Advanced Energy Storage: How PNNL Supports Industry from the Lab to the Grid

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Northwest Energy Systems Symposium

Seattle, WA

April 3 2024

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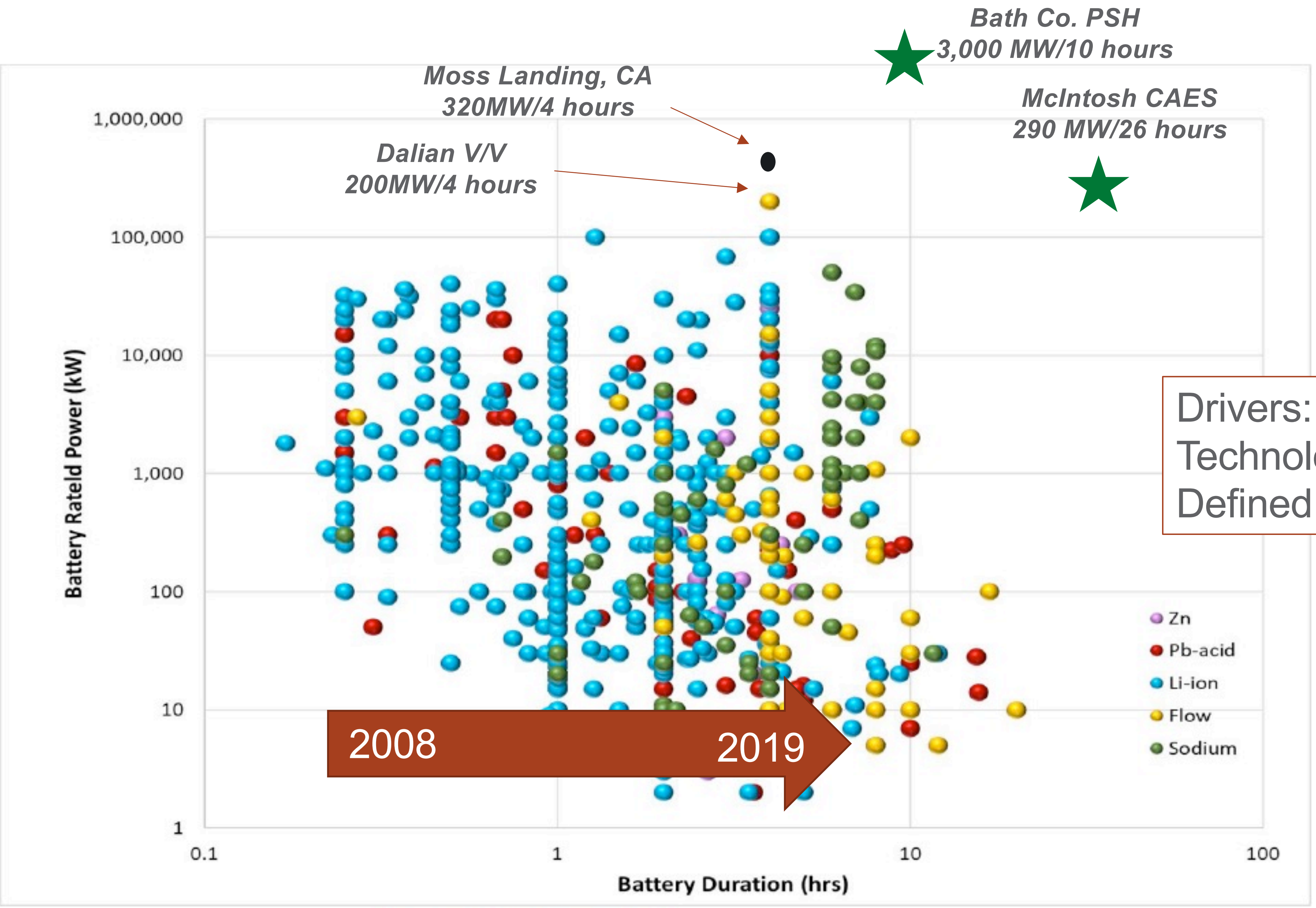
PNNL-SA-196842

DOE's 17 national laboratories tackle critical scientific challenges

- Big problems, mission-driven
- High-risk, potentially high-reward
- Large, long-term, multidisciplinary research
- Maintain capabilities and facilities for DOE's mission, S&T community, and the nation
- Supports U.S. competitiveness

Battery Storage Deployment Trends

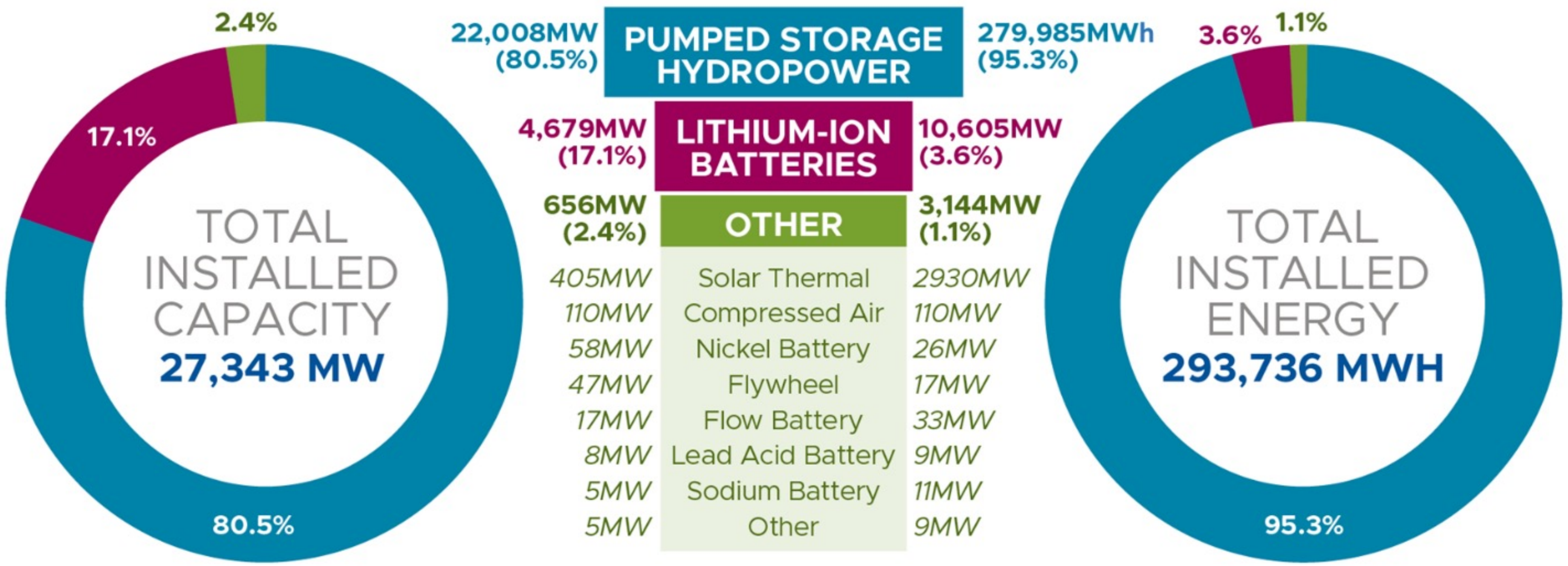


Drivers:
Technology Cost Reduction
Defined Value/Market

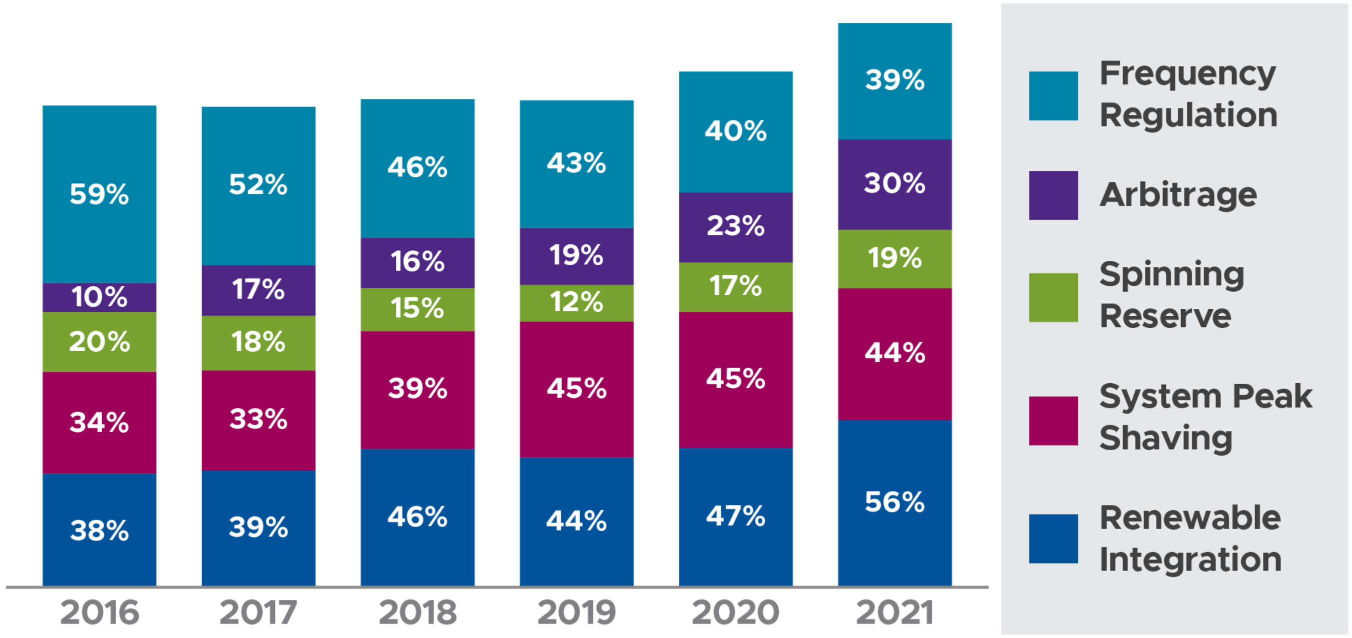
Source: US DoE Energy Storage Database, March 2019, https://www.energystorageexchange.org/
Based on Shell International Exploration & Production (US) Inc.; analysis presented by Shell 11 March 2019, ARPA-e DAYS

Where are we now - Grid Storage

Technology



Applications



J. Twitchell, D. Wu, et al "Energy Storage: A Key Enabler for Renewable Energy" NAE Bridges

Driver for Long Duration Energy Storage (LDES)

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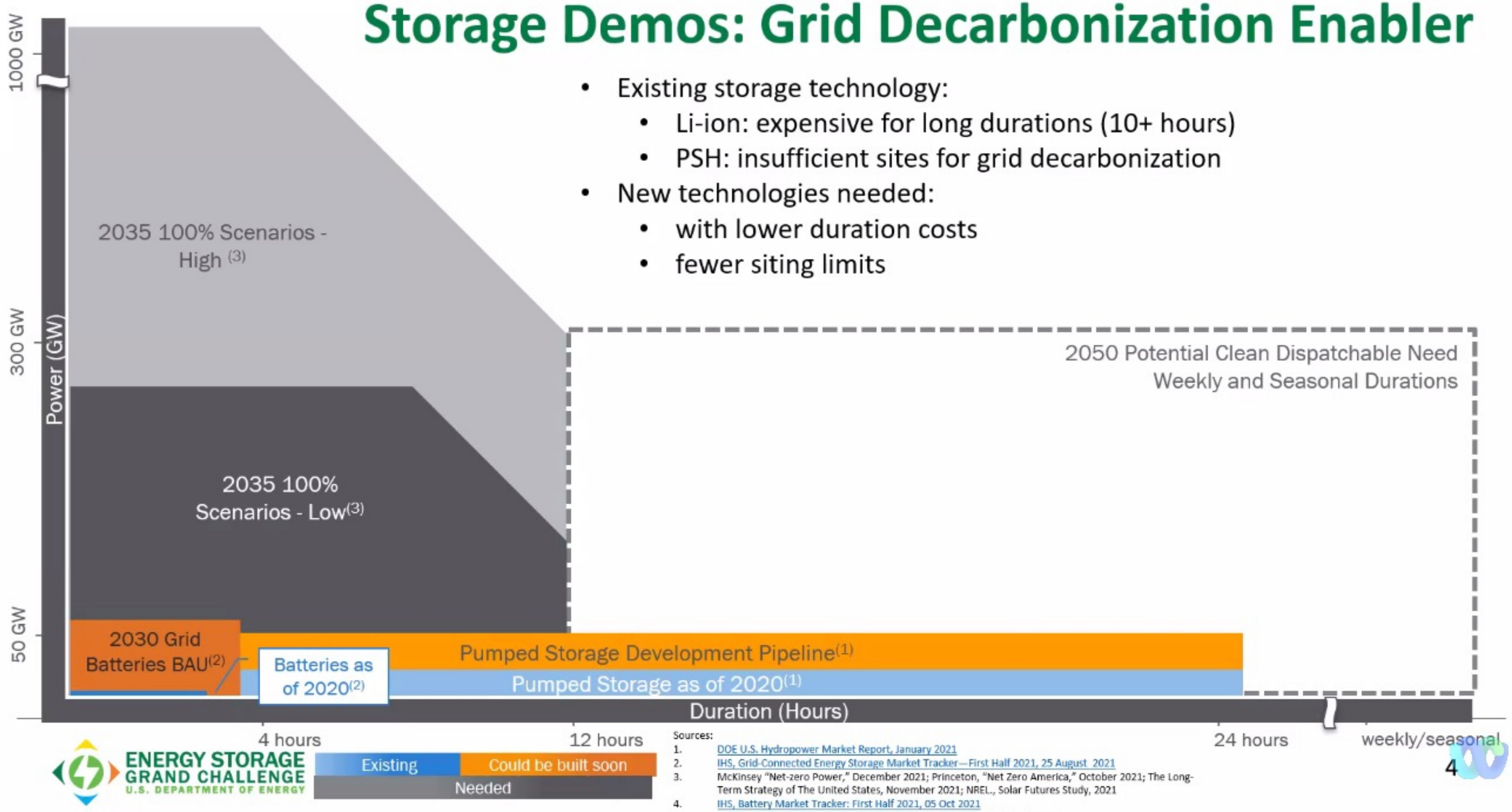
Storage Demos: Grid Decarbonization Enabler

- Existing storage technology:
  - Li-ion: expensive for long durations (10+ hours)
  - PSH: insufficient sites for grid decarbonization
- New technologies needed:
  - with lower duration costs
  - fewer siting limits

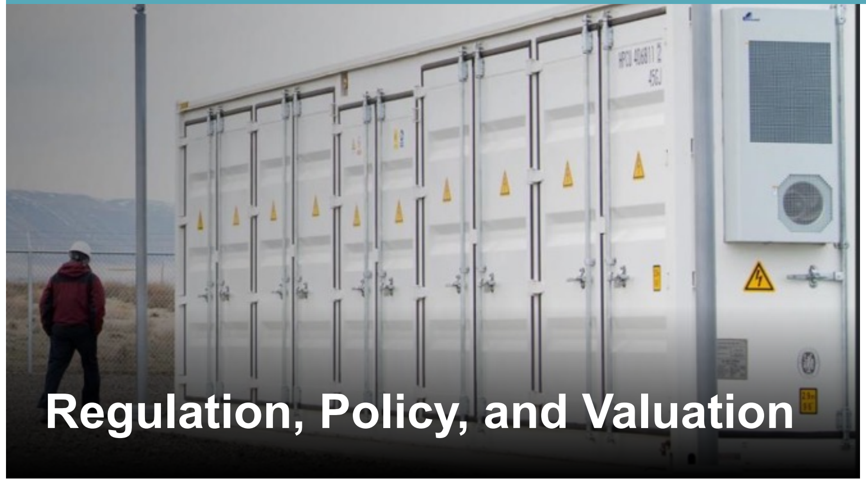


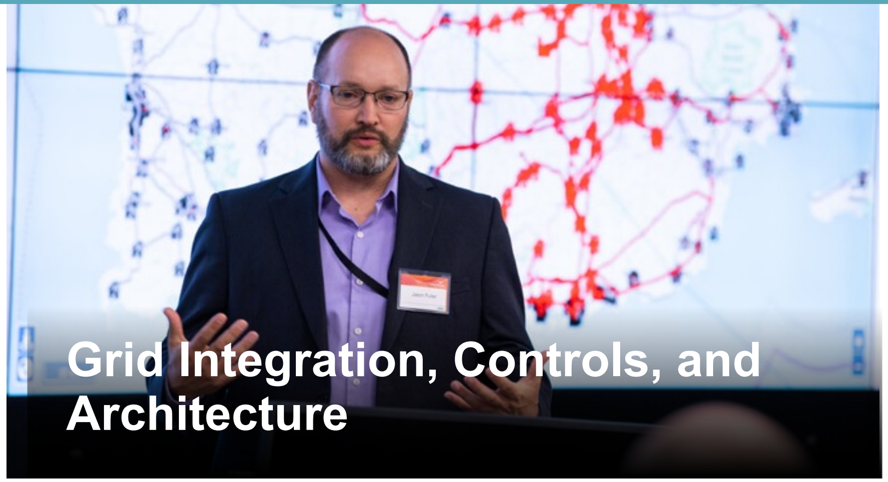
Sources:
1. DOE U.S. Hydropower Market Report, January 2021
2. IHS, Grid-Connected Energy Storage Market Tracker—First Half 2021, 25 August 2021
3. McKinsey "Net-zero Power," December 2021; Princeton, "Net Zero America," October 2021; The Long-Term Strategy of The United States, November 2021; NREL., Solar Futures Study, 2021
4. IHS, Battery Market Tracker: First Half 2021, 05 Oct 2021
5. DOE, Supply Chain Review: Water Electrolyzers and Fuel Cells, Forthcoming

Energy storage research at PNNL

Science and Technology

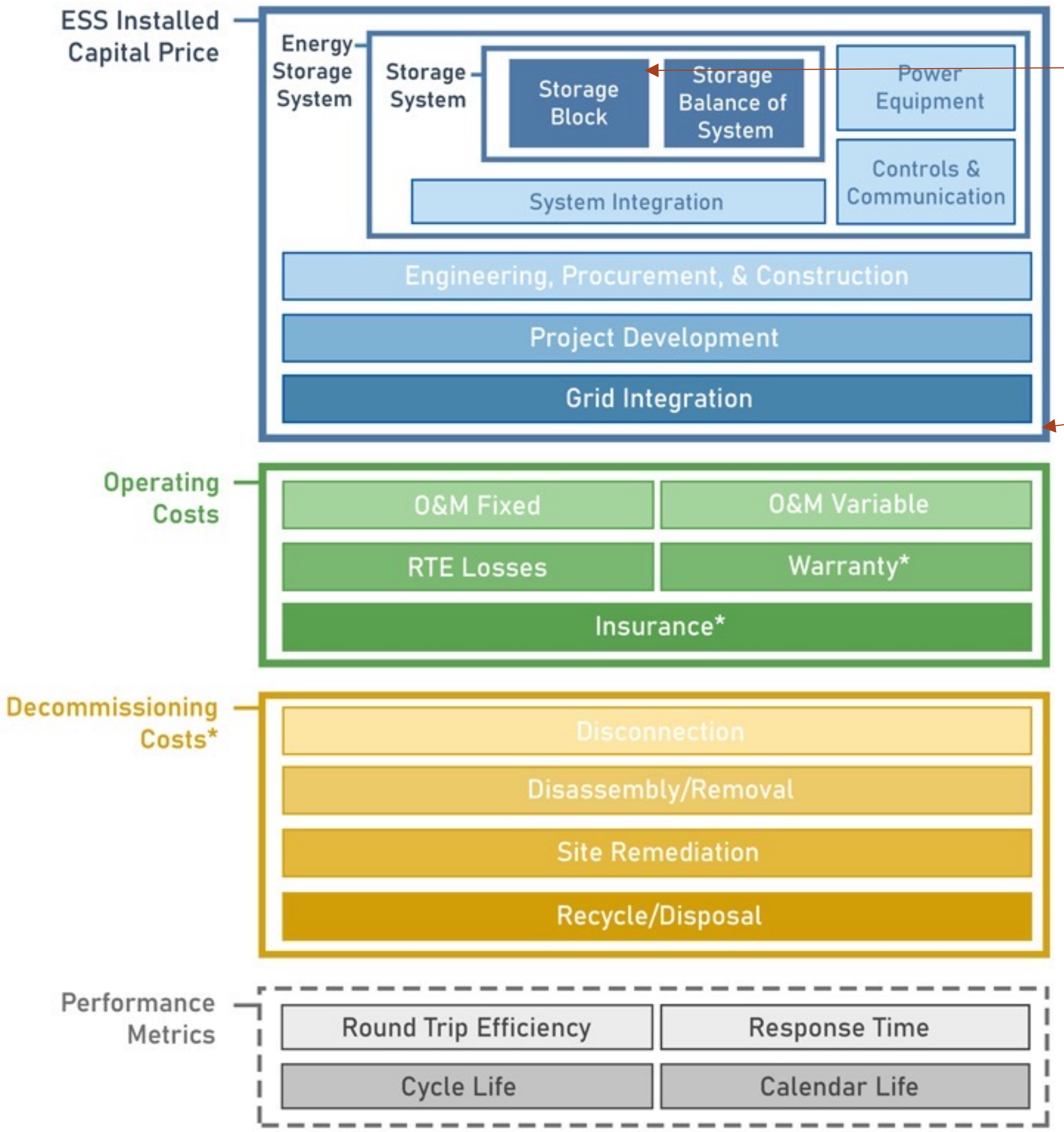
Deployment and Implementation





Science and Technology

Before discussing specific battery technologies - important to understand the entire system



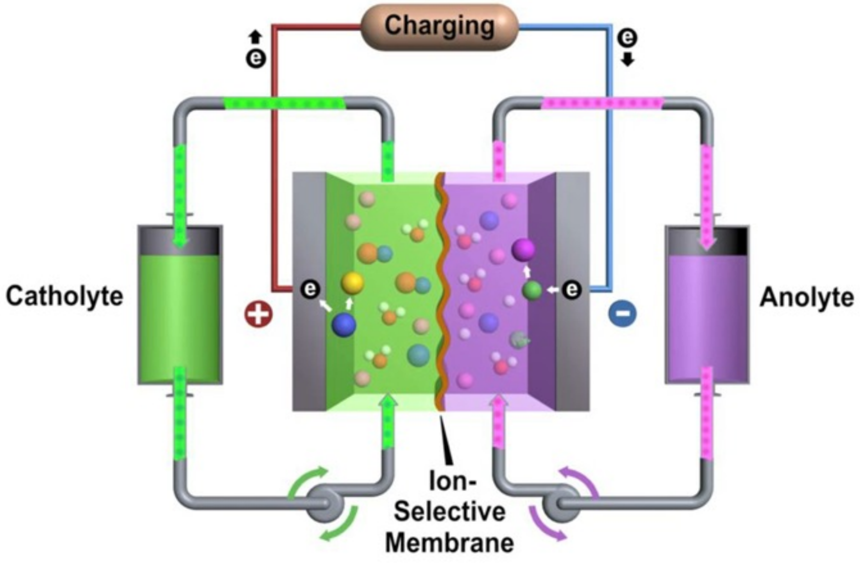
Cost of most basic storage element in system, expressed in $/kWh. e.g. for Li-ion, price would include battery module, rack, BMS, comparable to vehicle pack price.

Total installed storage cost including balance of system, power conversion, controls, construction (EPC), permitting, PPA (Project development), and interconnection. See slide X for details.

https://www.pnnl.gov/ESGC-cost-performance

LDES Technologies

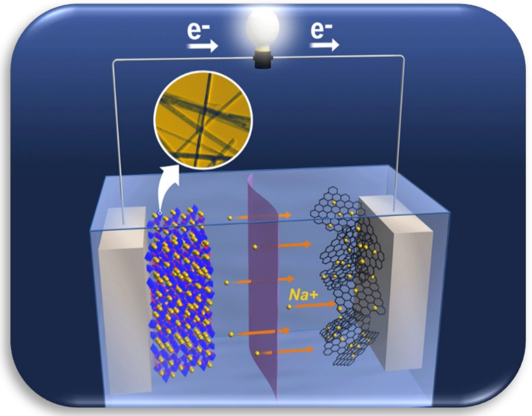
Flow Battery



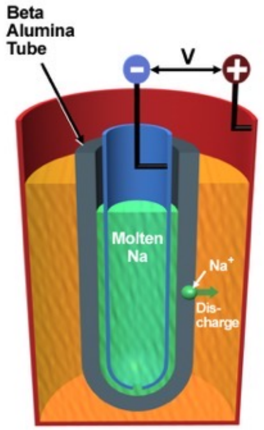
- Organics to replace commodity metals for LDES applications
- Water based technologies for improved safety
- _Needs:_ lower cost materials, improved durability, energy density, supply chain

Sodium Batteries

Sodium ion



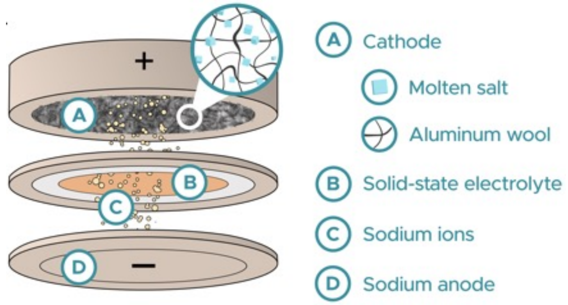
Molten Sodium



- **Na-ion:** replacing lithium with low cost, abundant element.
- _Needs:_ higher energy density, improved performance, scale-up
- **Molten Sodium:** proven, durable technology with 6-8 hour discharge.
- _Needs:_ lower temperature operation, lower cost system.

Zinc, Lead, Iron, Aluminum

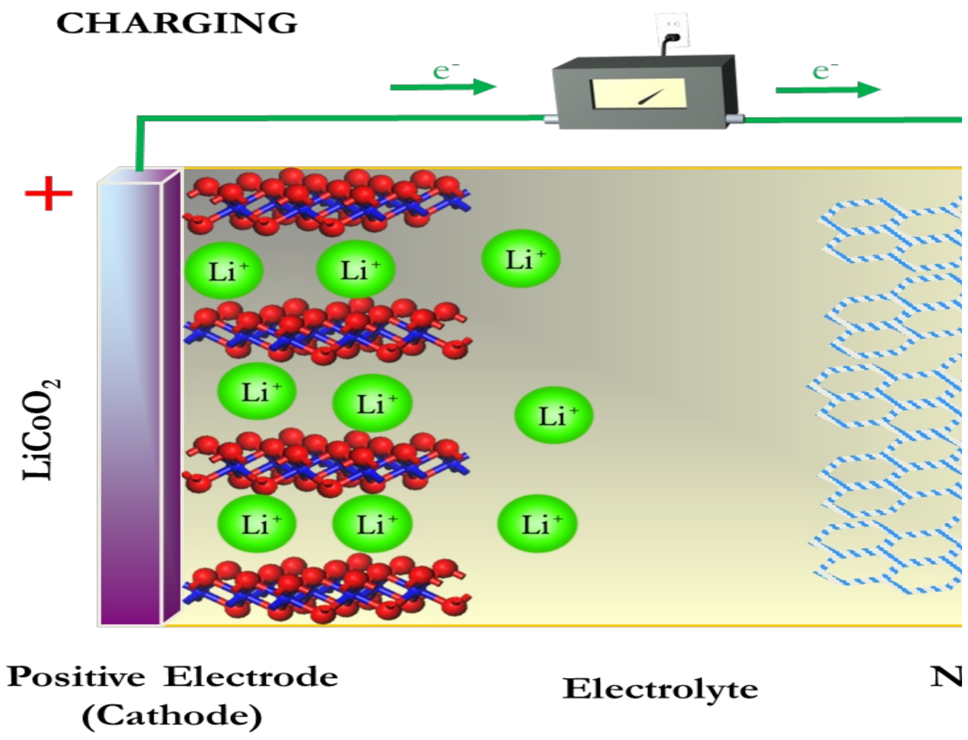
Sodium-Aluminum



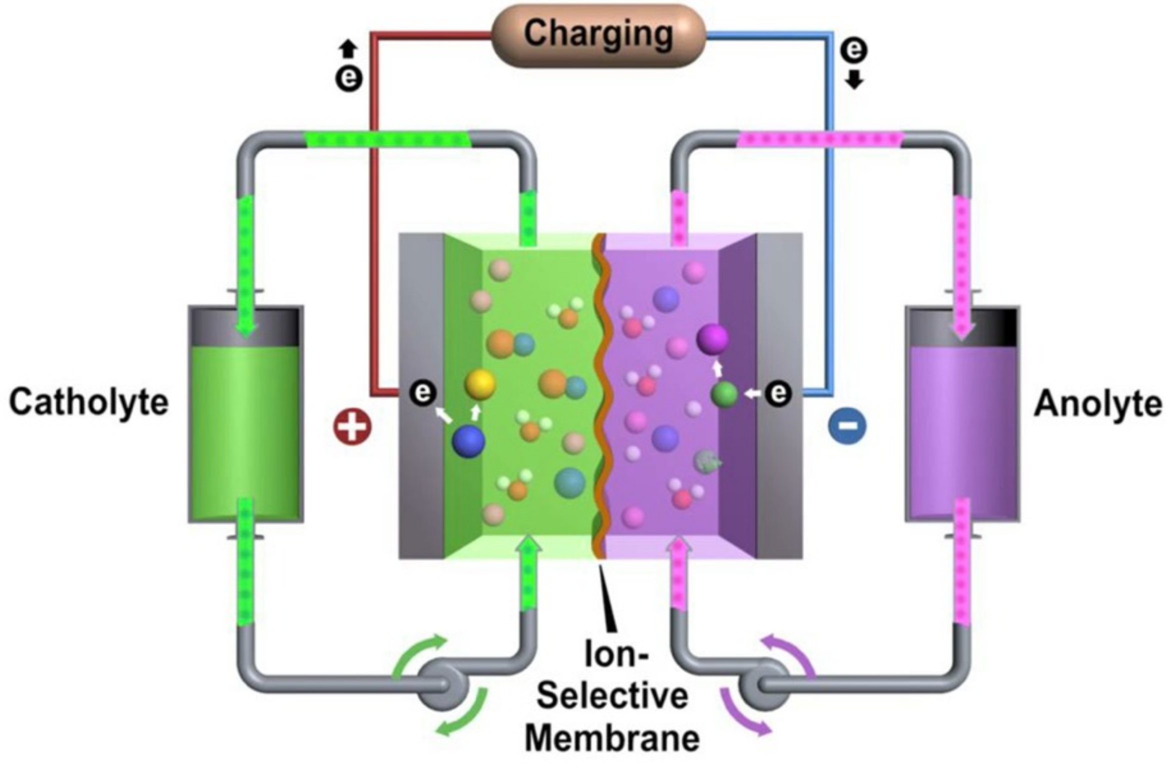
- **Na-Al:** potential for seasonal storage – need to scale-up and improve durability.
- **Zinc:** established technology - need to improve cycling ability/minimize degradation.
- **Lead***:* Strong US manufacturing and recycling - need to improve lifetime for grid applications.
- **Iron:** low cost materials and neutral pH - need to improve energy density and durability

Basic Battery Architectures

Standard Architecture
e.g (Li-ion)



Flow Battery Architecture
e.g (Li-ion)

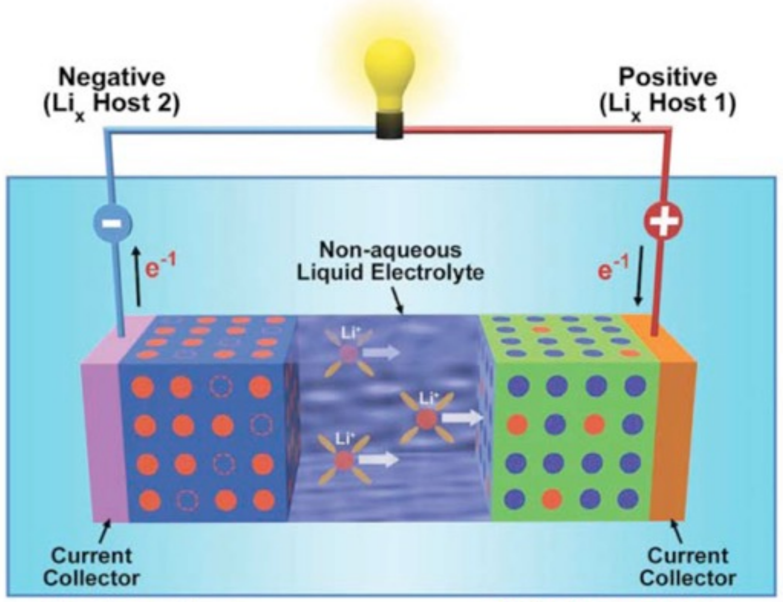


__Hybrid Flow:__ Replacing one flowing electrode with plating electrode

Li-ion Batteries

- Advantages
  - High energy density
  - Better cycle life than Lead - Acid
  - Decreasing costs – Stationary on coattails of increasing EV.
  - Ubiquitous – Multiple vendors
  - Fast response
  - Higher efficiency* (Parasitic loads like HVAC often not included)

- Applications
  - Traditionally a power battery but cost decreases and other factors allow them to used in energy applications



Anode reactions:

$$C + xLi^+ + xe^- \underset{Discharge}{\overset{Charge}{\rightleftharpoons}} Li_xC$$

$$Li(Li_{1/3}Ti_{5/3})O_4 + e^- + Li^+ \underset{Discharge}{\overset{Charge}{\rightleftharpoons}} Li_2(Li_{1/3}Ti_{5/3})O_4$$

Cathode reactions:

$$LiMO_2 \underset{Discharge}{\overset{Charge}{\rightleftharpoons}} Li_{1-x}MO_2 + xLi^+ + xe^-$$

$$LiFePO_4 \underset{Discharge}{\overset{Charge}{\rightleftharpoons}} Li_{1-x}FePO_4 + xLi^+ + xe^-$$

Cathodes

Chemistry	Specific Capacity	Potential vs. Li+/Li	
$LiCoO_2$	273 / 160	3.9	iphone
$LiNiO_2$	274 / 180	3.6	
$LiNi_xCo_yMn_zO_2$	~ 270 / 150~180	3.8	NMC – LG/Volt
$LiNi_xCo_yAl_zO_2$	~ 250 / 180	3.7	NCA - Tesla
$LiMn_2O_4$	148 / 130	4.1	
$LiMn_{1.5}Ni_{0.5}O_4$	146 / 130	4.7	
$LiFePO_4$	170 / 160	3.45	LFP
$LiMnPO_4$	171 / 80~150	4.1	
$LiNiPO_4$	166 / -	5.1	
$LiCoPO_4$	166 / 60~130	4.8	

Anodes

Chemistry	Specific Capacity	Potential vs. Li+/Li
Soft Carbon	< 700	< 1
Hard Carbon	600	< 1
$Li_4Ti_5O_{12}$	175 / 170	1.55
TiO_2	168 / 168	1.85
SnO_2	782 / 780	< 0.5
Sn	993 / 990	< 0.5
Si	4198 / < 3500	0.5 ~ 1

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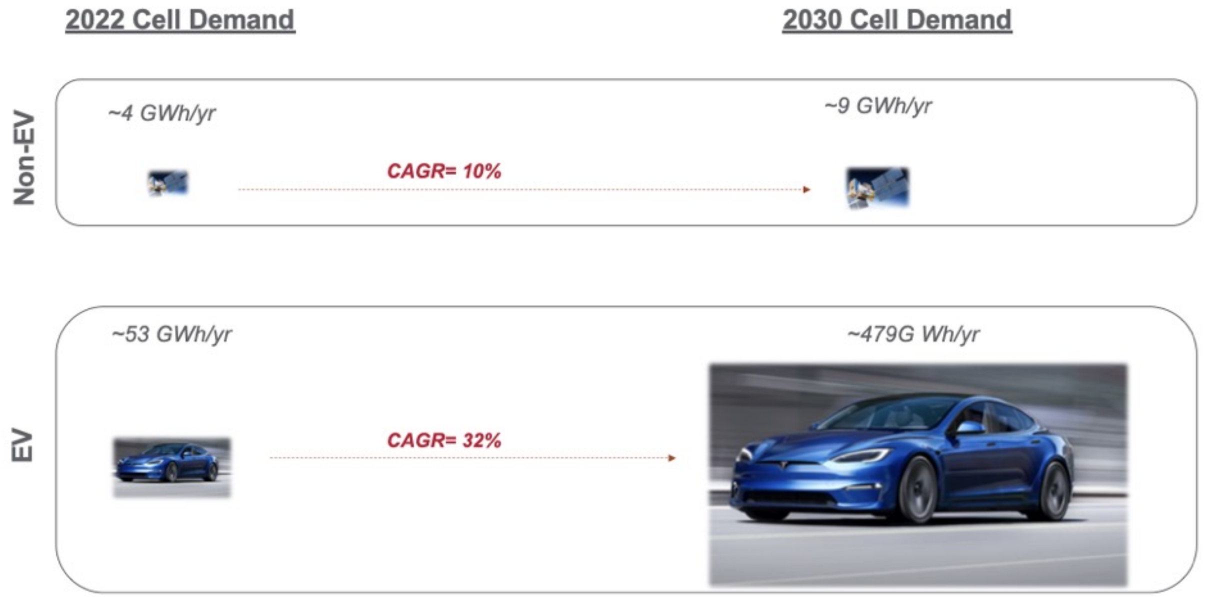
Li-ion Summary

- For grid applications
  - Costs continue to come down. However, BOM constitute ~70-80% of cell cost in a Lithium-ion cells.
  - Grid batteries in addition to low BOM and cost of manufacturing
  - Excess capacity in the large format automotive batteries driving the market for applications in the grid

- However
  - Safety and reliability continues to be significant concerns
  - Power control and safety adds significant cost to Li ion storage
  - Packaging and thermal management add significant costs
  - Deep discharge cycle life issues for energy applications (1000 cycles for automotive)



Li-ion Cost and Performance (LFP and NMC)

Lithium-ion LFP , 10 MW, 4 hr
Costs & Performance Parameters

	2021			2030		
	Low Estimate	Point Estimate	High Estimate	Low Estimate	Point Estimate	High Estimate
DC Storage Block ($/kWh)	$156.30	$173.67	$191.03	$94.64	$113.64	$129.68
DC Storage BOS ($/kWh)	$36.34	$40.38	$44.41	$26.42	$30.15	$34.26
Power Equipment ($/kW)	$65.75	$73.05	$80.36	$54.55	$64.62	$67.35
C&C ($/kW)	$6.97	$7.75	$8.52	$5.07	$5.78	$6.57
Systems Integration ($/kWh)	$41.99	$46.66	$51.32	$36.37	$39.59	$43.01
EPC ($/kWh)	$50.56	$56.18	$61.80	$43.79	$47.67	$51.79
Project Development ($/kWh)	$60.67	$67.42	$74.16	$52.55	$57.20	$62.15
Grid Integration ($/kW)	$22.32	$24.81	$27.29	$19.34	$21.05	$22.87
Total Installed Cost ($/kWh)	$369.63	$410.70	$451.77	$273.52	$311.11	$345.09
Total Installed Cost ($/kW)	$1,479	$1,643	$1,807	$1,094	$1,244	$1,380

Duration hr
- 2 hr
- 4 hr (selected)
- 6 hr
- 8 hr
- 10 hr
- 24 hr
- 100 hr

Power MW
- 1 MW
- 10 MW (selected)
- 100 MW
- 1,000 MW

Lithium-ion NMC , 10 MW, 4 hr
Costs & Performance Parameters

	2021			2030		
	Low Estimate	Point Estimate	High Estimate	Low Estimate	Point Estimate	High Estimate
DC Storage Block ($/kWh)	$184.75	$205.28	$225.81	$111.87	$134.33	$153.28
DC Storage BOS ($/kWh)	$35.43	$39.37	$43.31	$25.76	$29.40	$33.40
Power Equipment ($/kW)	$65.75	$73.05	$80.36	$54.55	$64.62	$67.35
C&C ($/kW)	$6.97	$7.75	$8.52	$5.07	$5.78	$6.57
Systems Integration ($/kWh)	$47.50	$52.78	$58.05	$41.14	$44.78	$48.65
EPC ($/kWh)	$57.17	$63.53	$69.88	$49.52	$53.90	$58.56
Project Development ($/kWh)	$68.61	$76.23	$83.85	$59.43	$64.68	$70.28
Grid Integration ($/kW)	$22.32	$24.81	$27.29	$19.34	$21.05	$22.87
Total Installed Cost ($/kWh)	$417.22	$463.58	$509.94	$307.46	$349.95	$388.38
Total Installed Cost ($/kW)	$1,669	$1,854	$2,040	$1,230	$1,400	$1,554

Duration hr
- 2 hr
- 4 hr (selected)
- 6 hr
- 8 hr
- 10 hr
- 24 hr
- 100 hr

Power MW
- 1 MW
- 10 MW (selected)
- 100 MW
- 1,000 MW

Lead Acid Batteries.

Grid Storage not a primary market for Lead Acid batteries but growing interest because of US manufacturing base and recycling infrastructure.

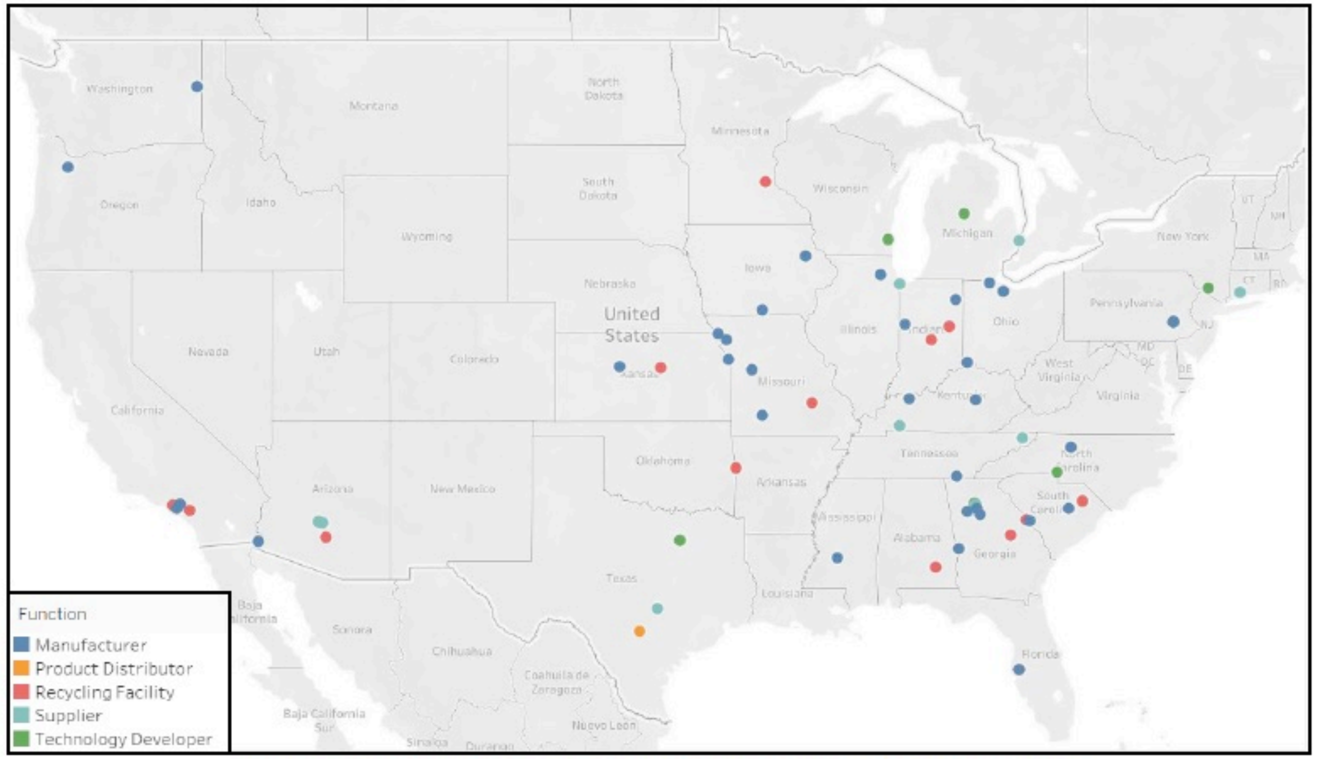
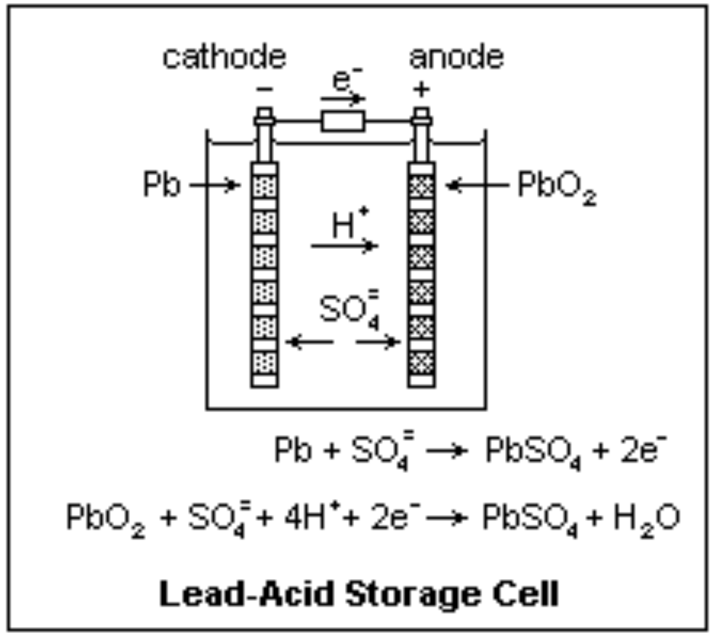
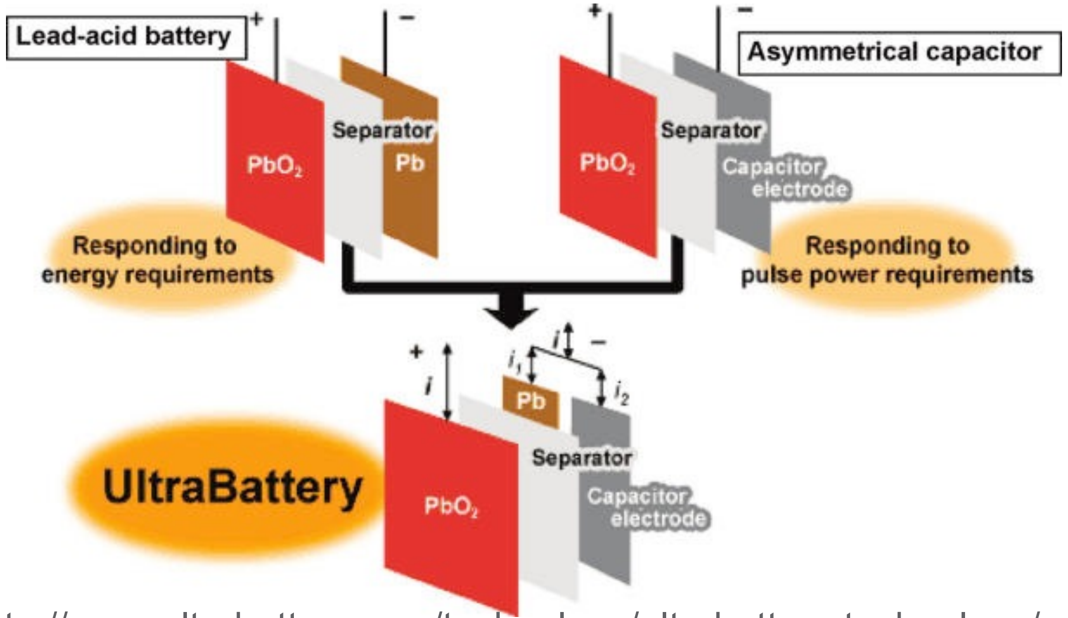


Figure 27. Domestic lead–acid industry and related industries

Source: [23] Battery Council International, "US Lead Battery Industry Business Infrastructure," Battery Council International, Chicago, 2020, unpublished.





http://www.ultrabattery.com/technology/ultrabattery-technology/

Energy Storage Grand Challenge Market Report

https://www.energy.gov/sites/default/files/2020/12/f81/Energy%20Storage%20Market%20Report%202020_0.pdf

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Lead Acid Redox Flow Battery Costs

Lead Acid , 10 MW, 4 hr
Costs & Performance Parameters

	2021			2030		
	Low Estimate	Point Estimate	High Estimate	Low Estimate	Point Estimate	High Estimate
DC Storage Block ($/kWh)	$220.96	**$235.07**	$249.17	$212.31	**$221.13**	$230.19
DC Storage BOS ($/kWh)	$44.19	**$47.01**	$49.83	$30.76	**$35.11**	$39.89
Power Equipment ($/kW)	$44.19	**$133.00**	$140.98	$54.51	**$117.65**	$122.61
C&C ($/kW)	$7.29	**$7.75**	$8.22	$5.07	**$5.79**	$6.58
Systems Integration ($/kWh)	$41.28	**$43.92**	$46.55	$34.24	**$37.26**	$40.49
EPC ($/kWh)	$46.01	**$48.95**	$51.88	$38.16	**$41.53**	$45.12
Project Development ($/kWh)	$57.83	**$61.52**	$65.21	$47.96	**$52.20**	$56.72
Grid Integration ($/kW)	$23.32	**$24.81**	$26.30	$19.34	**$21.05**	$22.87
Total Installed Cost ($/kWh)	$428.98	**$477.86**	$506.53	$383.15	**$423.35**	$450.42
Total Installed Cost ($/kW)	$1,716	**$1,911**	$2,026	$1,533	**$1,693**	$1,802
Fixed O&M ($/kW-year)	$5.14	**$6.44**	$6.72	$4.64	**$5.50**	$5.94
Recycling ($/kWh)	$19.49	**$23.09**	$26.97	$12.68	**$17.21**	$22.11
RTE (%)	73%	**73%**	73%	73%	**73%**	73%
Cycle Life (#)*	1,634	**1,634**	1,634	1,634	**1,634**	1,634
Calendar Life (yrs)	12	**12**	12	12	**12**	12
DOD (%)	68%	**68%**	68%	68%	**68%**	68%

Duration hr
- 2 hr
- 4 hr (selected)
- 6 hr
- 8 hr
- 10 hr
- 24 hr
- 100 hr

Power MW
- 1 MW
- 10 MW (selected)
- 100 MW
- 1,000 MW

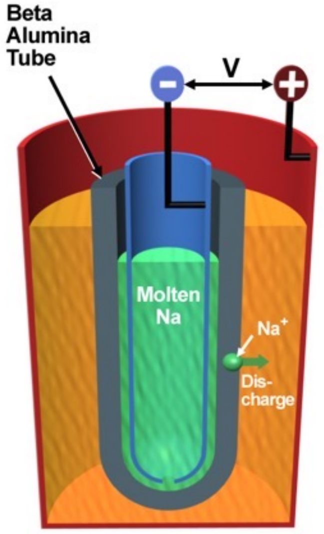
* Cycle Life (#) represents available cycles until remaining energy is equivalent to average DOD (%).

Na-Metal Batteries

Batteries consisting of *molten sodium anode* and *β"-Al_2O_3 solid electrolyte* (BASE).

- Use of low-cost, abundant sodium → low cost
- High specific energy density (120~240 Wh/kg)
- Good specific power (150-230 W/kg)
- Good candidate for energy applications (4-6 hrs discharge)
- Operated at relatively high temperature (300~350°C)

One of three NGK 20MW - 120 MWh NaS Batteries 108MW/648MW installation in Abu Dhabi.



- **Sodium-sulfur (Na-S) battery**
  - **$2Na + xS \rightarrow Na_2S_x$** (x = 3~5)
    - E = 2.08~1.78 V at 350°C
- **Sodium-nickel chloride (Zebra) battery**
  - **$2Na + NiCl_2 \rightarrow 2NaCl + Ni$**
    - E = 2.58V at 300°C
    - Use of catholyte ($NaAlCl_4$)

Redox Flow Batteries

- **Flow Battery Energy Storage**
  - Long cycle life
  - Power/Energy Decoupled
  - Lower efficiency
- **Applications**
  - Ramping
  - Peak Shaving
  - Time Shifting
  - Power quality
  - Frequency regulation
- **Challenges**
  - Developing technology
  - More Complex design
  - Lower energy density

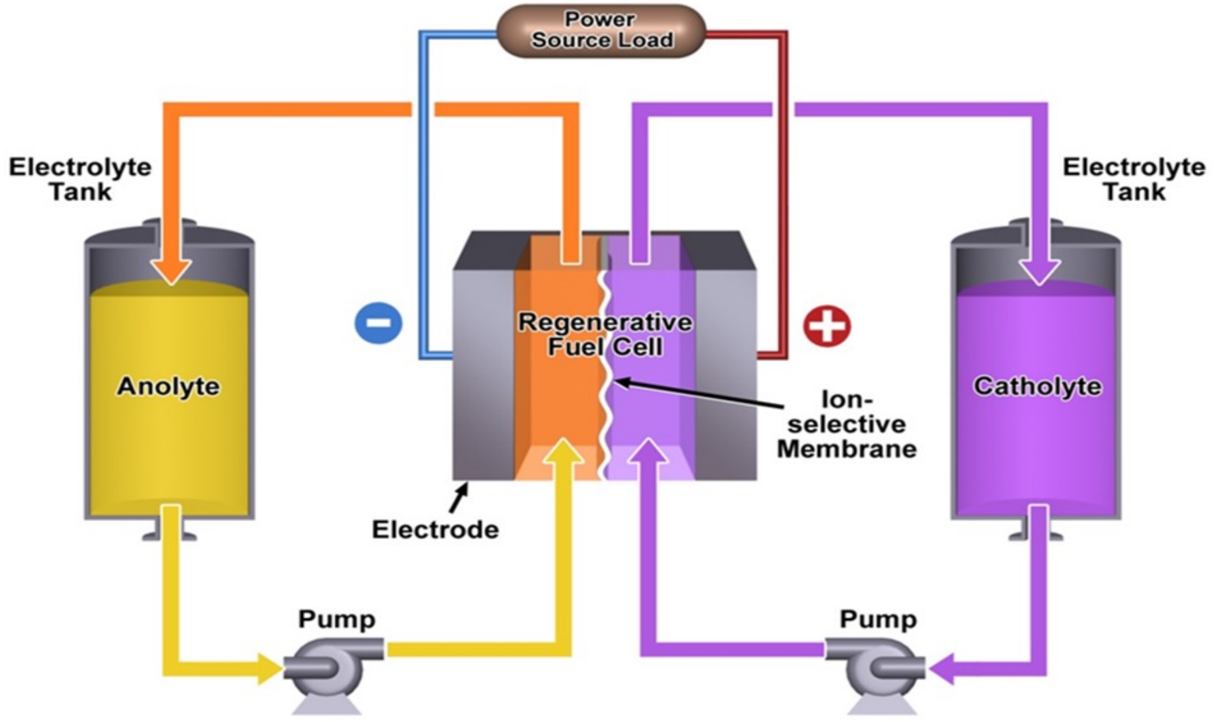


Figure 40. Largest vanadium redox flow battery facility (under construction)

Rongke Power 200MW/800MWh Vanadium Redox Flow Battery Dalian, China

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Vanadium Redox Flow Battery Costs

Vanadium Redox Flow , 10 MW, 4 hr
Costs & Performance Parameters

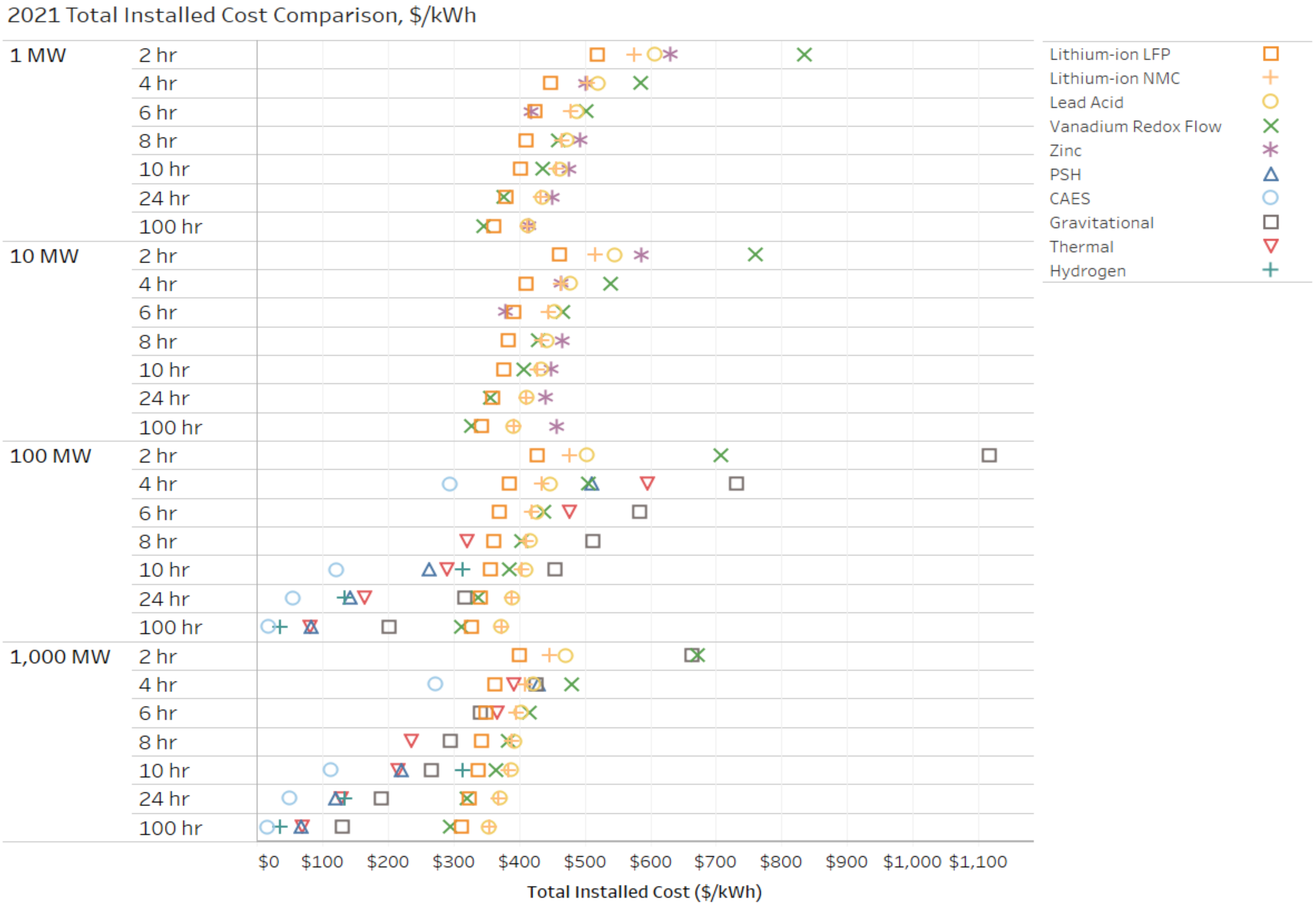
	2021			2030		
	Low Estimate	Point Estimate	High Estimate	Low Estimate	Point Estimate	High Estimate
DC Storage Block ($/kWh)	$180.00	$263.42	$302.33	$114.00	$218.95	$242.84
DC Storage BOS ($/kWh)	$22.50	$52.68	$60.47	$34.47	$39.34	$44.70
Power Equipment ($/kW)	$65.70	$133.00	$146.30	$54.51	$117.65	$122.61
C&C ($/kW)	$7.02	$7.80	$8.58	$5.10	$5.82	$6.62
Systems Integration ($/kWh)	$47.29	$52.55	$57.80	$40.96	$44.59	$48.44
EPC ($/kWh)	$54.52	$60.58	$66.63	$47.22	$51.40	$55.85
Project Development ($/kWh)	$62.70	$69.66	$76.63	$54.31	$59.11	$64.22
Grid Integration ($/kW)	$22.50	$25.00	$27.50	$19.49	$21.21	$23.05
Total Installed Cost ($/kWh)	$390.82	$540.34	$609.46	$310.74	$449.55	$494.13
Total Installed Cost ($/kW)	$1,563	$2,161	$2,438	$1,243	$1,798	$1,977
Fixed O&M ($/kW-year)	$4.30	$6.66	$8.02	$5.13	$6.03	$6.51
Warranty ($/kWh-yr)	$1.66	$1.84	$2.03	$1.28	$1.42	$1.56
Recycling ($/kWh)	$32.85	$36.50	$40.15	$28.25	$31.38	$34.52
RTE (%)	65%	65%	65%	65%	65%	65%
Calendar Life (yrs)	12.00	12.00	12.00	12.00	12.00	12.00
DOD (%)	80%	80%	80%	80%	80%	80%

Duration hr
- ○ 2 hr
- ● 4 hr
- ○ 6 hr
- ○ 8 hr
- ○ 10 hr
- ○ 24 hr
- ○ 100 hr

Power MW
- ○ 1 MW
- ● 10 MW
- ○ 100 MW
- ○ 1,000 MW

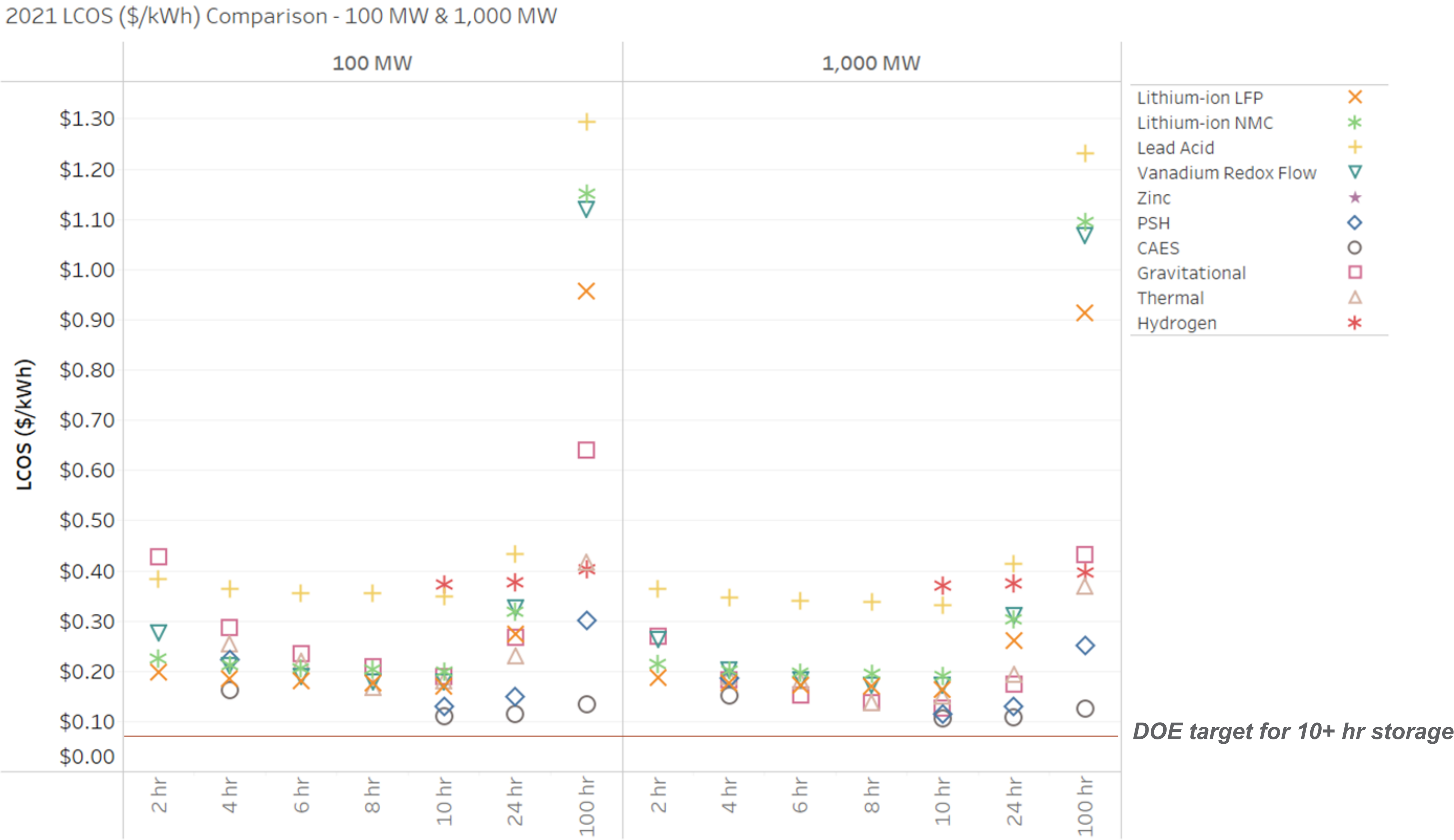
* Cycle Life (#) represents available cycles until remaining energy is equivalent to average DOD (%).

Installed Cost Comparison across Technologies



Levelized Cost of Storage Technologies

- Levelized Cost of Storage (LCOE): measures the ratio of the cost of owning and operating an asset over its usable life by the energy delivered.
  - Can be interpreted as the $/MWh that electricity output/discharge would need to be priced at to break even on the asset over its lifetime.



$$LCOS = \frac{(FCR \times CAPEX_{PV}) + (CRF \times FOM_{PV})}{AE} + O\&M_{Variable} + ECC$$

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PNNL leads Battery500 Consortium

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Brookhaven National Laboratory

INL Idaho National Laboratory

SLAC

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK

ATM

PennState

Stanford

W UNIVERSITY of WASHINGTON

UC San Diego

UNIVERSITY OF MARYLAND

gm

University of Pittsburgh

TEXAS The University of Texas at Austin

Partner logos as they appear on https://www.pnnl.gov/innovation-center-battery500-consortium/partners-and-people

- ***Double the specific energy (to 500 WH/kg) relative to today's battery technology*** while achieving 1,000 electric vehicles cycles.
- Aims to overcome the fundamental scientific barriers to extract the maximum capacity in electrode materials for next generation lithium batteries.
- Leverages advances in electrode materials and battery chemistries supported by DOE.
- First class team.
- Partnership and integration with current BMR programs.

PNNL leads Rapid Operational Validation Initiative

- **Rapid Operational Validation Initiative (ROVI) will validate the testing of new energy storage systems**
- $2M investment from DOE Office of Electricity
- Six national labs support ROVI
- First phase: labs will work closely with industry and academia to develop a framework outlining specific flow battery systems data needs, and a strategic roadmap to complete the program
- Next phase: collect data from real systems in the field and address critical gaps in data needs; opportunity to leverage artificial intelligence and machine learning for insights about the performance of LDES technologies

Advanced Battery Facility

Battery Reliability Laboratory

https://www.energy.gov/oe/articles/energy-department-selects-six-national-laboratories-validate-battery-energy-storage

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DOE Office of Electricity Grid Storage Launchpad

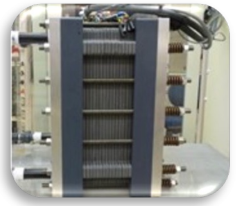
Validate Accelerate Collaborate Educate

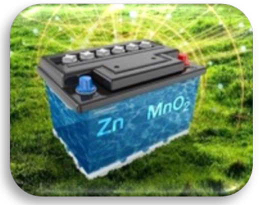
91,000 Square Feet	108 Workstations	30 Lab Modules	**$75 Million** Estimated Facility Cost

GSL is an integrated set of capabilities to develop and test new battery materials and systems

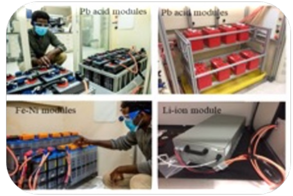
Deployment and Implementation

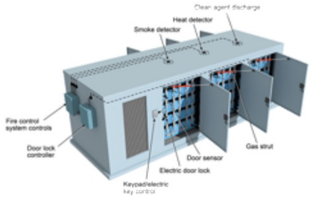
Grid Storage at PNNL



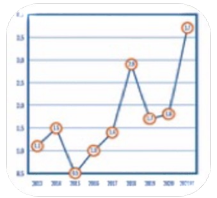


Cost Competitive Technologies – *Develop material improvements to resolve key cost and performance challenges for LDES technologies – flow, sodium, zinc, etc.*





Validated Safety and Reliability – *Develop evaluation protocols, materials, and system designs to ensure the safety and reliability of deployed energy storage systems.*



Equitable Regulatory Environment – *Analyze regulatory hurdles and foster an environment where storage services are recognized and appropriately valued.*


Grid Deployments – *Facilitate greater confidence in field deployments through advanced evaluation and optimization tools, and controls and supporting stakeholders.*

ES4SE – *An innovative technical assistance and technology deployment program advancing community prosperity, well-being, and resilience*

Battery Safety is a Systems Approach

- Chemistry
- Cell QC
- Integration
- BMS
- Communications
- HVAC
- Fire Protection
- Explosion Control
- Workmanship

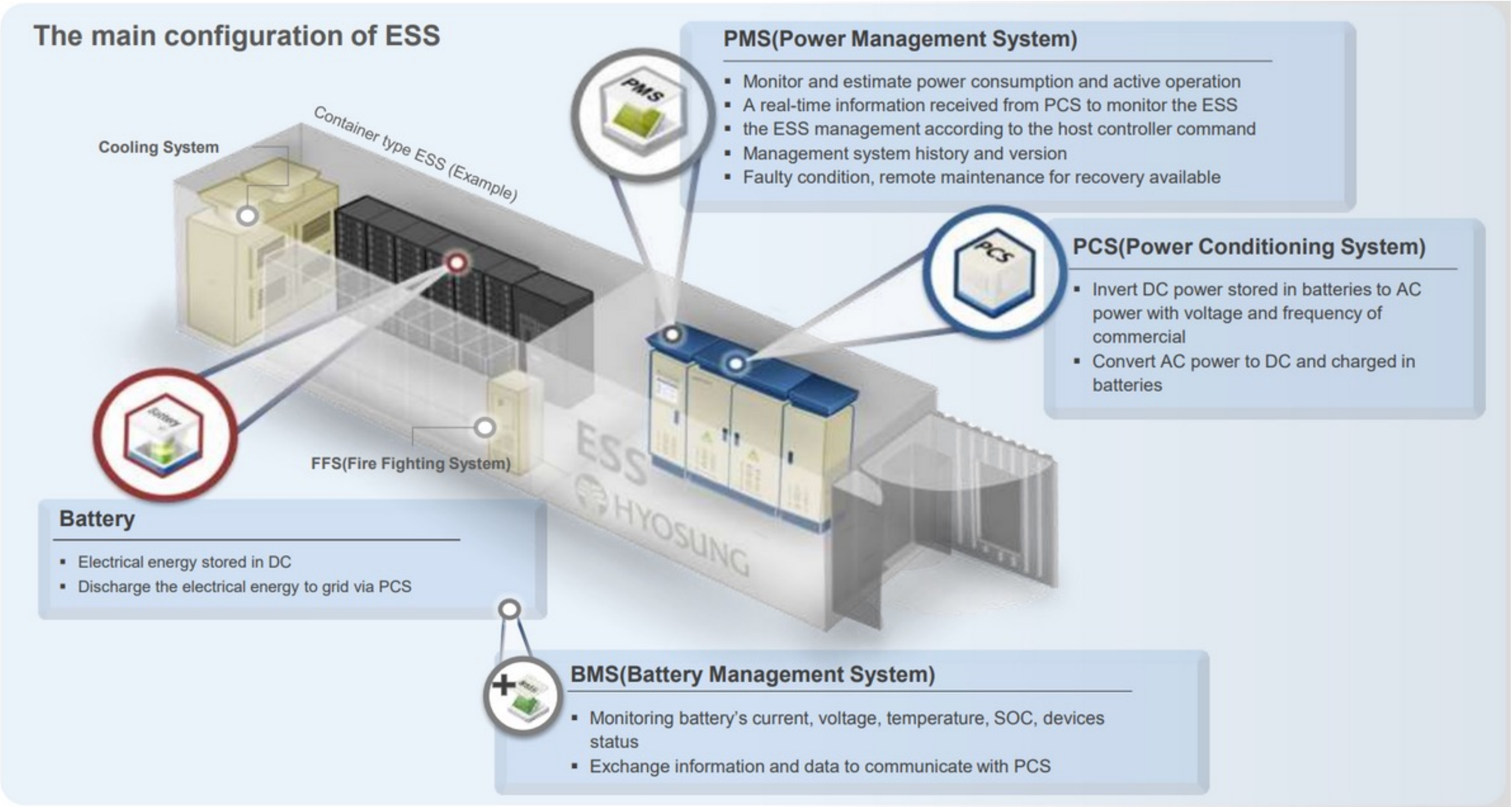
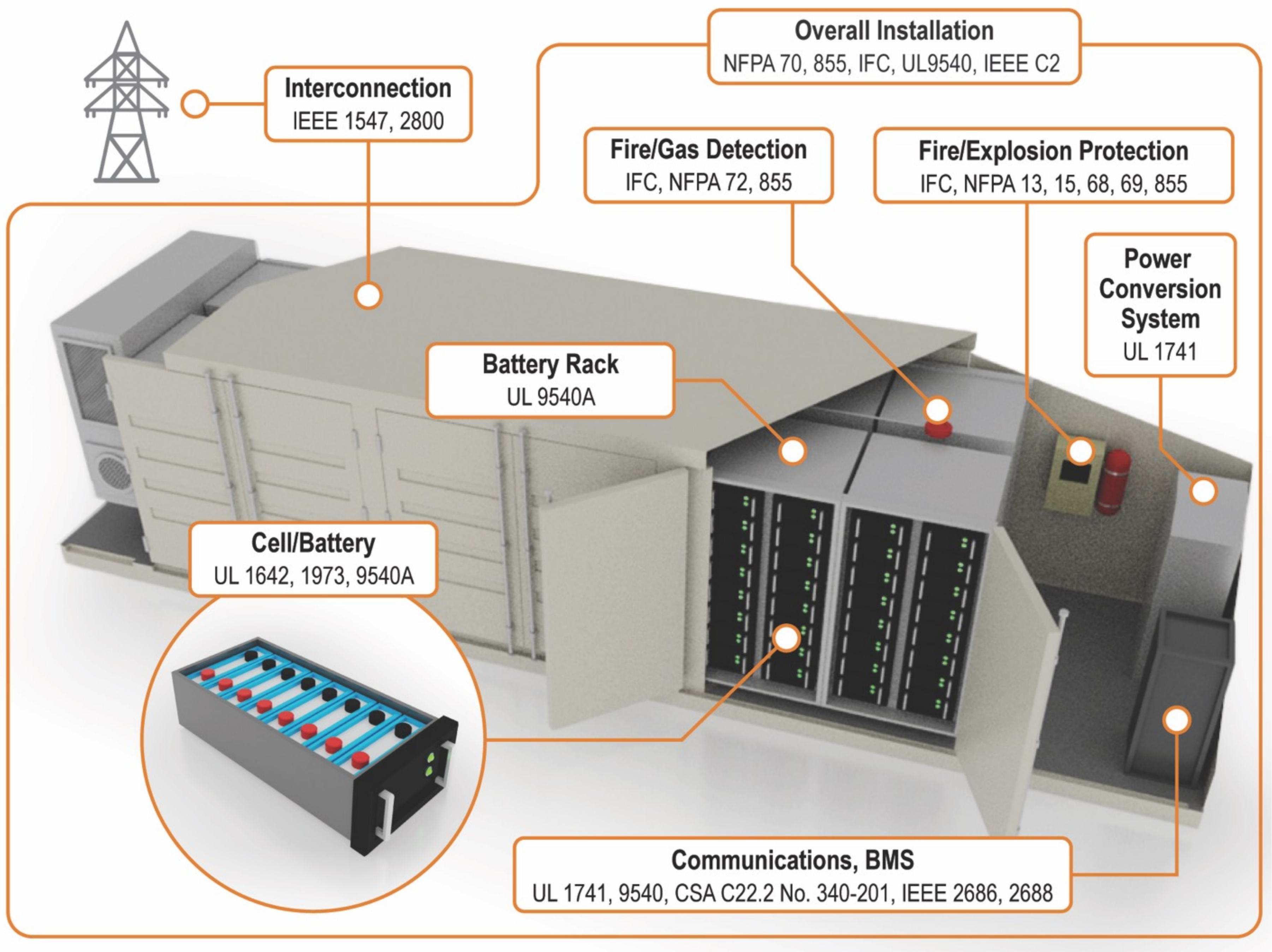


Image source: Hyosung Heavy Industries

Codes & Standards

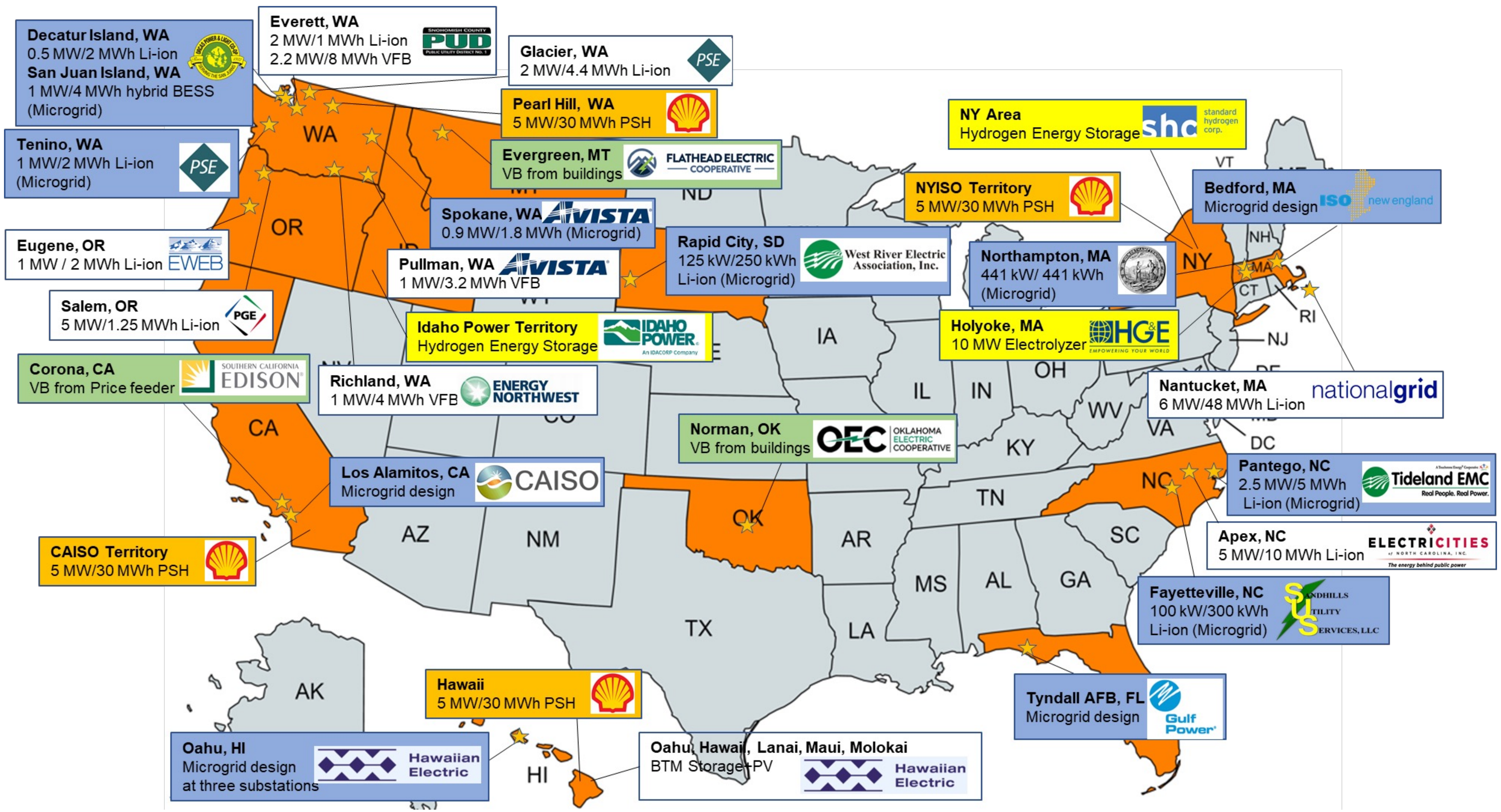


NFPA 855 & International Fire Code

- 2023 NFPA 855
- Key ESS Document
  - Covers
    - ✓ Design & HMA
    - ✓ Commissioning
    - ✓ Size & Separations
    - ✓ Explosion Control
    - ✓ Emergency Response & Training
    - ✓ Decommissioning
    - ✓ Retroactive Req's

- 2024 IFC
  - Closely harmonized with NFPA 855
  - Adopted in 42 states
  - 2027 edition may simply point to NFPA 855

Performance Validation of Deployed Storage Systems



Battery Energy Storage | Hydrogen | Microgrids | Building as storage | Pumped Storage Hydro

Small Island Co-op Utility Explores Microgrid Solution

- OPALCO BESS/PV at Decatur Island
- ESS sized at 1MW / 2.6 MWh co-located with PV sized at 504 kW (DC)
- Utility objectives include
  - Demand charge reduction
  - Load shaping
  - Submarine cable upgrade deferral
  - Outage mitigation
- PNNL support in development
  - Techno-economic assessment
  - Baseline and Use case testing
  - Validation of the techno-economic analysis
- Lessons learned – vendor controls do not support stacked values

Technical Team: Alasdair Crawford, Di Wu, Vish Viswanathan, and Diane Baldwin

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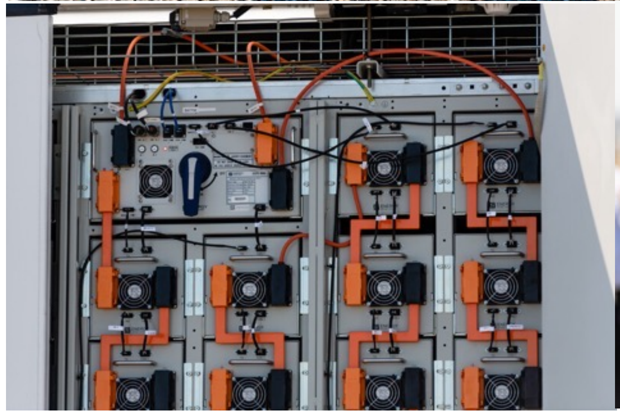
Energy Storage Workforce Development

- Energy Northwest: Horn Rapids Solar, Storage and Training Center
- ESS sized at 1 MW / 4 MWh and PV (4 MW)
- Facility located on land owned by electrician union IBEW and leased by the Regional Education & Training Center – a training ground for utility-scale solar and battery techs
- Utility objectives include
  - Demand charge reduction
  - Solar integration
- PNNL focus in FY22 – testing
  - BESS troubleshooting and repair
  - Baseline testing / use case testing
  - Revision of techno-economic analysis
- Lessons learned – battery performance evaluation is critical to confirming real-world value

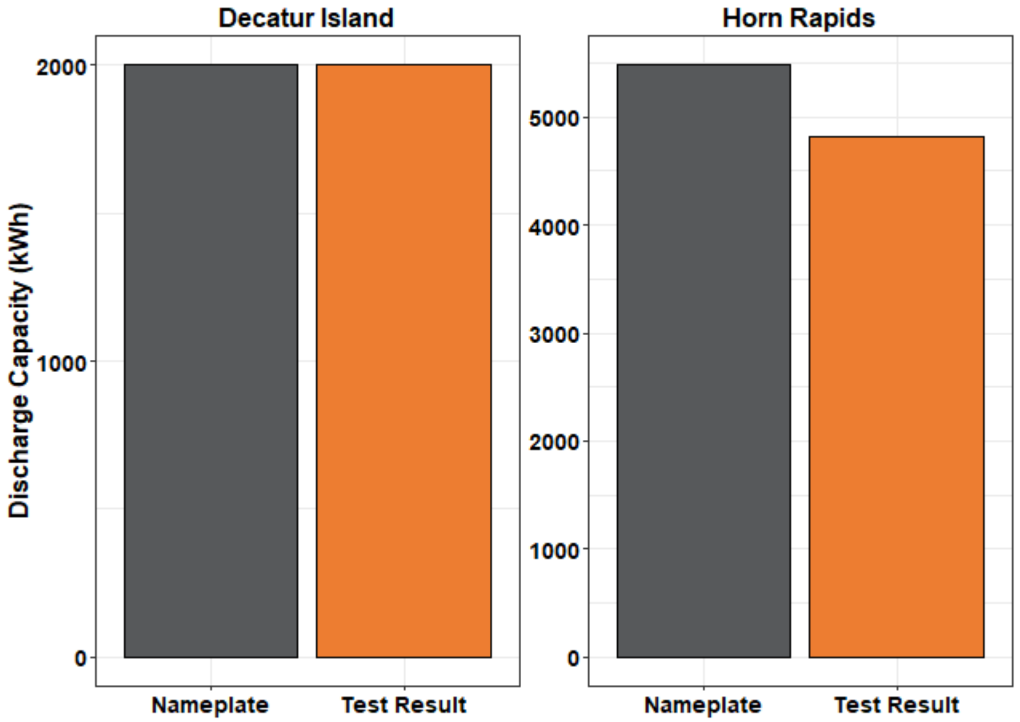


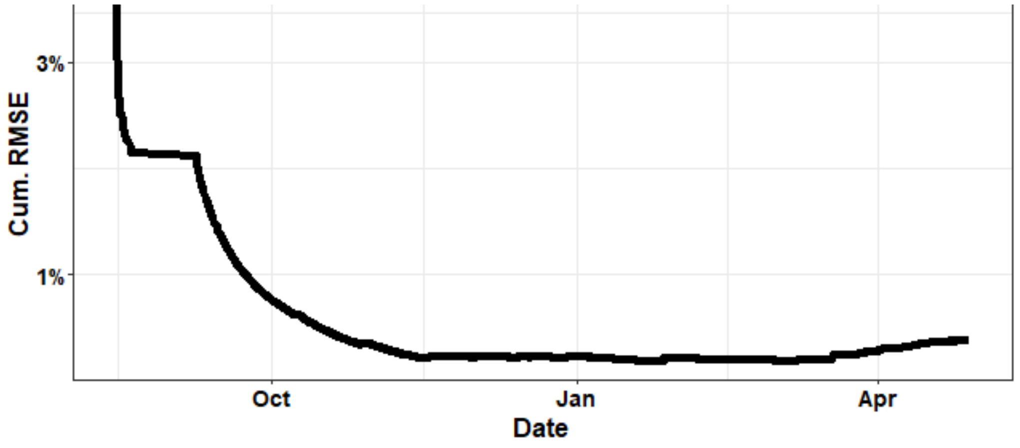
Technical Team: Di Wu, Alasdair Crawford, Xu Ma, Arthur Santos, Vish Viswanathan

Battery Performance Evaluation – Two Case Studies

OPALCO Decatur Island BESS testing highlights

- Efficiency is highest in the 40-90% SOC range
- Efficiency measurements 94% avg up to 99.9%
  - unrealistically high - small errors in the meters probably contributed
- Discharge Energy of the system (2000 kWh) met expectations
- Data availability less than optimal – had to extract from vendor dashboard
- Time resolution of data was 60 sec -- made testing for rapidly changing signals difficult
  - System designed for energy applications (luckily)
- Data rounding for SOC to nearest 1% casts some doubt on other values like efficiency



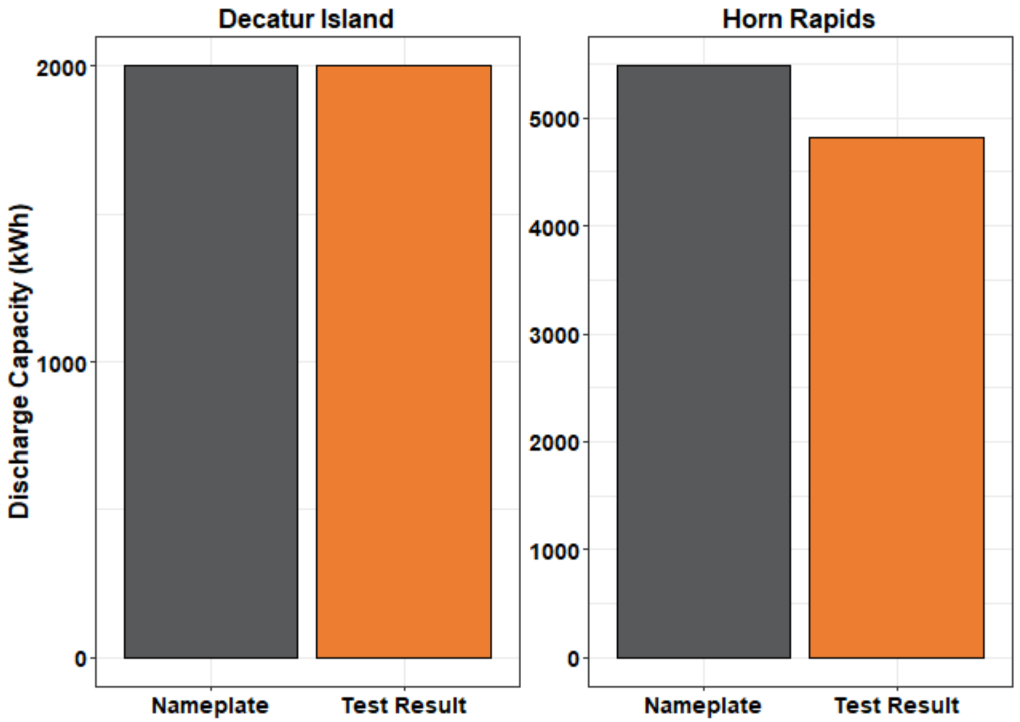


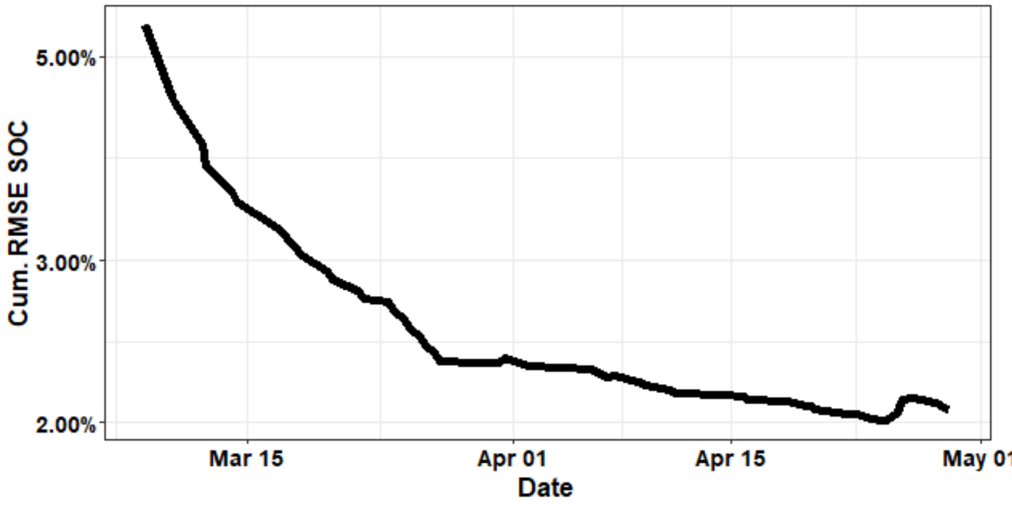
Decatur: Increasing confidence in battery model over test period

Battery Performance Evaluation – Two Case Studies

Energy NW Horn Rapids BESS testing highlights

- Discharge Energy of the system less than assumed
  - 5400 kWh ONLY if you extrapolate to 100% SOC
  - SOC is kept to 5-95%, so in practice discharge energy is limited to 4800 kWh
- Vendor warranty guarantees energy availability per day – that translates to a discharge limit
  - 4000 kWh limit, testing had to straddle midnight hour
- System does not allow a rapidly changing signal
  - Manual entry was necessary for testing
- Vendor provided an API for obtaining data
- Out of the 18 strings, 2 were down during testing. Vendor was not able to resolve.
- Significant findings in battery performance evaluation led to revised economic assessment





Energy NW: Increasing confidence in battery model - longer test period needed

Conclusions

- Technology cost is one component of the overall installed cost of an energy storage system.
- As storage costs drop, storage discharge durations have increased. Still need significant cost reductions to enable battery storage with 10+ hours of peak discharge duration.
- DOE's Energy Storage Grand Challenge/Long Duration Storage Shot targeting a 5¢/kWh Levelized Cost of Storage (LCOS) by 2030 and is tracking technology costs for targeted R&D.
- Challenges around safety, regulatory policy, performance validation and grid-scale deployment require the continued support of researchers at the National Labs to realize the promise of energy storage.

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Thank you

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