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Advances in Grid Energy Storage

Babu Chalamala, Ph.D.

Sandia National Laboratories

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SAND2021-

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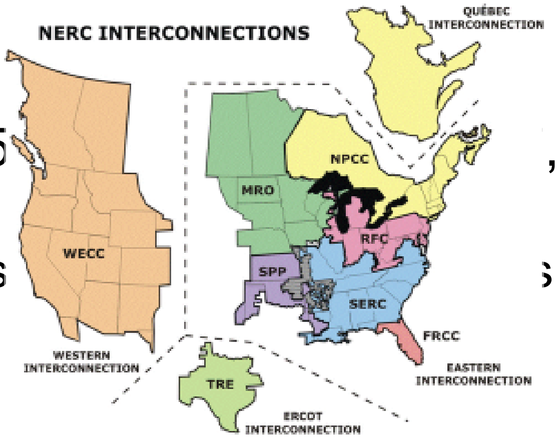
U.S. Electric Grid Today

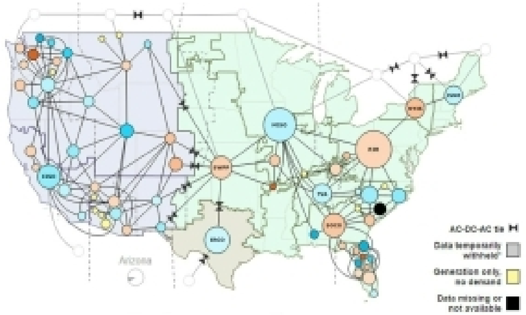
Big interconnected system with ~850GW baseload, 125 ,000 operational power plants

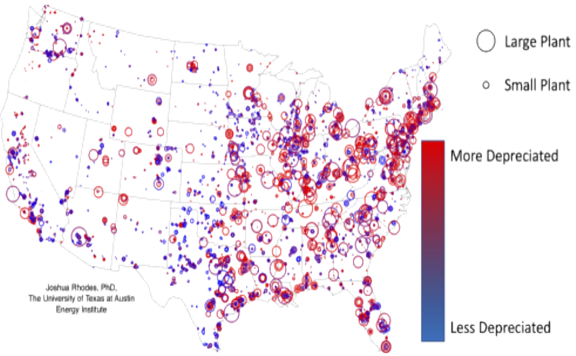
- 3,200 utilities, 60k substations, 642k miles of HV transmiss s of distribution circuit, 159 million customers.
- Revenues reaching $400 B, ~10.42 c/kWh avg
- Increasing NG and renewable generation

Four interconnect regions and a number of balancing

- Eastern Interconnection (31 US, 5 Canada)
- Western Interconnection (34 US, 2 Canada,1 Mexico)
- ERCOT, Hydro-Quebec





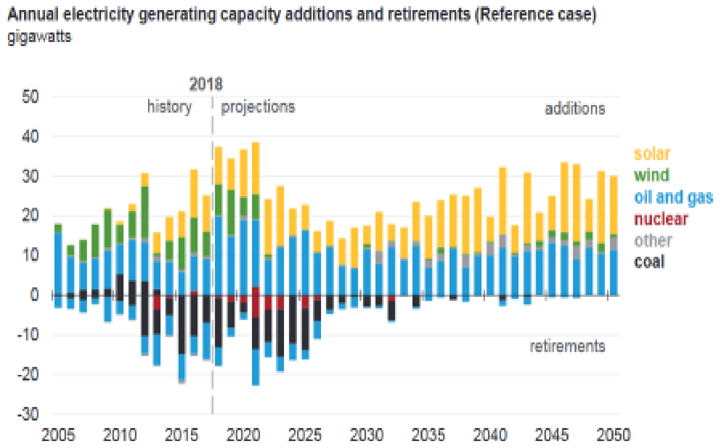


Sources: EIA, EEI http://www.nerc.com

Electricity Industry – Current Changes

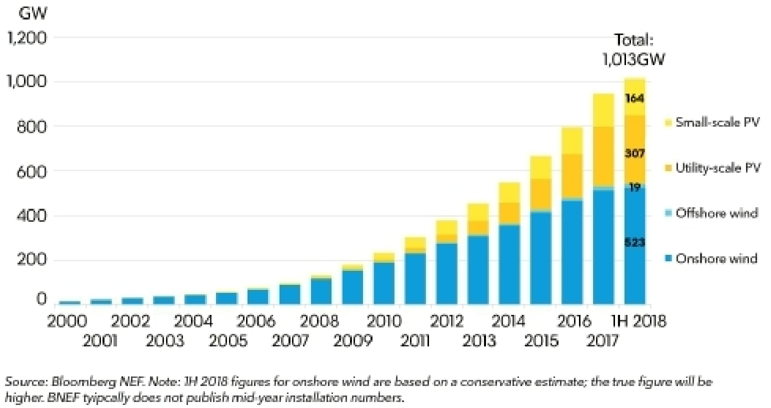
- Major grid infrastructure is aging
- Accelerating retirements of coal fired power plants
- Stalled replacement/expansion of nuclear generation
- Growth of NG and renewables
- T&D congestion starting to impact deployment of renewables
- Meagre demand growth
- Rapid changes at the grid edge

Capacity Additions and Retirements

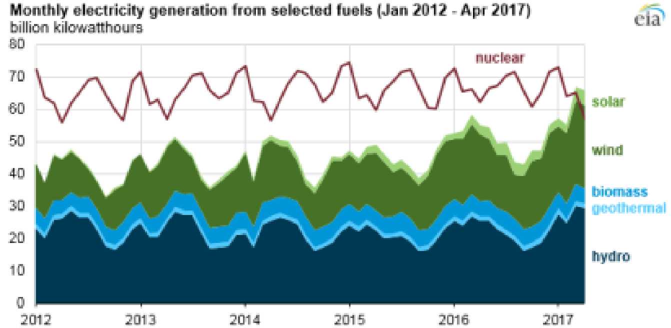


EIA Annual Energy Outlook 2019

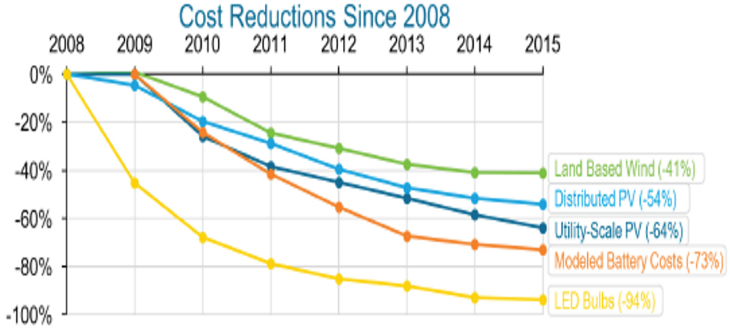
Cumulative global solar and wind capacity (June 2018)



Utility-scale Renewables Generation surpassed Nuclear Generation (April 2017)



Cost reductions primarily due to high volume manufacturing and large scale deployments

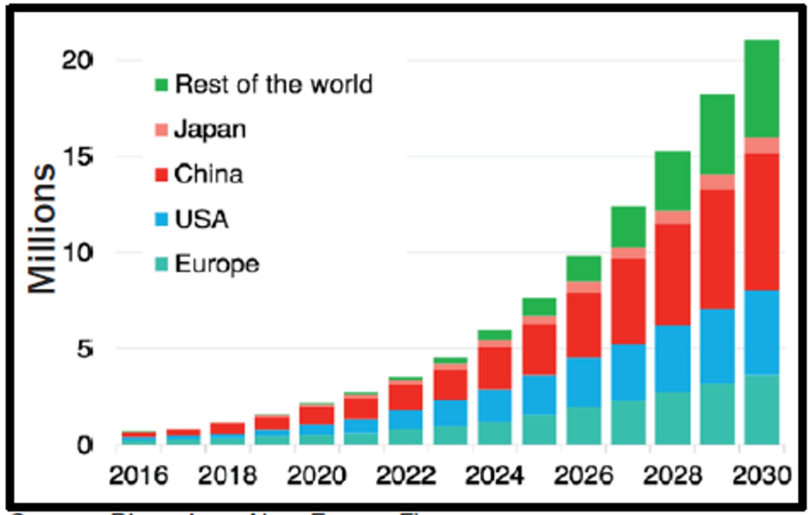


http://energy.gov/eere/downloads/revolutionnow-2016-update

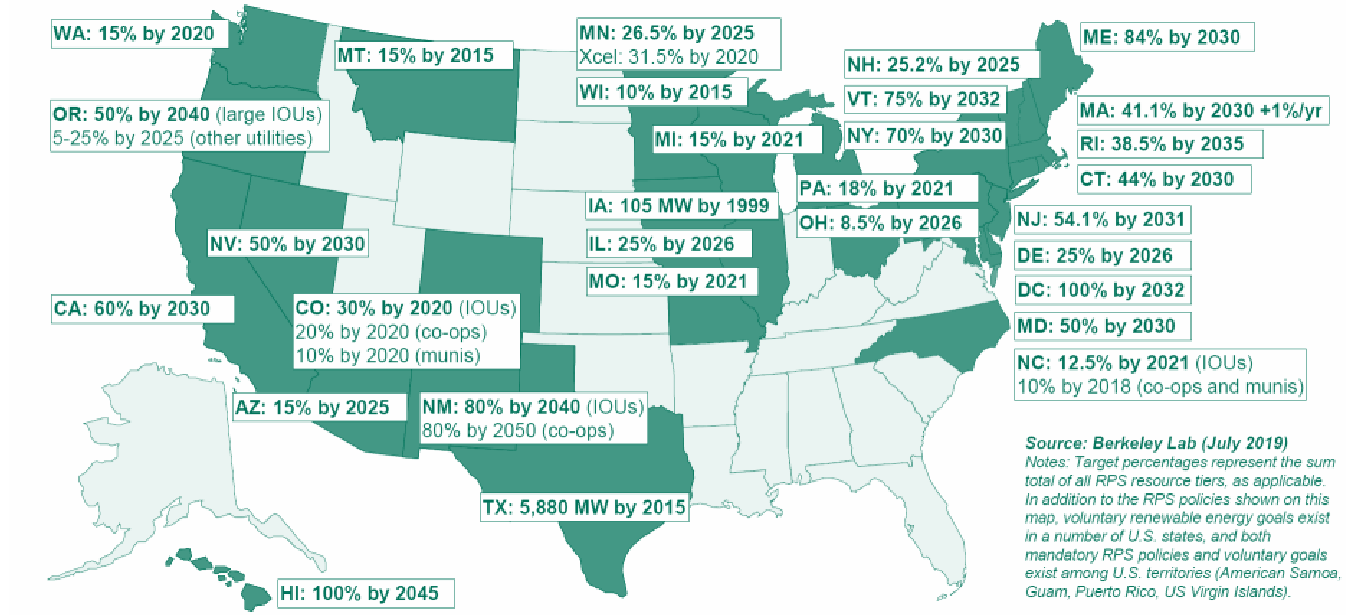
Coal-fired unit retirements driven by low NG prices (EIA, 2017)
In California, solar, storage and wind capacity additions expected to exceed NG by ‘21(GTM)

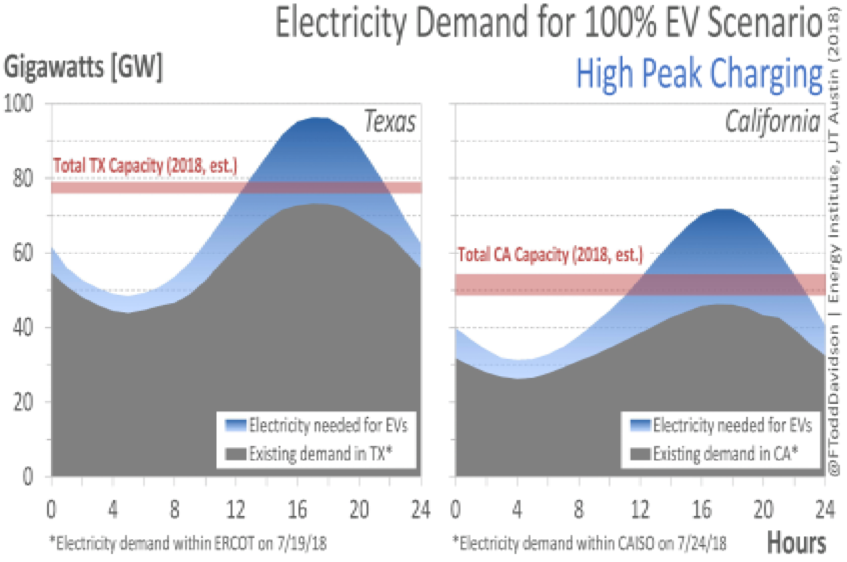
Electricity Industry - Coming Changes

- Electrification of transportation
  - Annual production of EVs reaching 20M by 2030, 130M-230M case (BNEF, IEA, 2018)
- RPS becoming wide spread across all states
- Drive towards fossil free generation

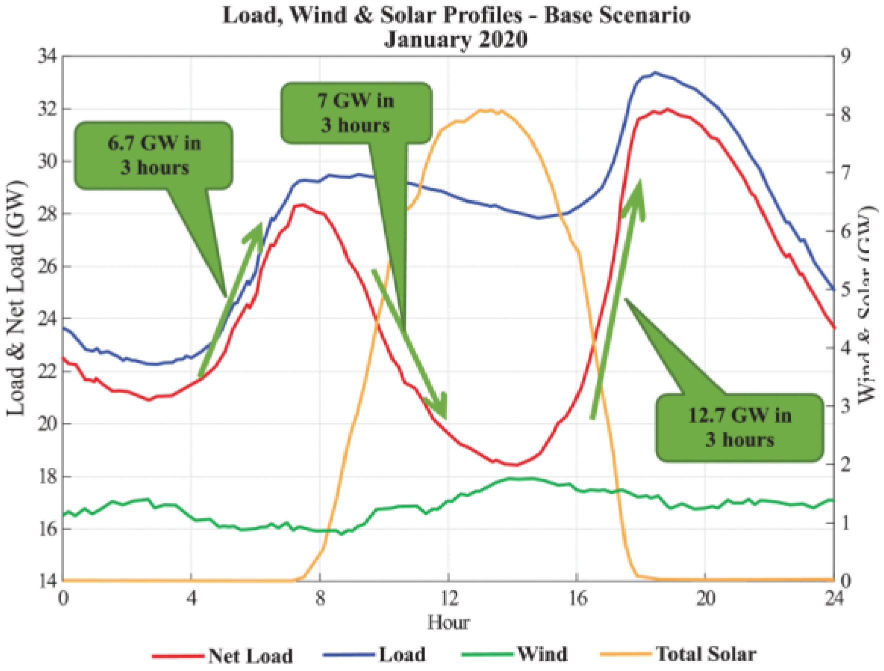


Source: Bloomberg New Energy Finance

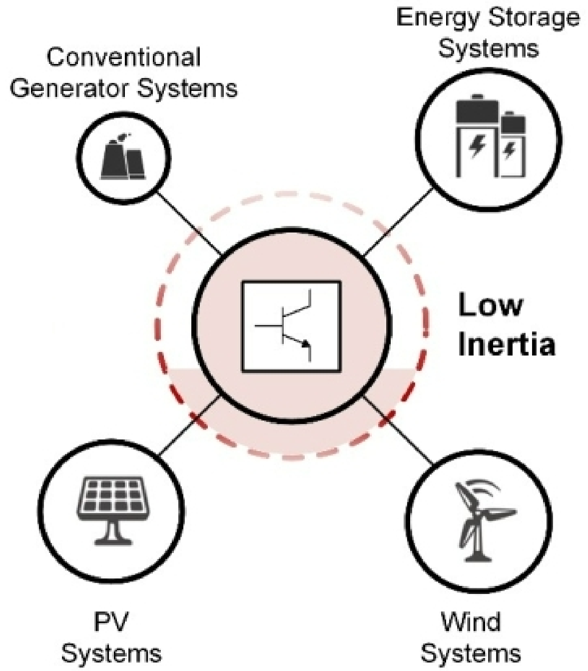




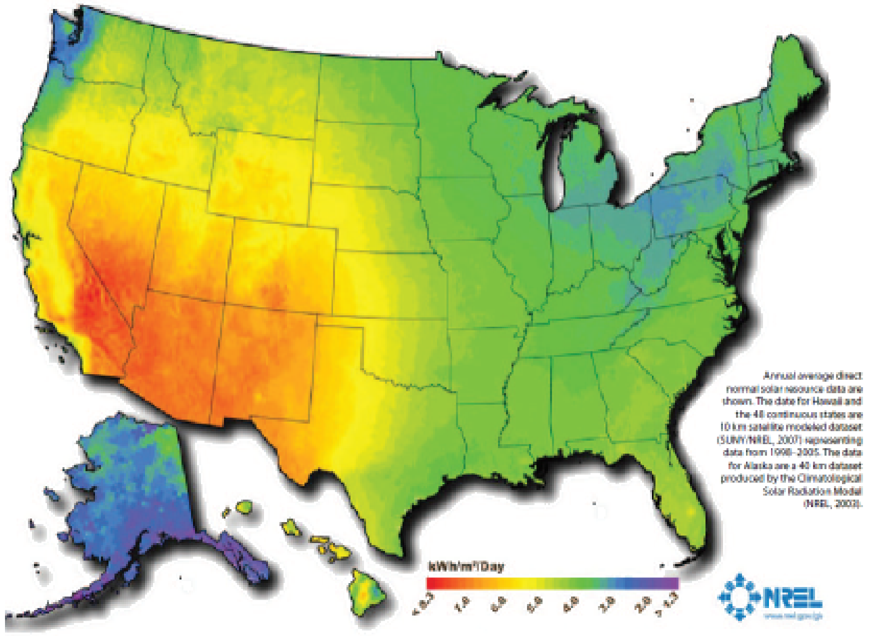
Challenges for Grid Reliability



Source: CAISO



Source: U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," Applied Sciences, vol. 7, no. 7, p. 654, Jun. 2017.



High Variability And Uncertainty

Large amount of generated renewable energy is not coincident with the peak load creating large ramps

Zero Inertia Grid

Inverter-dominated power systems have low or no inertia creating large frequency fluctuation after disturbances.

Transmission Infrastructure

Most attractive resources for wind and solar are located far from load center requiring enormous transmission expansion.

Maintaining Grid Reliability

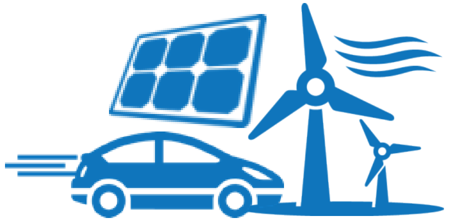
Must have sufficient generation and transmission capacity to meet peak demand

Able to maintain steady system frequency

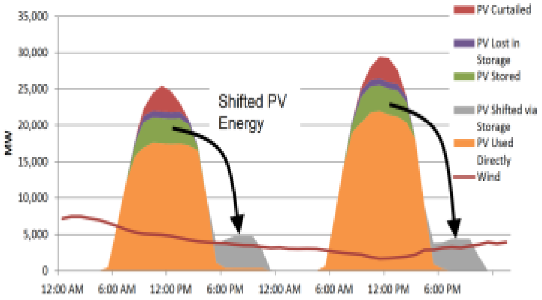
Must be able to maintain steady local voltages

Role of Energy Storage in the Grid

- Energy storage is a key resource for grid operators:
  - Provides flexibility, resiliency and reliability
  - Improves power quality
  - Improves the efficiency of existing generation fleet
  - Facilitates demand management
  - Supports large scale renewable integration; T&D upgrade deferrals
  - Provides alternative to “locational marginal price”
  - Supports multiple grid services and value streams
- Energy storage is essential to achieving 100% renewable generation, especially considering declining cost of solar and wind.
  - Large grid-scale energy storage can be a solution for intermittency and overcapacity of 100% renewable generation scenario

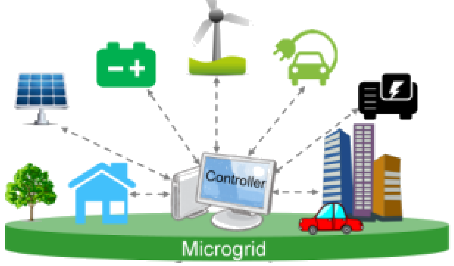


Balancing renewable variability



Peak shaving and energy shifting

Regulation/contingency reserves



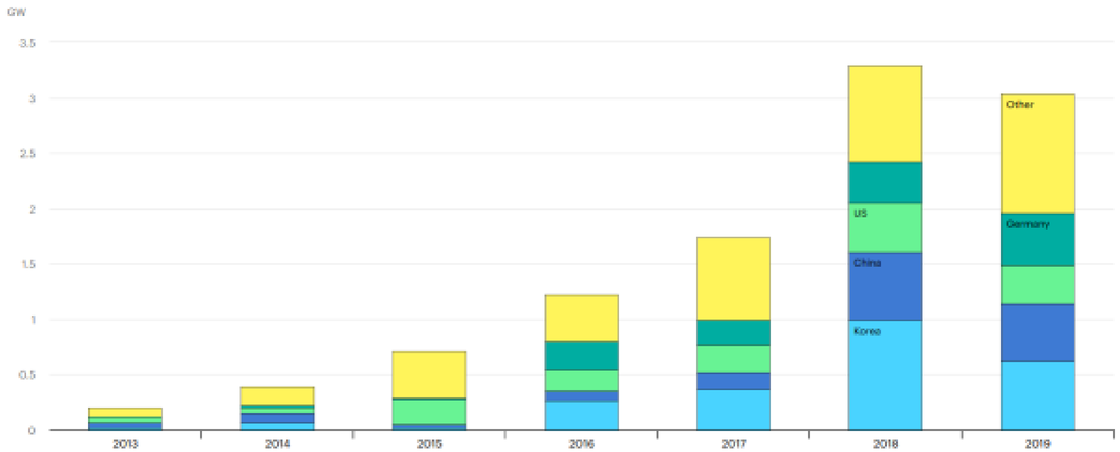
Microgrid

Key metrics: MW, MWh, cost, scale, cycles, safety and performance

Sources: Berkeley Lab, NREL, Energy Sage.

Energy Storage in the Grid Today

- Energy storage installations increasing globally.
  - Total 2.9 GW Battery ES capacity added in 2019 worldwide, despite temporary sluggishness due to COVID-19.
- Key driver of growth in energy storage has been the co-location of renewable energy with energy storage, for firm capacity and peak demand.
  - 15 GW co-located storage projects with solar PV in utilities in the pipeline in the United States
- Battery energy storage is the majority of new capacity installed, benefitting from the spill-over of EV technology development to grid-scale batteries.
  - US installed capacity of BESS over 2 GW, new capacity coming fast
  - Lithium-iron phosphate batteries used for the majority of grid-scale installations in 2019 in China



Global energy storage installation keeps growing

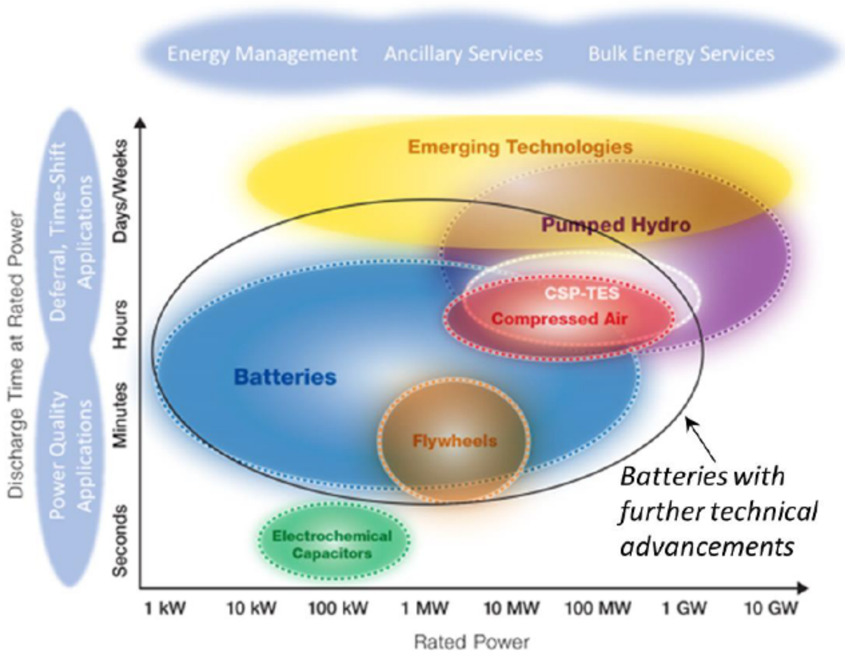
Key driver of energy storage growth is co-location with renewables

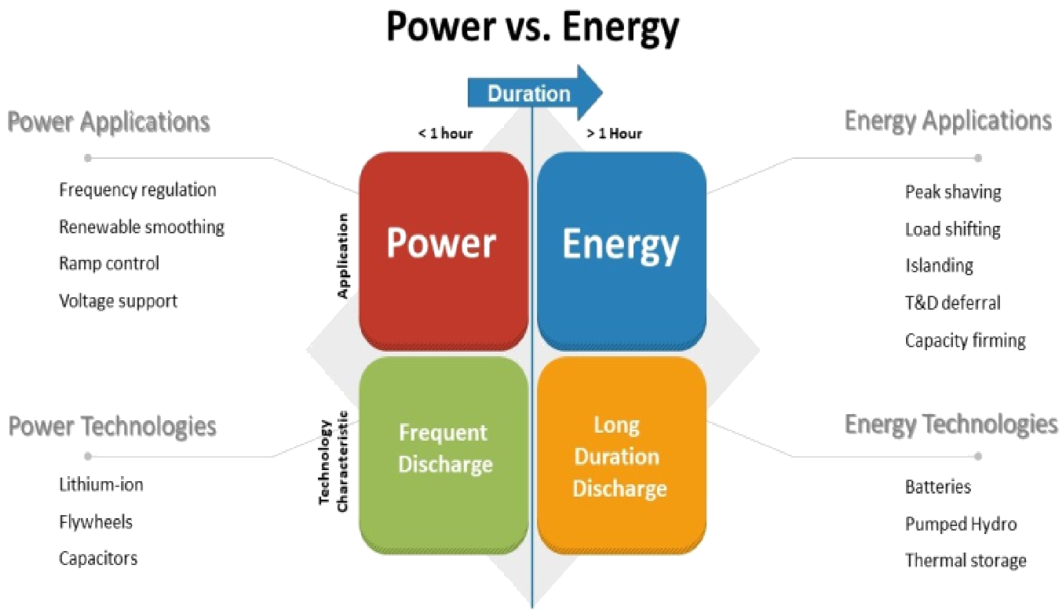
Sources: IEA (https://www.iea.org/reports/energy-storage)

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

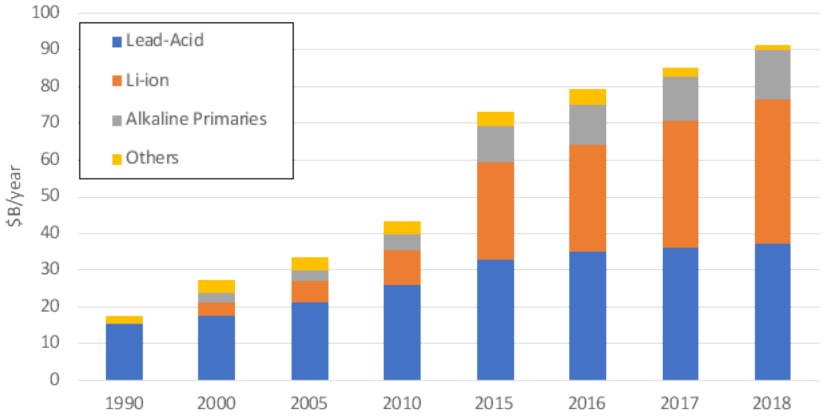
Battery Energy Storage Technologies

Traditional Batteries
e.g. Lead-acid, Ni-Cd, Ni-MH, Zn-MnO_2

Lithium Batteries
e.g. Li-ion, Li-polymer, Li-metal, Li-S

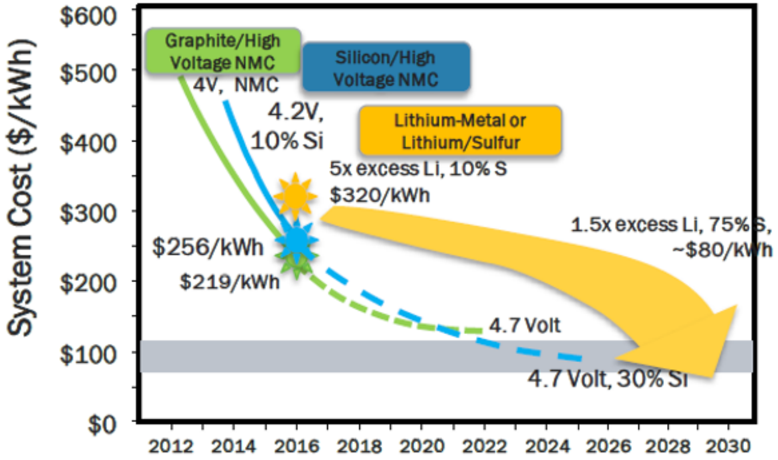
High-temperature Batteries
e.g. Na-S, Na-$NiCl_2$

Flow Batteries
e.g. Vanadium redox, Zn-Br



- Lead-Acid: 350 GWh production capacity, $38B/yr
- Li-ion: over 400 GWh and growing capacity, $40B/yr
- Zn-MnO_2 Primary cells: $13B/yr

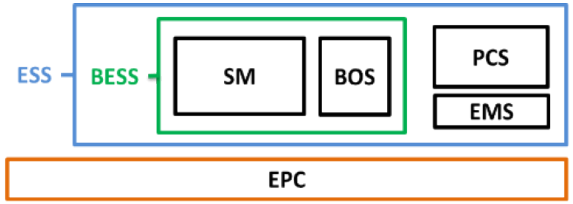
Source: S. Banerjee, DOE ESGC South/Southwest Workshop, June 2020



Cost trends for Li-based EV Batteries (pack level)
Source: David Howell, DOE VTO, 2018

- **Market Drivers**
  - Consumer electronics, mobile devices and EVs – primarily Li-ion batteries.
  - Grid energy storage – growing market, currently modest size. Range of technologies.

Battery Energy Storage is not just about Batteries …



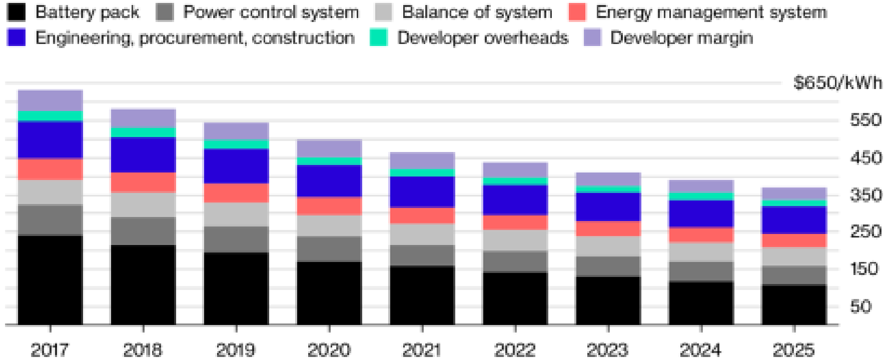
SM Storage Module
Rack Level System (DC)

BESS Battery Energy Storage System
Containerized System (DC)

ESS Energy Storage System
Complete Storage System (AC)

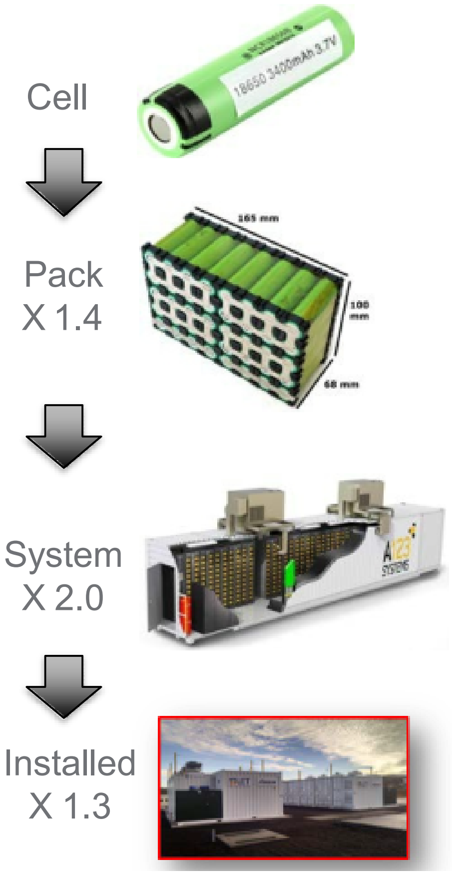
Storage Module (SM)	Balance of System (BOS)	Power Conversion System (PCS)	Energy Management System (EMS)	Engineering Procurement & Construction (EPC)
Racking Frame / Cabinet	Container	Bi-directional Inverter	Application Library	Project Management
Local Protection (Breakers)	Electrical Distribution & 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

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



Note: Benchmark numbers for a 1MW/1MWh project
Source: Bloomberg New Energy Finance (BNEF)

Bloomberg



Cell Architecture
- Cell format
  - Cylindrical, Prismatic
  - Bipolar
  - Flow Cell

Cell Chemistry
- Aqueous
- Non-aqueous

Thermal management
- Heating
- Cooling

Safety
- Abuse resistance
- Flammability
- Toxicity
- Containment

Plant Models
- Modularized

Power vs. Energy
- High-power, short-duration discharge
- High-energy, long-duration discharge
- Fast Charging

Modularity and Scalability
- kW to MW (Power Scaling)
- kWh to MWh (Energy Scaling)
- Module stacking and Containerization

Cycle Life
- Electrical
- Thermal

Operational Aspects
- Round-trip efficiency
- Auxiliary power consumption
- O&M Costs

Cell to Battery to a Storage System
doubling or tripling in cost from cell to installed system

Integration costs are significant
Big savings in systems and integration..

Li-ion BESS Driving Large Commercial Deployments

Saft 6 MW / 4.2 MWh ESS
Kauai - Grid Stability

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

GWh size BESS Plants no longer at the conceptual stage

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

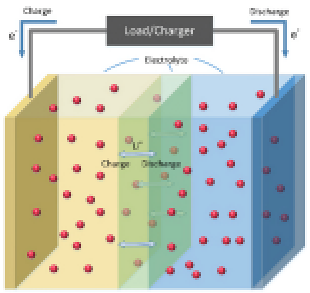
Vistra Energy, Moss Landing Power Plant, Monterey, CA - 300 MW / 1200 MWh – Peaker Replacement, Grid Reliability

Images: Company websites, Wikipedia

Making Energy Storage Mainstream: Gaps

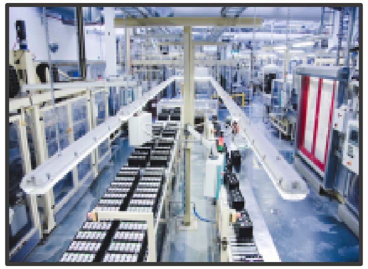
Technology

- Lower cost, longer duration energy storage is a major gap
- Technologies that can scale from microgrids to large transmission applications
- Further improvements in safety and reliability



Manufacturing

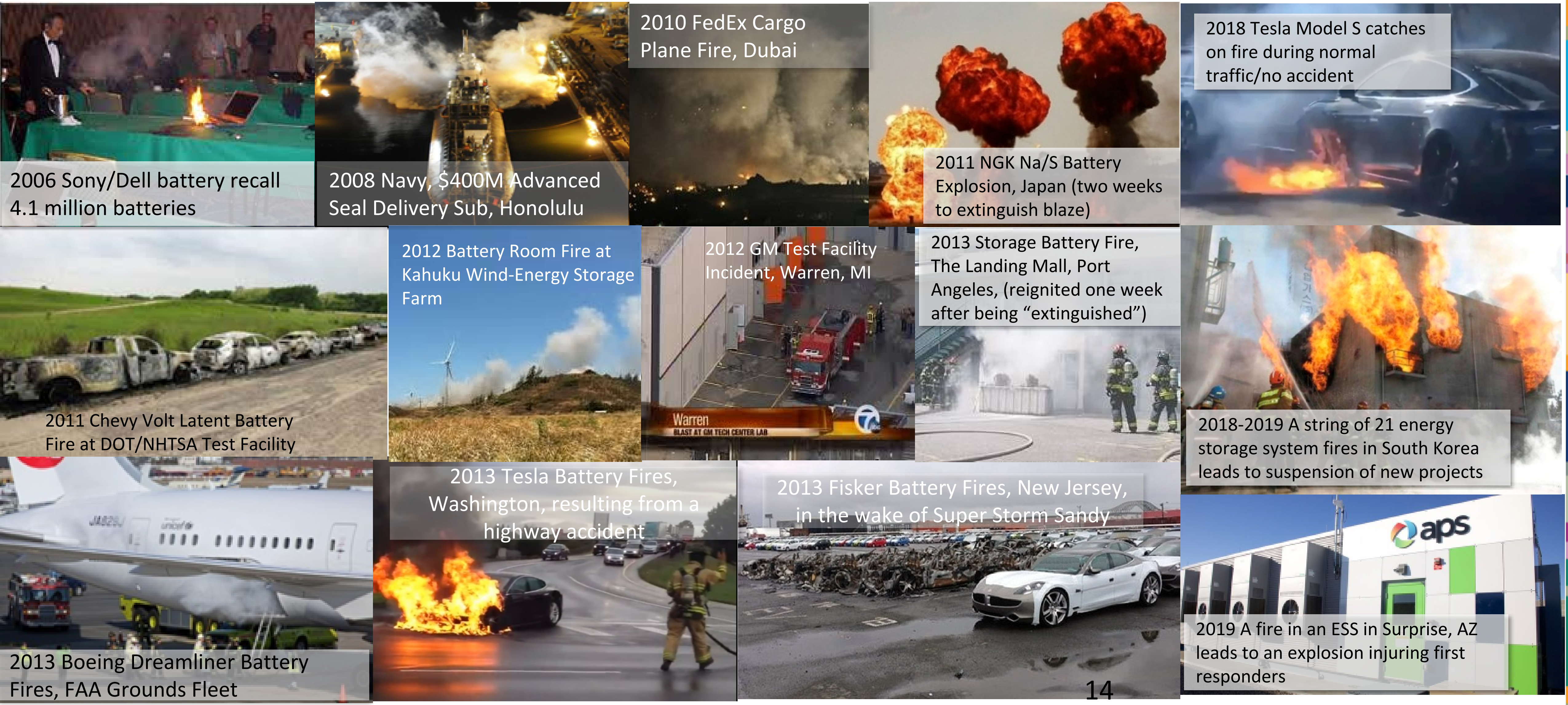
- Industry needs cycles of learning – manufacturing scale through deployments
- Project finance – bankable, warrantees, performance guarantees, risk management
- Standardization – equipment, permitting, construction processes



Grid Operation

- Markets and Operations – business models and operational tools
- Analytics – economics and planning tools
- Appropriate Regulatory Policy – business models, asset classification

Grid ESS - Battery safety is a major concern



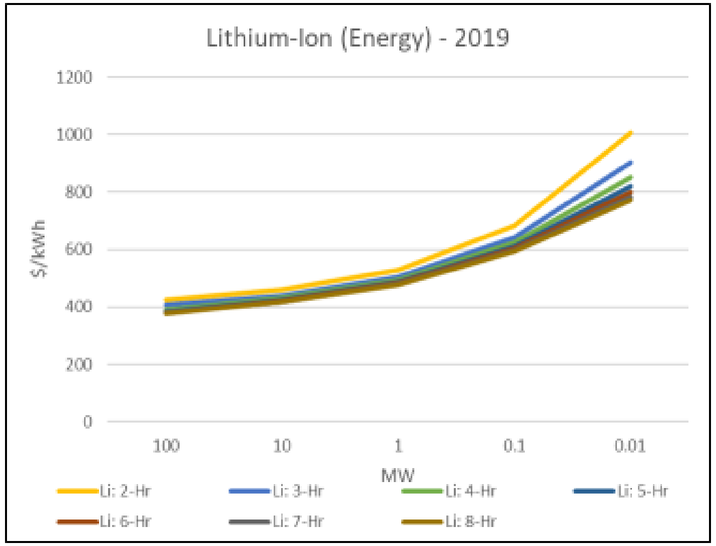
Costs need to come down further
2019 Energy Storage System Pricing Survey

2019 Energy Storage Pricing					
	Size (MW)				
	100	10	1	0.1	0.01
$/kW					
PHS	1676.9				
CAES	1506.2				
FW SD		984.0	1190.0	1500.0	
$/kW (1 Hr)					
Li (Power)	504.2	545.6	629.1		
$/kW (4 Hr)					
LAES	451.0	511.5			
GES	903.0				
FW LD		677.8	766.0	855.3	975.0
Li (Energy)	392.0	430.6	493.4	623.0	850.3
Zn	271.4	289.7	336.8	398.7	
Pb			352.0	425.5	588.4
PbC			557.2	620.0	768.2
$/kW (6 Hr)					
Na	376.3	389.6	428.7		
FB ZnBr	450.9	464.9	478.8	510.6	
$/kW (8 Hr)					
FB V	309.7	372.2	439.0	620.2	
FB Fe	362.7	381.7	404.7	438.4	

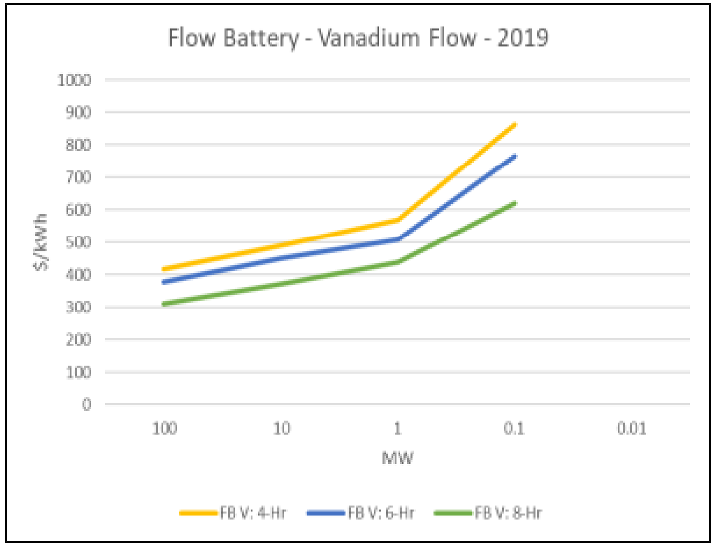
Source: R. Baxter, "Energy Storage Pricing Survey& Energy Storage Financing Study Series," DOE ESS Program 2020 Peer Review, Sept 30, 2020 and 2019 Energy Storage Pricing Survey, Sandia Report: SAND-XXXX, 2020
R. Baxter, Energy Storage Financing: Performance Impacts on Project Financing Sandia Report: SAND2018-10110, Sept 2018

Pricing data based on a survey of 77 data sources from OEMs, System Integrators and utilities.

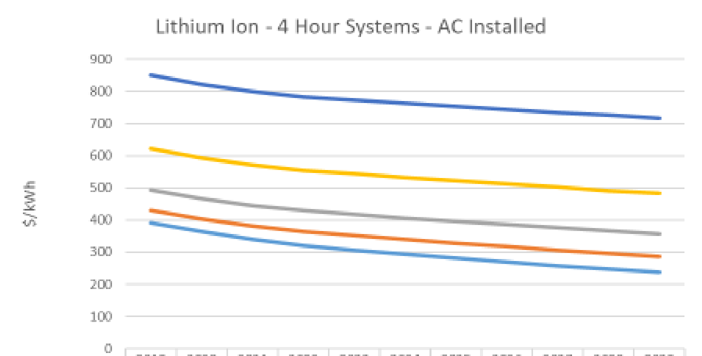
Installed System Costs



Installed System Costs

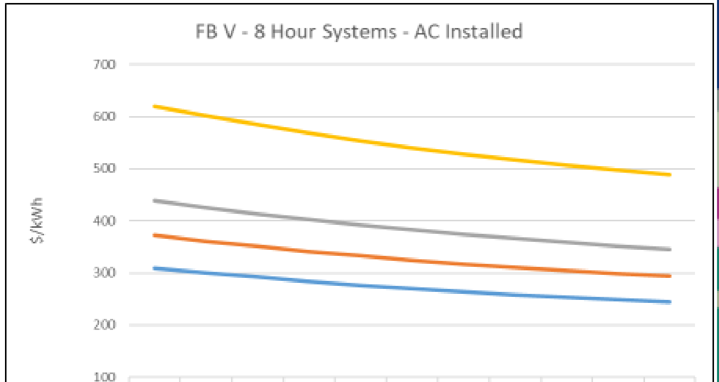


System Price Forecast (Installed)



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	392.0	363.1	339.8	321.2	306.7	293.2	280.7	268.8	257.5	246.8	236.6
10 MW	430.6	403.2	381.5	364.5	351.7	339.4	328.1	317.3	306.8	296.8	287.2
1 MW	493.4	466.6	445.7	429.9	418.2	406.7	396.2	386.0	376.1	366.5	357.2
0.1 MW	623.0	594.0	571.7	555.2	543.9	532.8	522.2	511.9	501.8	491.9	482.3
0.01 MW	850.3	822.0	800.0	783.9	773.3	762.8	752.5	743.7	735.1	726.6	718.3

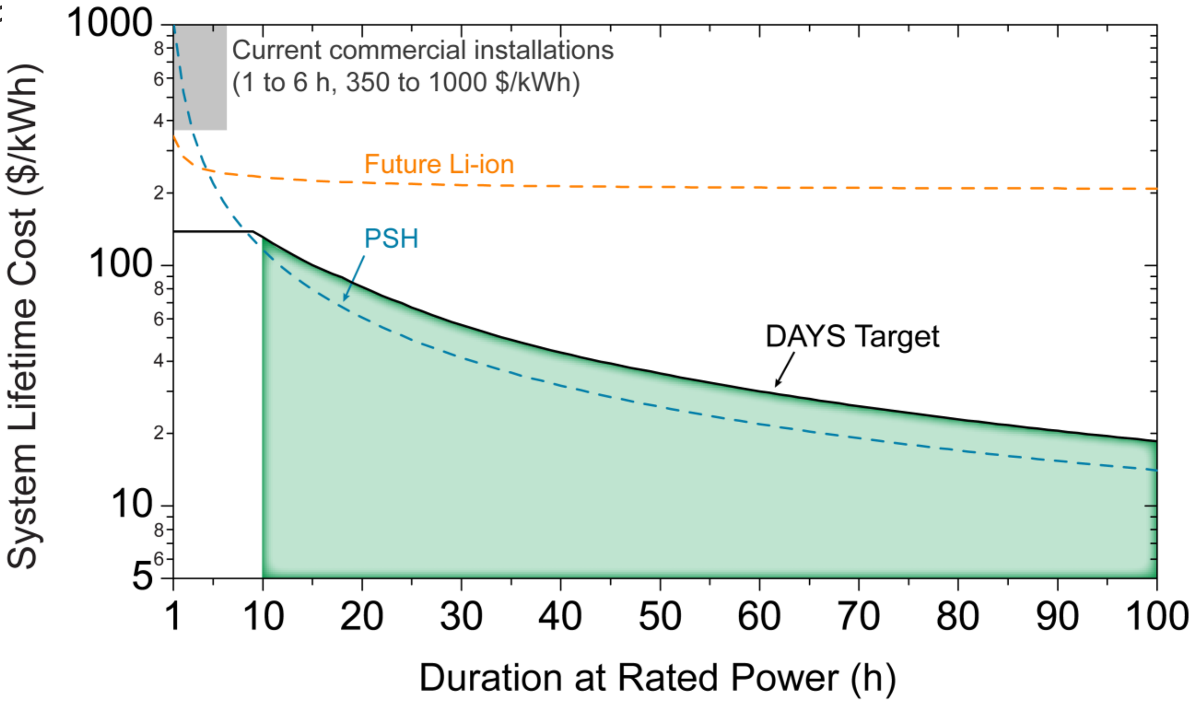
System Price Forecast (Installed)



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	309.7	300.4	291.8	283.9	276.6	269.9	263.7	258.1	253.0	248.3	244.1
10 MW	372.2	361.1	350.7	341.2	332.5	324.4	317.1	310.3	304.1	298.5	293.5
1 MW	439.0	425.8	413.6	402.4	392.1	382.6	373.9	365.9	358.6	352.0	346.0
0.1 MW	620.2	601.6	584.4	568.6	553.9	540.4	528.1	516.7	506.4	496.9	488.4

Long Duration Energy Storage is a Serious Gap

- 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.
- Longer duration energy storage economic requirements are significantly different from battery storage.
- Projects have to be la



Sources: Albertus et al., Joule 4, 21-32, Jan. 15, 2020.

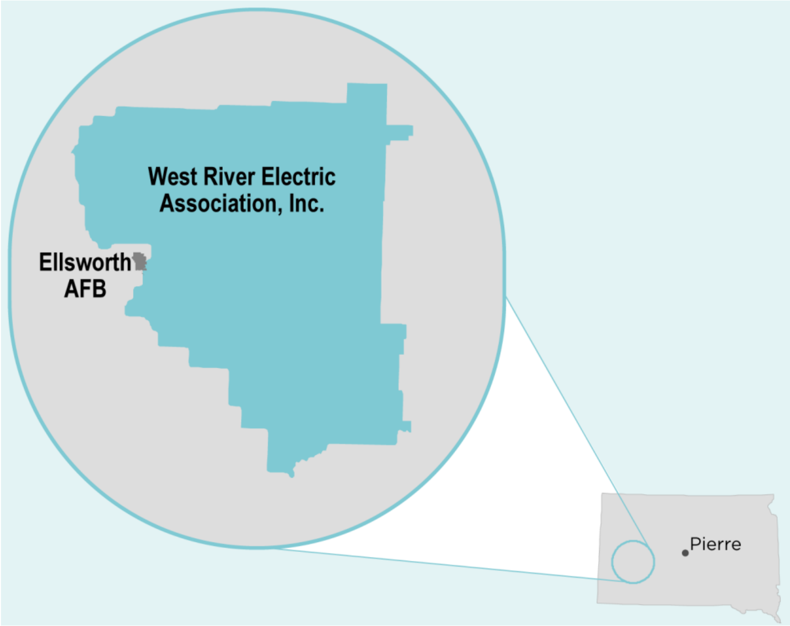
Energy Storage and Grid Resiliency - Examples

Growing application of energy storage for grid resiliency
- distribution system resiliency
- reducing dependency on diesel backup

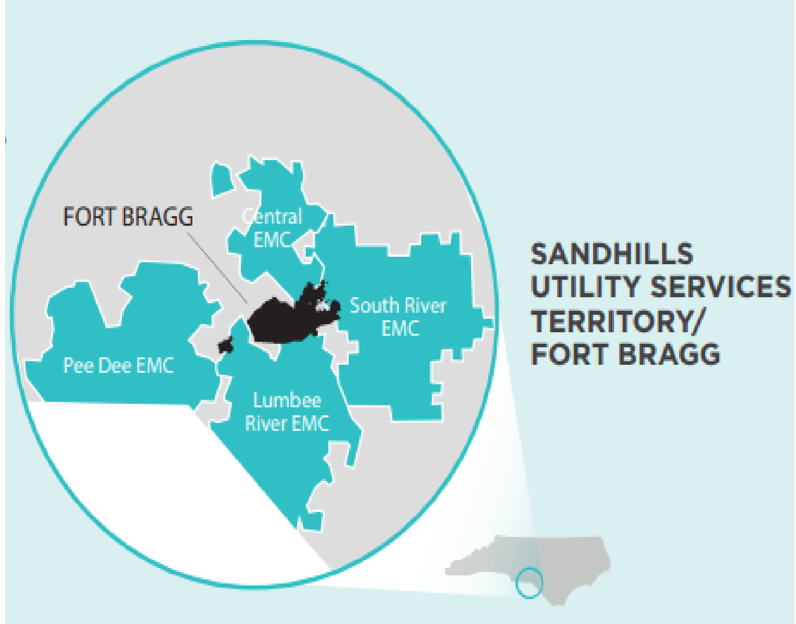
Military installations rely on uninterrupted electrical power to execute their national security missions – these loads are primarily backed up with an N+1 or N+2 back up diesel generator(s)

Prior to 2017, 72 hours of grid-independent readiness was the DoD standard for energy security, after 2017 the standard is 7-14 days

DOE OE ESS program is supporting two BESS projects with micro-grid, islanding and black start capabilities can help mission critical DoD loads



Who: West River Electric Association (WREA)
Where: Ellsworth AFB, South Dakota
What: BESS/250kW/250-500kWh paired with an existing generator for building microgrid
Why: Resilience of critical loads at critical military installation and peaking shaving



Who: Sandhills Utility Services, LLC (SUS)

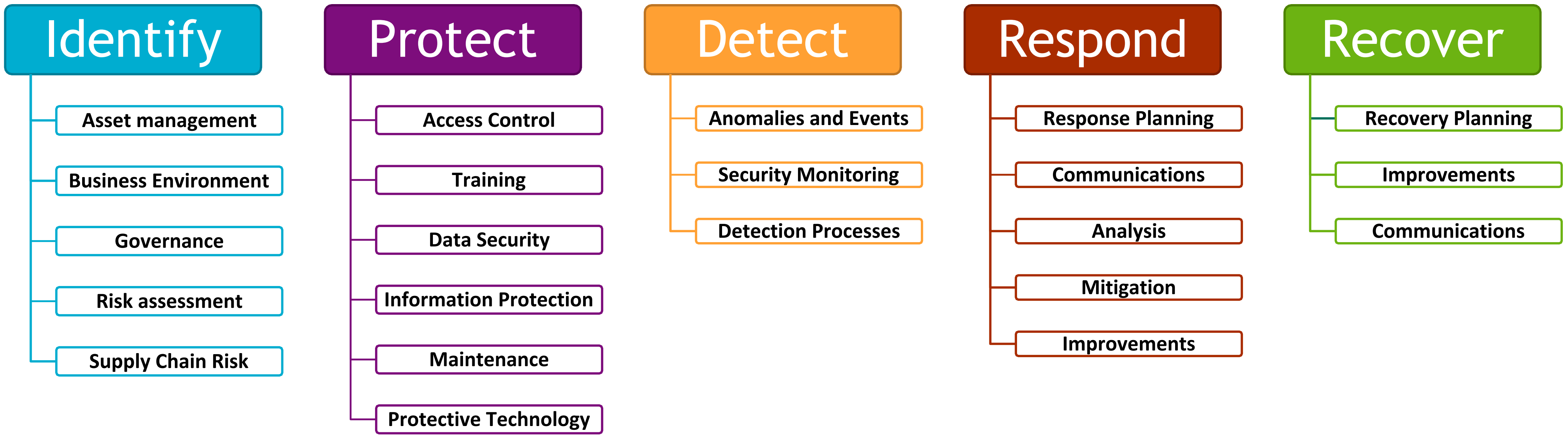
Where: Fort Bragg, North Carolina

What: Li-Ion BESS/ 90kW/270kWh paired with an existing generator for building microgrid

Why: Resilience of critical loads at critical military installation

BESS Systems – Vulnerabilities

- Due to their importance in resiliency, ESS might become a potential target for physical and cyberattacks
- Critical ESS must include physical and cybersecurity technologies to protect them from adversary actions that could damage or disable the equipment.
- Physical and cyberattacks to ESS can lead to critical failure with serious hazards to humans (e.g. fire)
- Understanding risks and appropriate system design and application of countermeasures require adopting processes in organizational level and performing risk assessment
- For civil use, there are several standards and guidelines available:
  - NERC CIP, NIST, IEC, etc.
- NIST Cybersecurity Framework:



Advances in High Performance Rechargeable Batteries

No near term alternatives to Li-ion batteries for energy dense batteries for high performance applications including EVs, Electric Aircraft.

- Solid state batteries – promising, need significant improvements
- Metal-air batteries – energy dense, need technical breakthroughs to fully realize

Application	Consumer Electronics, Hybrid EVs	Electric Grid Electric Vehicles	Electric Flight
Advance Technologies	Incremental Li-ion: Si anodes, low Co cathodes Adv. Pb-acid: Pb-carbon Adv. rechargeable alkaline	Significant Adv. Li: Li metal anode, Solid state electrolytes Zn metal: adv. MnO2 cathodes Adv. Flow	Breakthroughs Beyond Li-ion: Li-S, Li-Air Mg & Al Ion Zn-Air High voltage Zn Metal
Needed Technology Advances	Modest	Significant	Major

Adapted from G. Crabtree's presentation at Xlab, 2018

Future of High Performance Rechargeable Batteries

Battery technologies for electric vehicles and grid applications are advancing rapidly.

Engineering energy storage systems with higher energy and high power capacities while keeping safety and reliability remains a challenging task

Technical gaps exist for high power and energy applications

- How do we manage the universal tradeoff between energy and power due to a combination of electrical, ionic, structural and chemical effects?
- How to improve energy capacity without sacrificing safety and life?
- How do we optimize power and energy at multiple length scales, large format cells?
- How do we enable fast ion and electron transport without sacrificing energy density, while maintaining long life and safety?
- How do we design materials to realize high energy and power simultaneously?
- How to achieve high reversibility, with low capacity loss, and low over-potentials

ENERGY STORAGE R&D AT SANDIA

BATTERY MATERIALS

Large portfolio of R&D projects related to advanced materials, new battery chemistries, electrolyte materials, and membranes.

CELL & MODULE LEVEL SAFETY

Evaluate safety and performance of electrical energy storage systems down to the module and cell level.

POWER CONVERSION SYSTEMS

Research and development regarding reliability and performance of power electronics and power conversion systems.

SYSTEMS ANALYSIS

Test laboratories evaluate and optimize performance of megawatt-hour class energy storage systems in grid-tied applications.

DEMONSTRATION PROJECTS

Work with industry to develop, install, commission, and operate electrical energy storage systems.

STRATEGIC OUTREACH

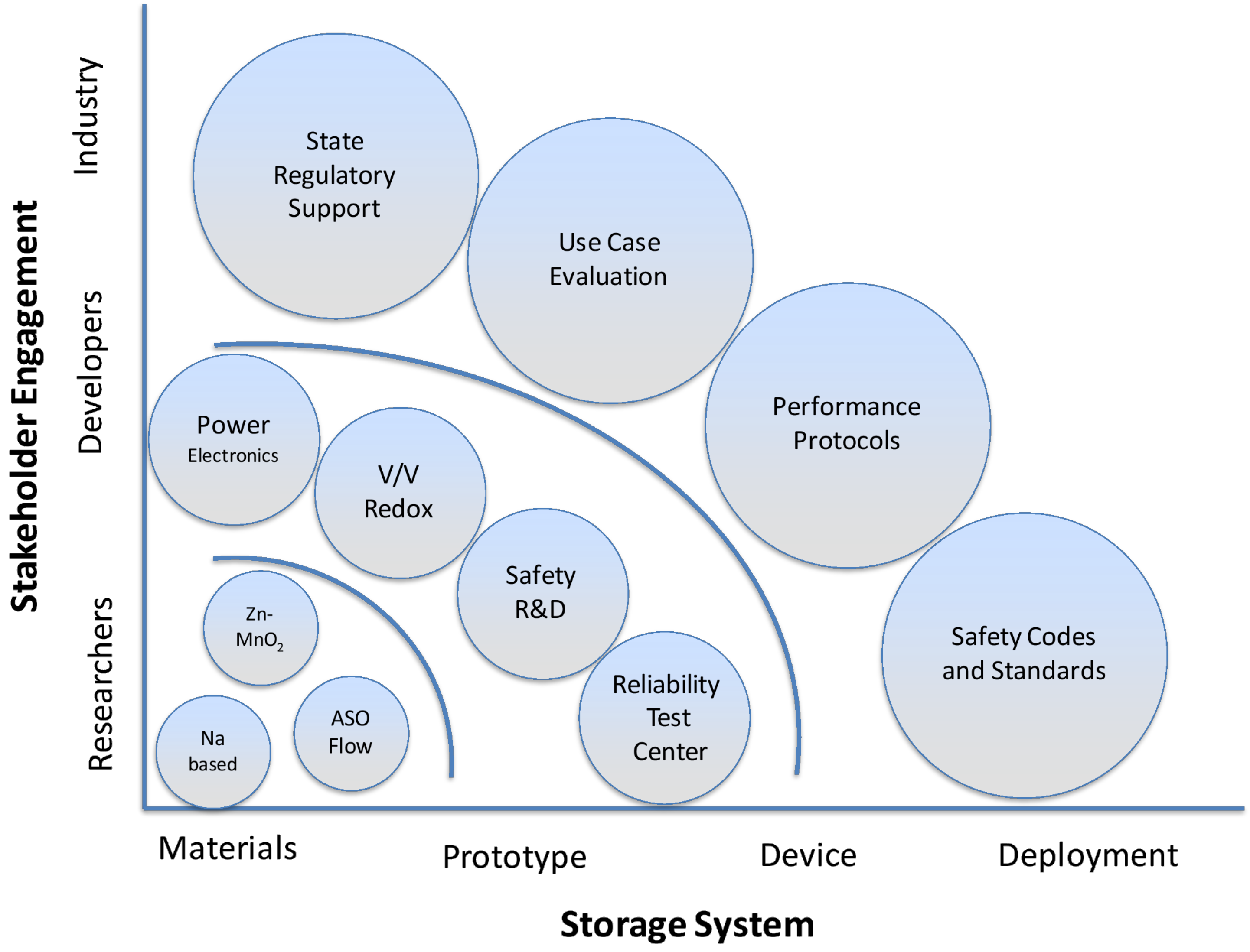
Maintain the ESS website and DOE Global Energy Storage Database, organize the annual Peer Review meeting, and host webinars and conferences.

GRID ANALYTICS

Analytical tools model electric grids and microgrids, perform system optimization, plan efficient utilization and optimization of DER on the grid, and understand ROI of energy storage.

Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

DOE Office of Electricity - Energy Storage Systems Program

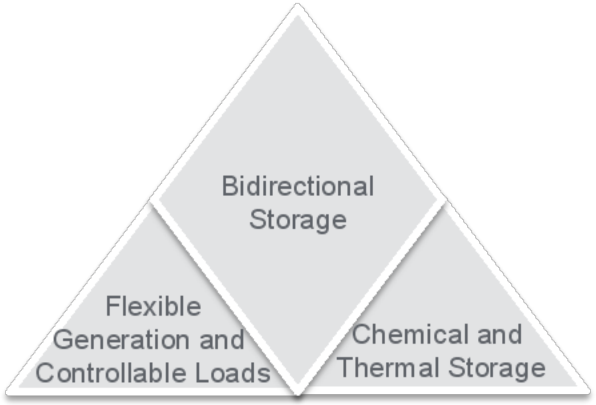


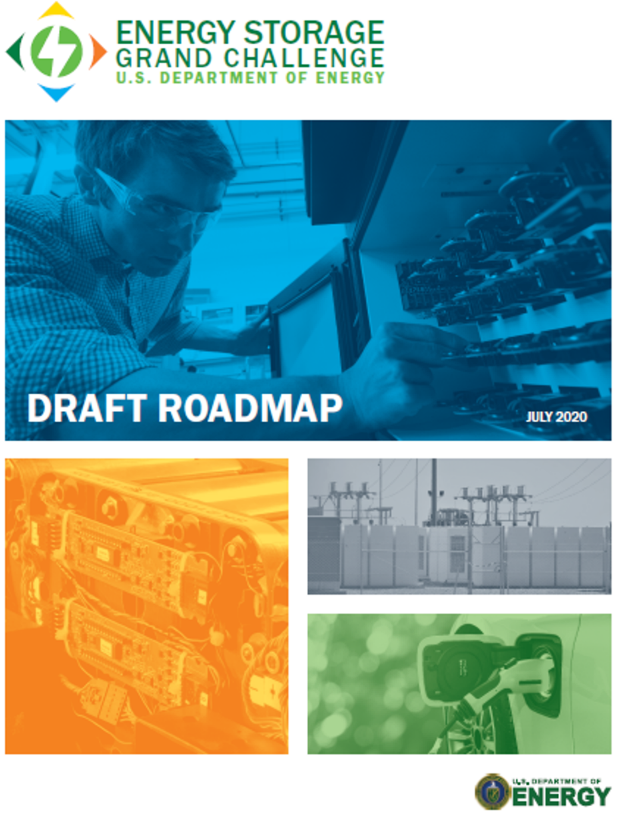
Focus Areas

- **Cost competitive energy storage technologies**
  - Targeted scientific investigations of key materials and systems
- **Validated reliability & safety**
  - Independent testing of prototypic devices and understanding of degradation.
- **Equitable regulatory environment**
  - Enable industry, utility, developer collaborations to quantify benefits, provide input to regulators.
- **Industry acceptance**
  - Highly leverage field demonstrations and development of storage system design tools .

https://www.energy.gov/oe/energy-storage

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY





Vision: By 2030, the U.S. will be the world leader in energy storage utilization and exports, with a secure domestic manufacturing supply chain independent of foreign sources of critical materials

Science

ARPA-E

EERE

OE

NE

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https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

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For Additional Info:

bchalam@sandia.gov

energystorage.sandia.gov