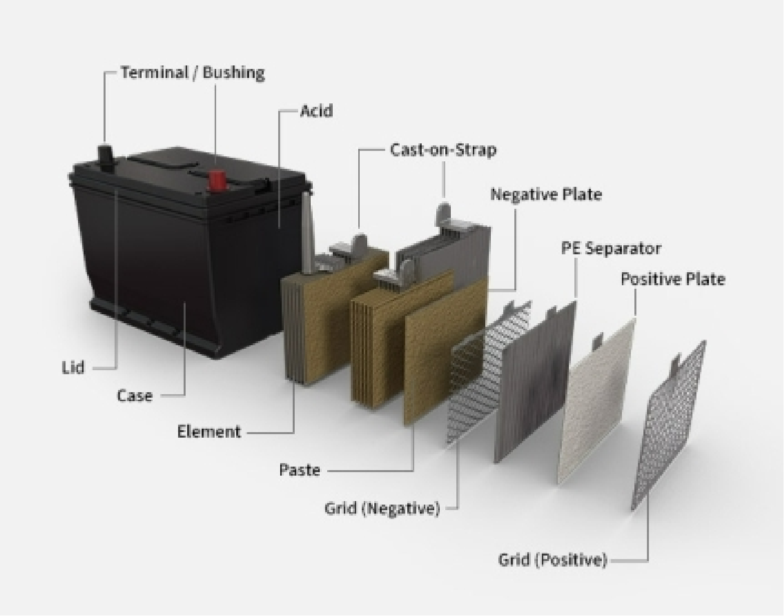
Shishir Jairam, Lux Research, October 27, 2021

Lead-Acid Batteries

- Sealed lead-acid
  - Gel and Absorbed Glass Mat (AGM)
  - More temperature dependent
- Advanced Lead Acid Energy Storage
  - Carbon plates significantly improve performance
- Mature technology with established global manufacturing footprint
- Highly recycled system

- Advantages/Drawbacks
  - Low cost/Ubiquitous
  - Limited life time (5~15 yrs)/cycle life (500~1000 cycles) and degradation w/ deep discharge (>50% DoD)
  - New Pb/C systems > 5,000 cycles.
  - Low specific energy (30-50 Wh/kg)
  - Overcharging leads to H2 evolution
  - Sulfation from prolonged storage

Simple & standardized construction



Ultrabattery and PV system at PNM Prosperity site. Source: PNM Resources

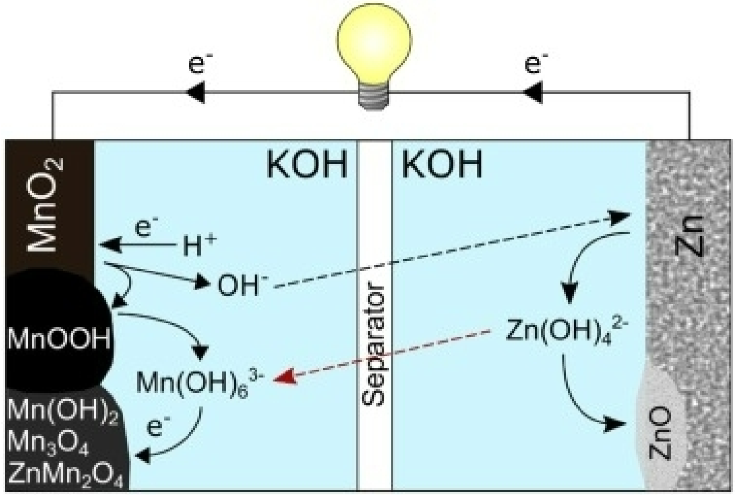
Zn-based Batteries an Environmentally Friendlier Alternative to Lead Acid

Range of alkaline battery chemistries
- Zn-Ni, Zn-MnO2

Aqueous chemistry, on-flammable

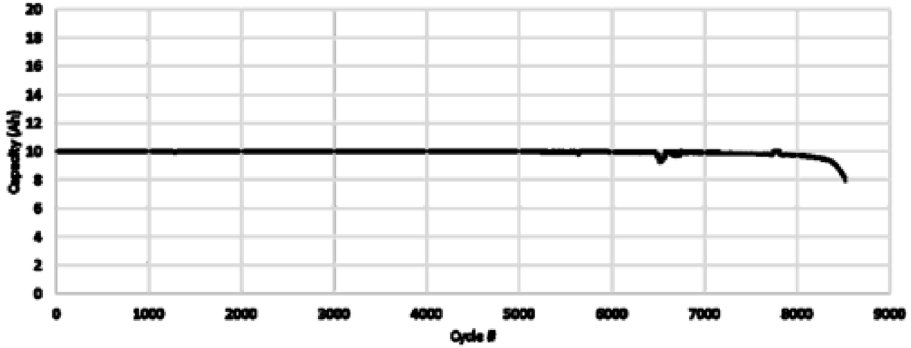
Long shelf-life, Limited thermal management required

Reversibility and cycle life have been the primary technical challenges for Zn-MnO_2



Source: M. Lim et al., Mat. Sci. Eng. Reports, 2021

Zn-Ni at 1C charge/discharge



Source: Design and Performance of Large Format Nickel-Zinc Batteries E. Listerud and A. Weisenstein ZAF Energy Systems

UEP Zn-MnO_2 Cylindrical Battery

ZAF Ni-Zn Prismatic Battery

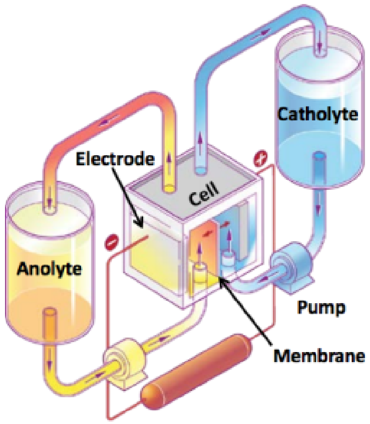
Flow Batteries Allow Decoupling of Energy and Power

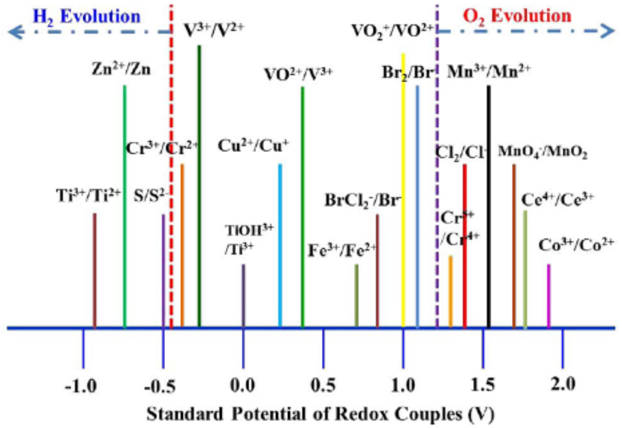
Range of redox chemistries.

Most large commercial flow batteries are based on V-V chemistry

Benefits: Decouple energy and power; electrolyte has a long life

Issues: low energy density ~ 30 Wh/L; Costs remain high, Many mechanical parts





Chalamala, et.al., Proc IEEE, vol. 102, pp. 976-999, June 2014

Modular systems (<50kWh)

Primus Power modular Zn-Br, each unit is 25kW/125kWh

Utility scale systems

Sumitomo 2MW/8MWhr vanadium Redox Flow Battery system in San Diego, CA

Many New Energy Storage Technologies Under Development

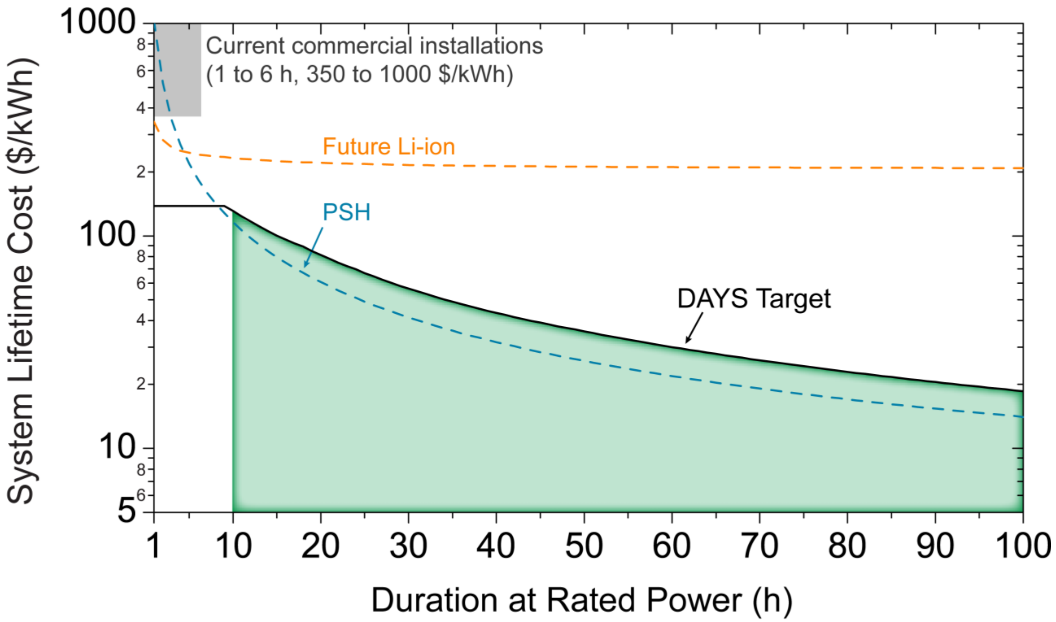
Metal-air and Na-ion are under development

Existing Na-S and Na-halide battery technology continues to be improved

Source: DOE Energy Storage Database (2022)

Long Duration Energy Storage is Needed

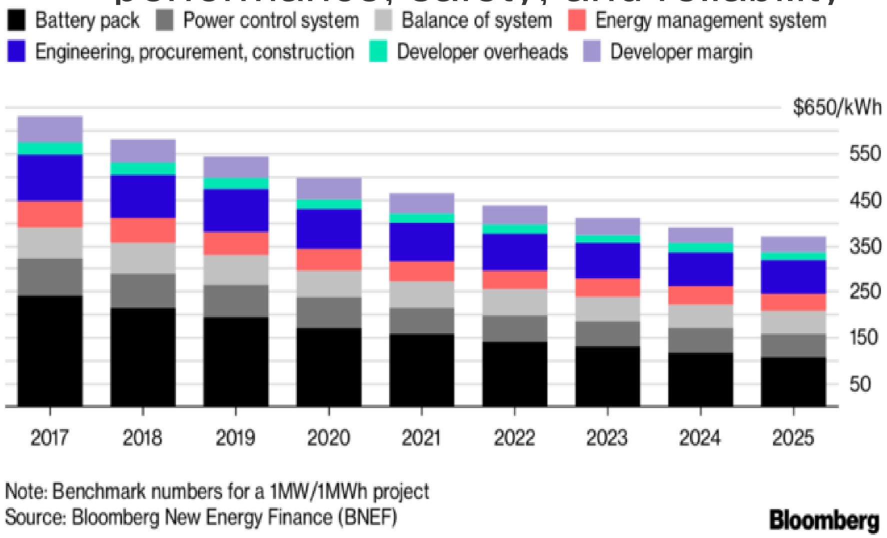
- Majority of current battery energy storage today are for applications that require ~4 hours at rated power. Requirement for 10 hours coming up quickly.
- No ready solutions for longer duration storage, days to seasonal.
- Potential for liquid fuels, hydrogen, thermal storage are all options
- Longer duration energy storage economic requirements are significantly different from battery storage.
- Projects have to be larger to justify lower system costs.

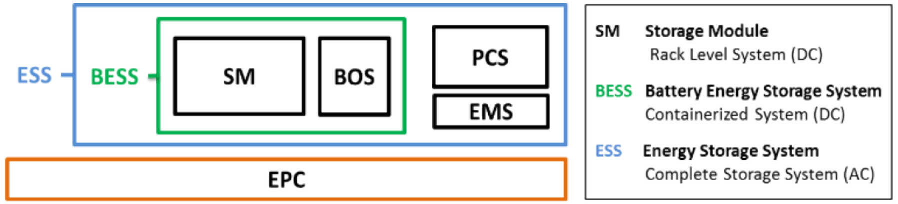


Source: Albertus et al., Joule 4, 21-32, 2020.

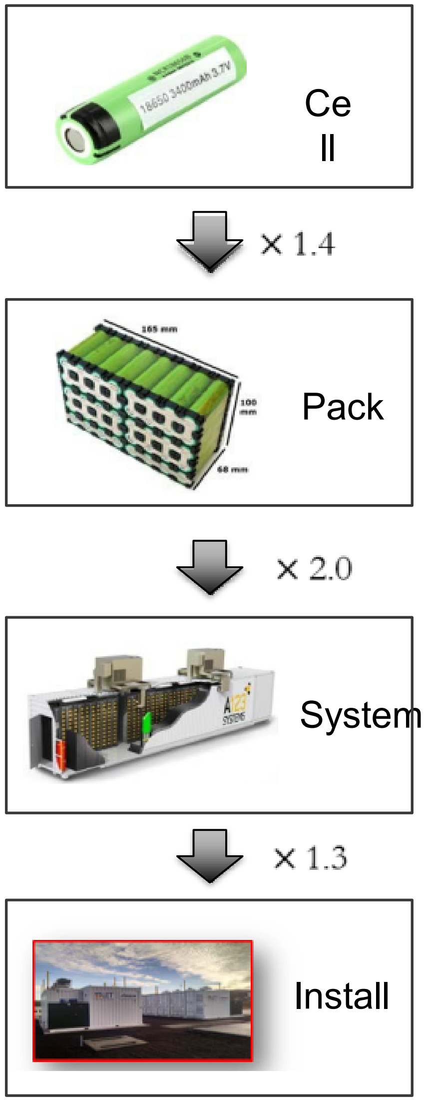
Energy Storage is Not Just Batteries – Engineered Systems

- Integration costs are significant to meet safety and performance requirements
- Performance of battery energy storage systems are not solely dependent on the cell itself, but in the systems and integration level
  - System-level integration modules, e.g., BMS, PCS, are crucial for the performance, safety, and reliability





Storage Module (SM)	Balance of System (BOS)	Power Conversion System (PCS)	Energy Management System (EMS)	Engineering Procurement & Construction (EPC)
Racking Frame / Cabinet	Container	Bi-directional Inverter	Application Library	Project Management
Local Protection (Breakers)	Electrical Distribution & Control	Electrical Protection	Economic Optimization	Engineering Studies / Permitting
Rack Management System	Fire Suppression	Connection to Transformer	Distributed Asset Integration	Site Preparation / Construction
Battery Management System	HVAC / Thermal Management		Data Logging	Foundation / Mounting
Battery Module			Communication	Commissioning



Integration costs increase as cell → battery → Storage System. For example, doubling in cost, $250/kWh battery leads to $500-$700/kWh at the system level.

Various components are required for system-level integration of batteries for safety, performance, and compliance.

Sources: R. Baxter, I. Gyuk, R.H. Byrne, B.R. Chalamala, IEEE Electrification, Aug 2018

Battery Energy Storage – Design and Application Aspects

- **Cell Architecture**
  - Cylindrical, prismatic, bipolar, flow cell
- **Cell Chemistry**
  - Aqueous, non-aqueous
- **Cycle Life**
  - Electrical
  - Thermal
- **Modularity and Scalability**
  - kW to MW (Power Scaling)
  - kWh to MWh (Energy Scaling)
  - Module stacking and Containerization
- **Operational Aspects**
  - Round-trip efficiency
  - Auxiliary power consumption
  - O&M Costs
- **Plant Models**
  - Modularized
- **Power vs. Energy**
  - High-power, short-duration discharge
  - High-energy, long-duration discharge
  - Fast Charging
- **Safety**
  - Abuse resistance, flammability, toxicity, containment
- **Thermal Management**
  - Heating, cooling

Safety R&D is Largely Focused on Li-ion BESS

- Li-ion batteries: knowledge base mostly from consumer electronics, safety issues adequately addressed.
  - Safety issues for larger size (EV, grid) just beginning to be dealt with
- New technologies are being introduced
  - Is testing adequate for new technologies?
  - Li-ion – High energy anode materials
  - Li metal, solid state batteries
  - Advanced aqueous batteries
  - Molten salt batteries
- Large storage systems targeting non-traditional locations, and areas near population centers
- Grid-scale systems are complex, including not only a large battery but sophisticated power electronics
  - How do you qualify for safety? Is full-scale testing necessary?

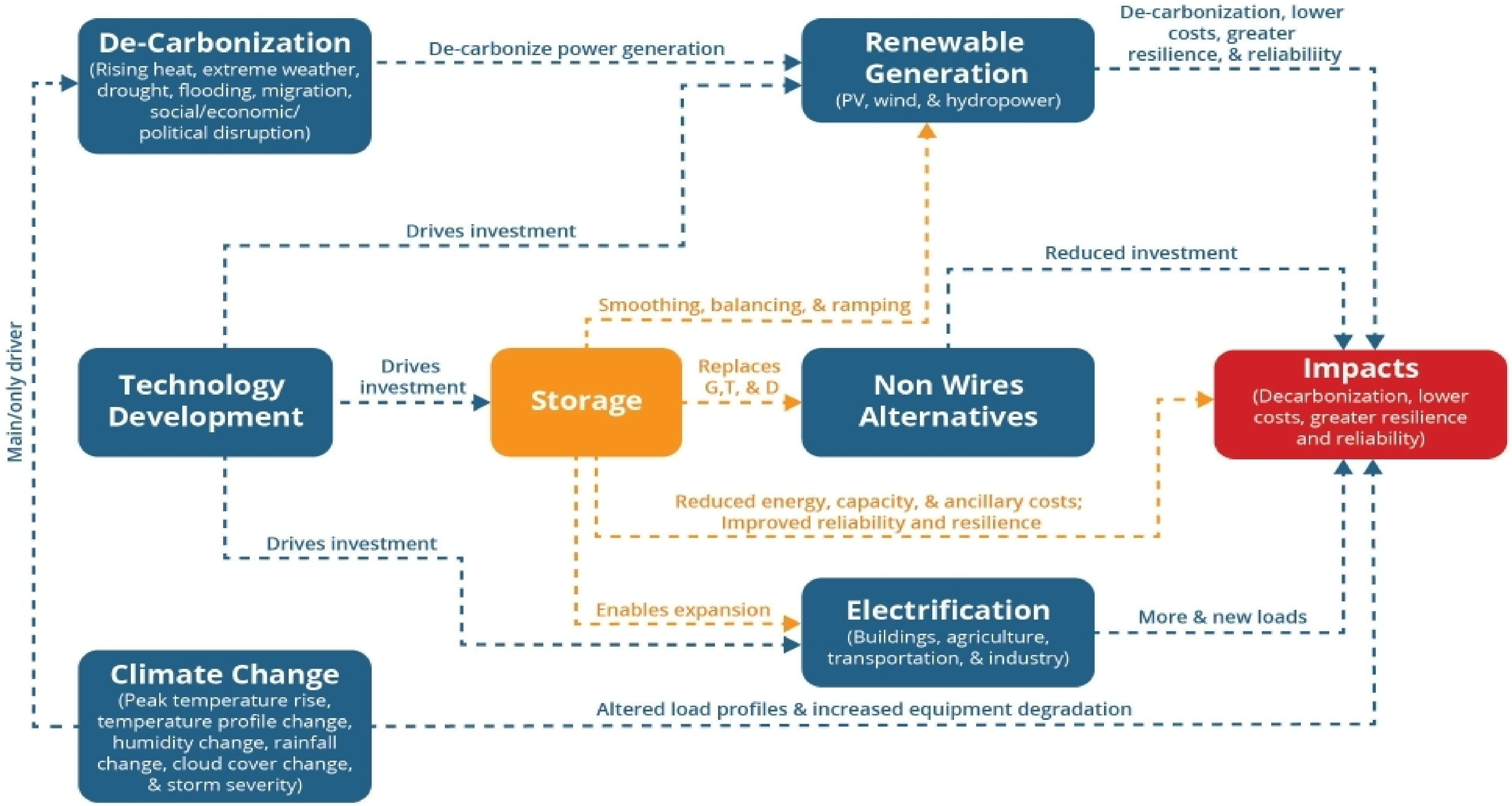

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm


2018-2019 A string of 21 energy storage system fires in South Korea leads to suspension of new projects

2019 A fire in an ESS in Surprise, AZ leads to an explosion injuring first responders

Energy Storage in the Evolving Grid

Large scale energy storage integration is a critical enabler for renewable integration, support electrification, and deeper decarbonization of the electric system



Graphic source: R. Masiello, R. Fioravanti, B. Chalamala, and H. Passell, Proc. IEEE, to appear (2022).

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