SAND2021-11036PE

Electric Grid Modernization - Overview

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Sandia National Laboratories

5th International Summer School on Materials for Energy Storage and Conversion

September 10, 2021

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Activity locations

- Kauai, Hawaii
- Waste Isolation Pilot Plant, Carlsbad, New Mexico
- Pantex Plant, Amarillo, Texas
- Tonopah, Nevada

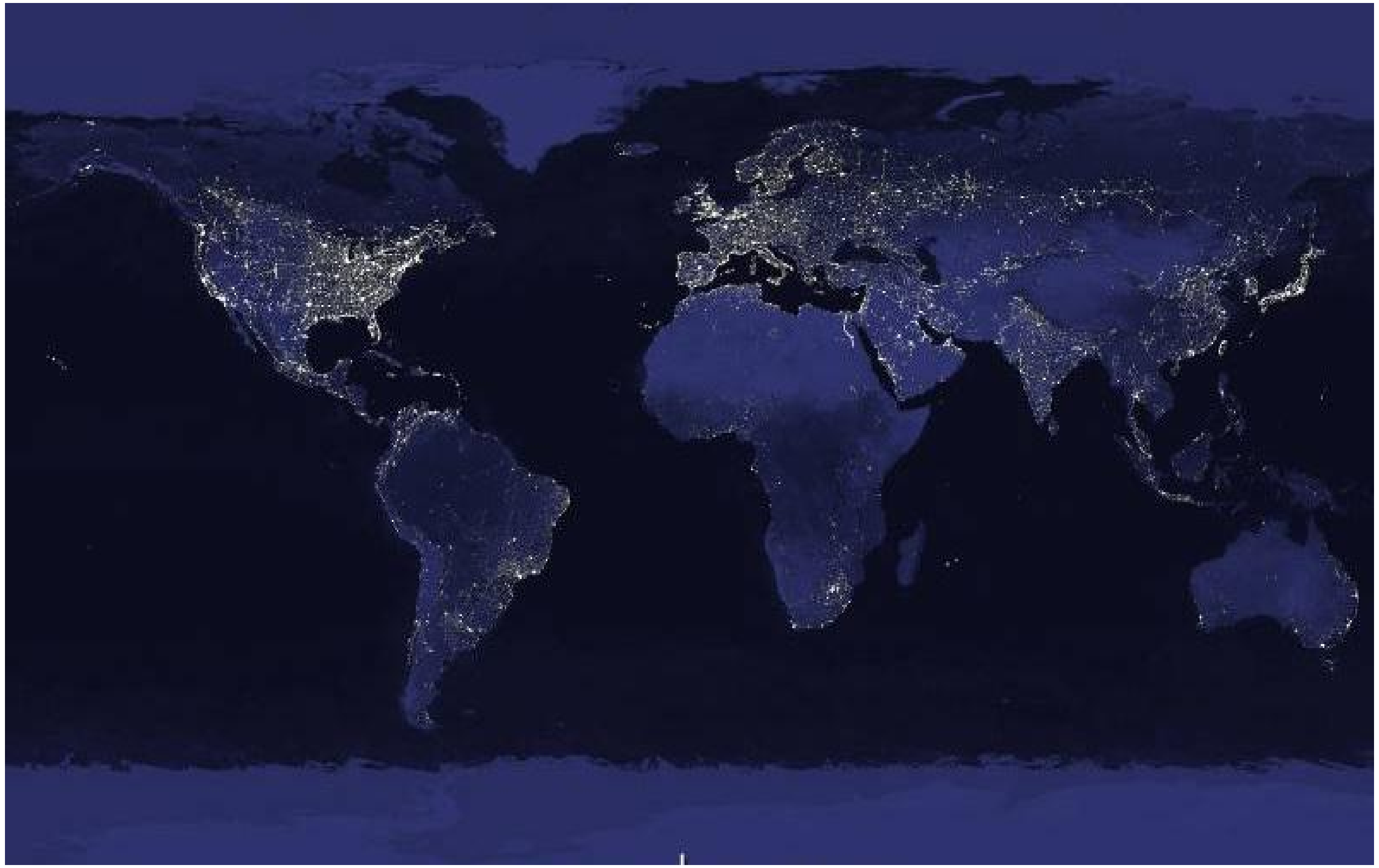
Main sites

- Albuquerque, New Mexico
- Livermore, California

Over 14,000 employees

$3.9B budget (FY21)

Electric Grid



Electrification is the greatest engineering achievement of the 20th century[1]

Night lights are a proxy for a country's gross domestic product[2]

[1]National Academy of Engineering, "Great Achievements and Grand Challenges", *www.nae.edu*.
[2]T. Ghosh, A. J. Anderson, C. D. Elvidge and P. C Sutton, "Using Nightime Satellite Imagery as a Proxy Measure of Human Well-Being", *Sustainability*, Volume 5, 2013, pp. 4988-5019.

Electric Power Delivery Model Today

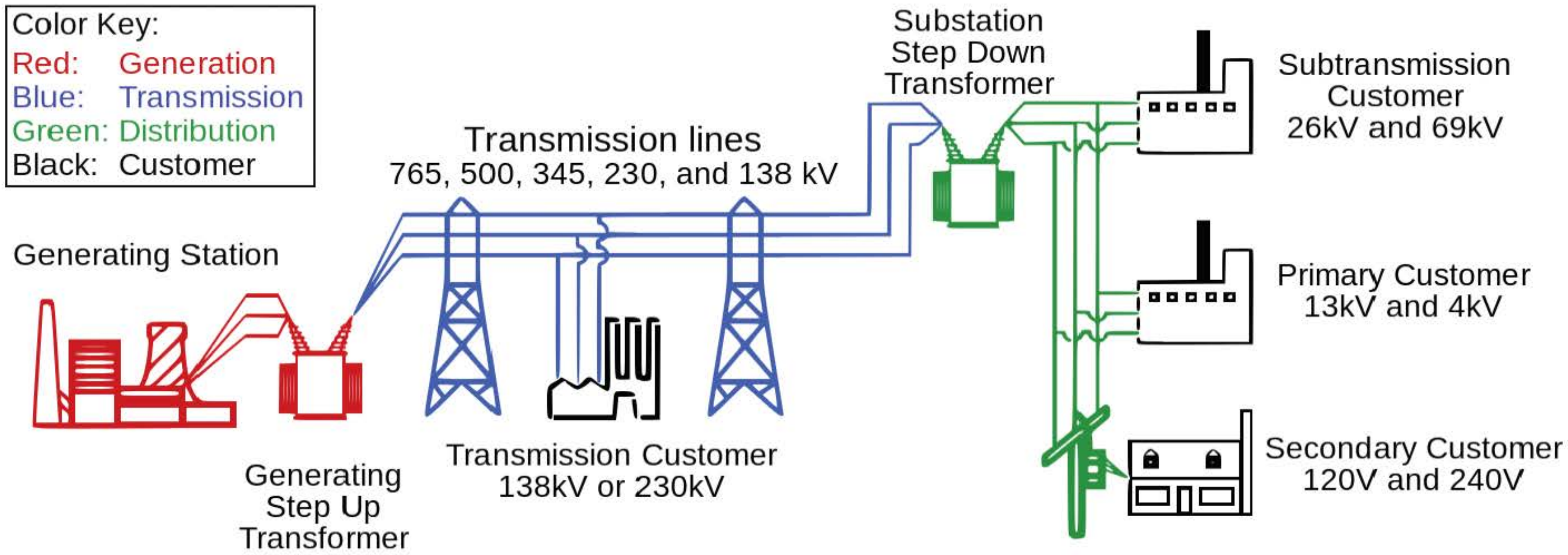


Figure Source: North American Electricity Reliability Corp (NERC), 2016

Grid 1.0

- A one way delivery system with very little flexibility, with generation and load always balanced
- Utilities deliver reliable power at prices set by regulators in most markers, and variable market driven pricing in a few markets

Grid 2.0

- Fast evolving, changes in generation mix and the grid edge

Generation

- **Traditional:** coal, nuclear, natural gas, hydro
- **Renewable:** wind, PV solar, concentrating solar, hydro, geothermal, biomass
- **Distributed:** PV solar, microturbines, wind

Transmission or Bulk System

- Move bulk electricity from generation to load centers
- Long distance (10's to 100's of miles), high capacity, high voltage, balanced 3-phase
- Meshed topology

Distribution System

- Distribute electricity to end users (last mile)
- Short distance (several miles), lower capacity, lower voltage, unbalanced 1-3 phase
- Radial topology

Load

- Commercial/Industrial
- Residential

Global Electric Power Industry

Global Facts

Over 6 TW of global generation capacity

Rapidly growing solar and wind capacity additions

27,000 TWh of Electricity produced (2020)

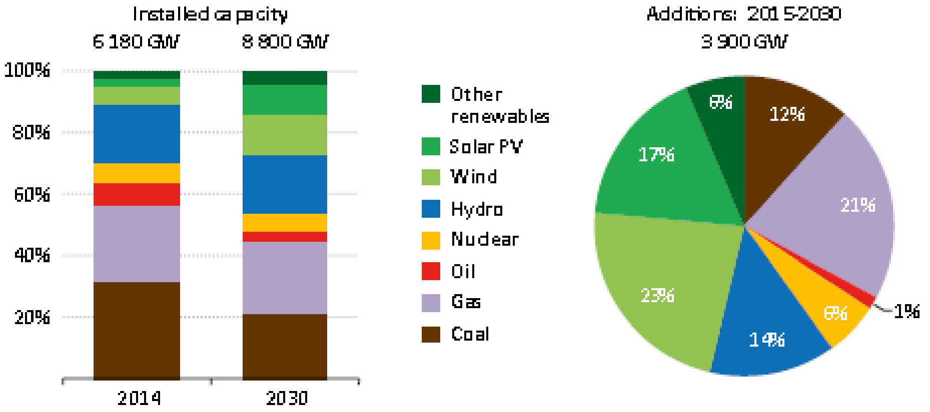
Utility industry revenues: ~$1400 B (2020)

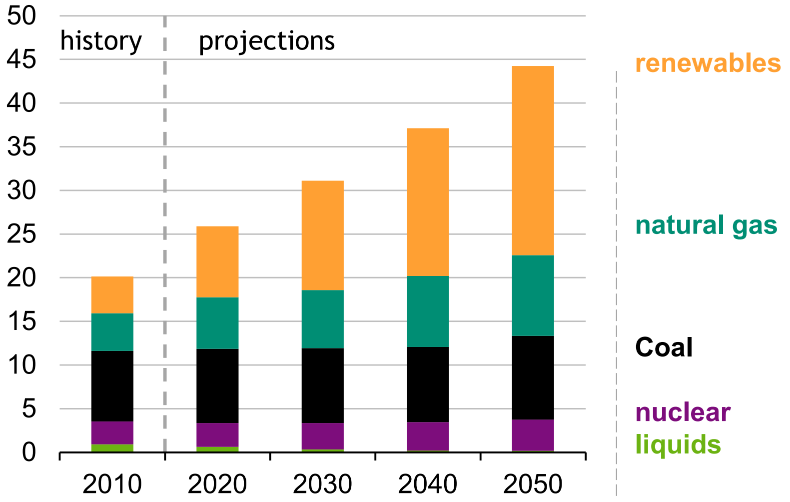
US Facts

850 GW baseload, 1250 GW Summer Peak, 3,811 TWh of generation (2019)

Total revenues: $401 B, average revenue 11 cents/kWh (2019)

Sources: EIA Electric Power Annual 2019, Annual Energy Outlook (2019)
BP Energy Outlook 2021





Global generation mix with projections to 2050
International Energy Outlook 2019, US Energy Information Administration, Feb 2019

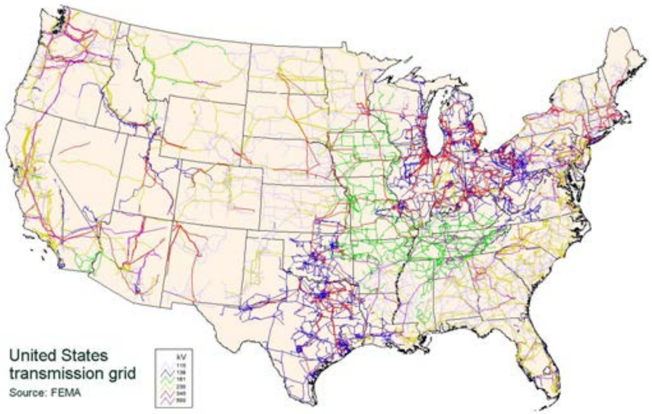
U.S. Electric Grid

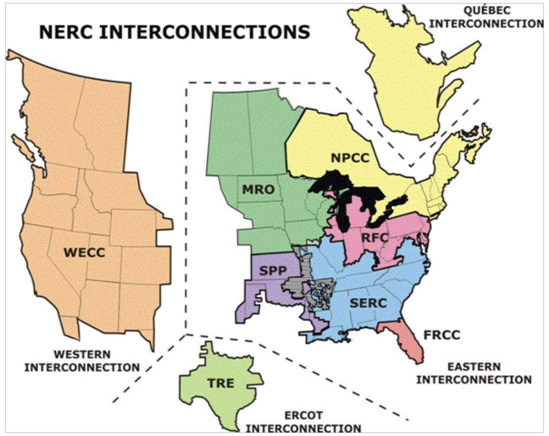
Big interconnected system with ~850GW baseload, 1250 GW summer peak, 7,000 operational power plants

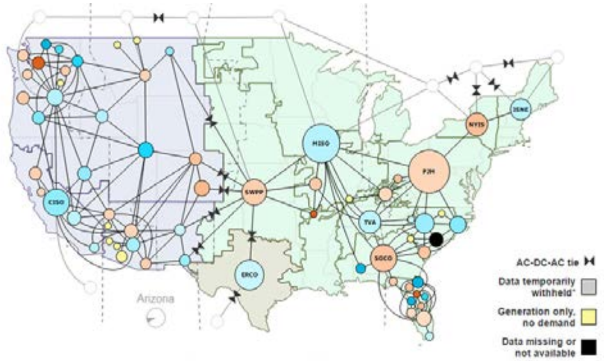
- 3,200 utilities, 60k substations, 642k miles of HV transmission lines, 6.2 million miles of distribution circuit, 159 million customers.
- 4,000 TWh of generation (2020)
- Revenues reaching $400 B, ~10.42 c/kWh avg

Four interconnect regions and a number of balancing authorities:

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







Sources: EIA, EEI, FEMA and NERC http://www.nerc.com

U.S. Electricity Generation

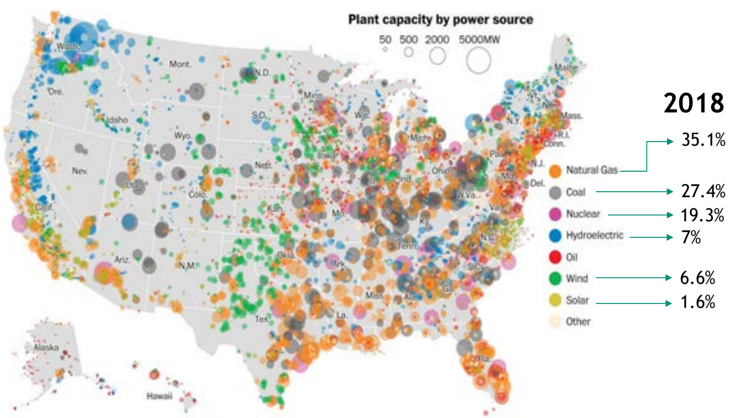
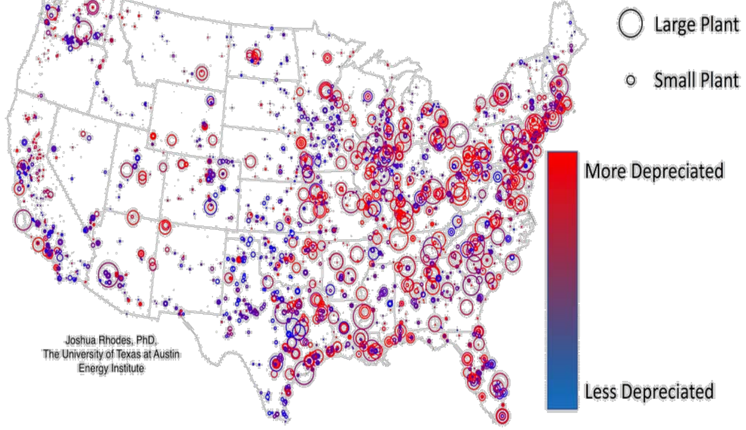
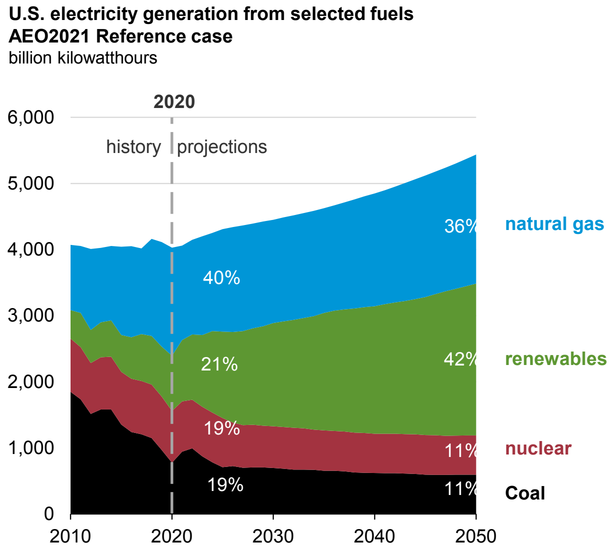
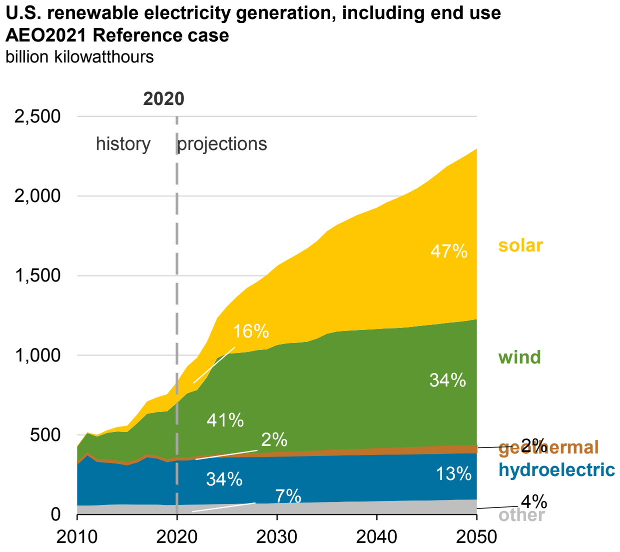
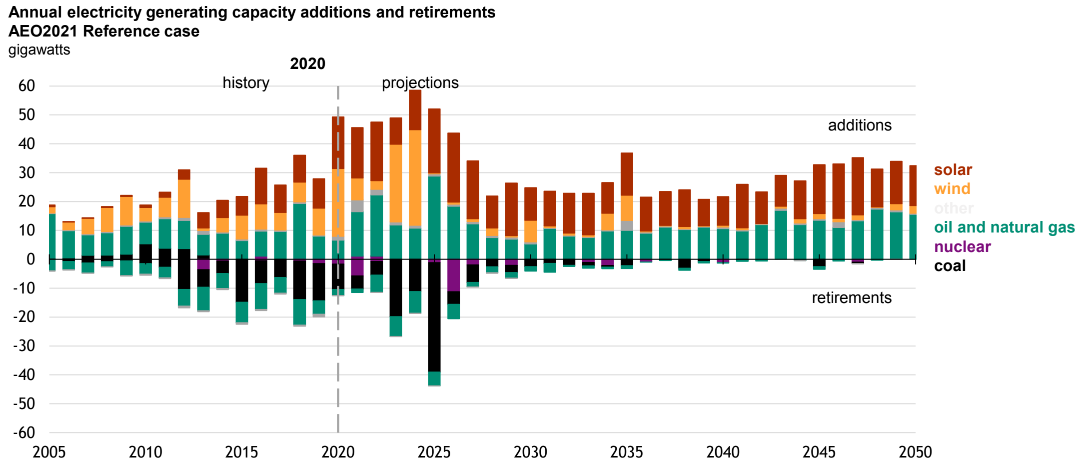


Image credit: Washington Post







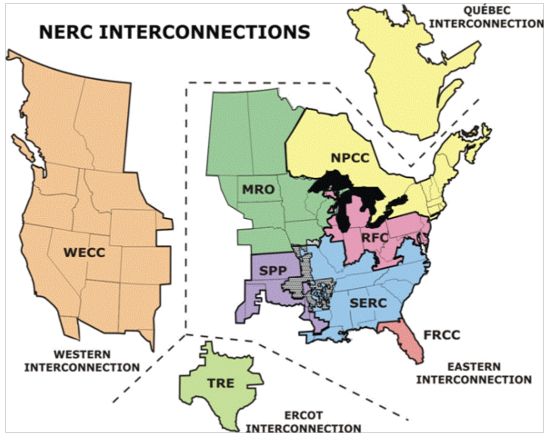


- 7000 power plants (name plate capacity of 1 MW or larger
- Accelerating retirements of coal fired power plants
- EIA projection – RE providing 42% of electricity by 2050
- Amount of storage deployment will significantly impact growth of renewables

Source: Form EIA-860M, *Monthly Update to the Annual Electric Generator Report*, July 2020
U.S. Energy Information Administration, *Annual Energy Outlook 2021 (AEO 2021)*
www.eia.gov/aeo

Bulk Transmission Grid

- Big interconnected systems through high-voltage AC transmission lines or HVDC lines
- Mostly powered by large centralized generations (hydro, nuclear, natural gas, coal) and also increasingly by renewables (wind and solar)
- Examples:
  - **USA:** 4 interconnected regions, 65 balancing authorities, approximately 1250 GW net capacity
  - **Europe:** continental synchronized grids throughout 34 countries with 977 GW capacity, managed by European transmission system operators for electricity (ENTSO-E) consisting of 41 transmission system operators
  - **India:** 5 operating regions with 487 GW net generation capacity
  - **China:** 6 synchronous regional grids with 1500 GW net generation capacity



US Interconnected Grids

European Continental Grids

India Interconnected Grids

China's Interconnected Grids

Sources: EIA, EEI, ENTSO-E, GEOELEC, NREL

Transmission Development

Costly, Slow, Difficult
- Planning
- Permitting
- Financing
- ROW acquisition
- Engineering design
- Construction

Non-Wire Alternatives
- Storage
- Load management
- Distributed generation
- Other smartgrid concepts

Climate Change - States Driving Major Policies for Clean Energy

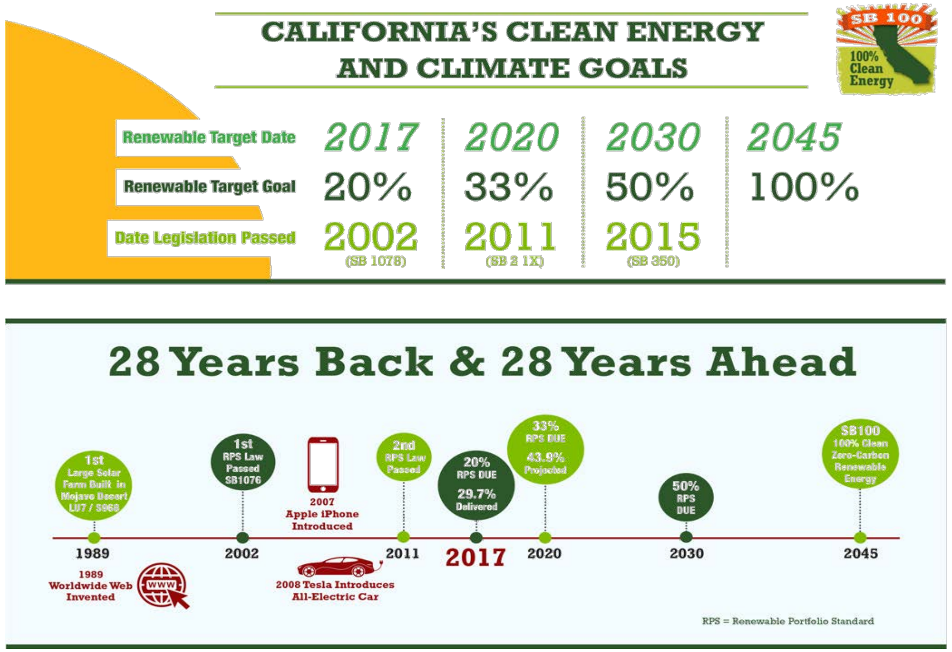
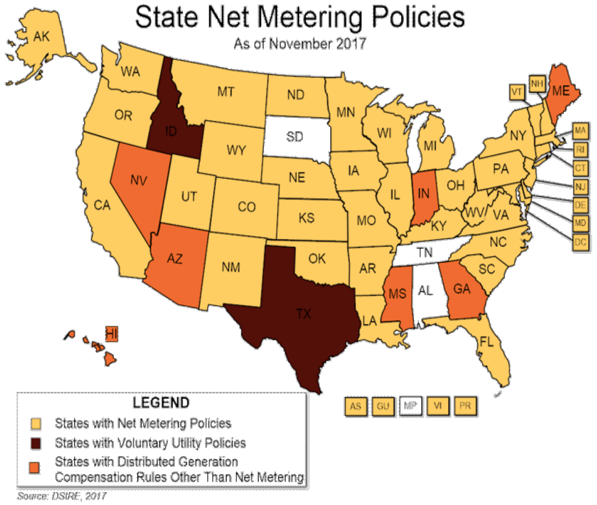
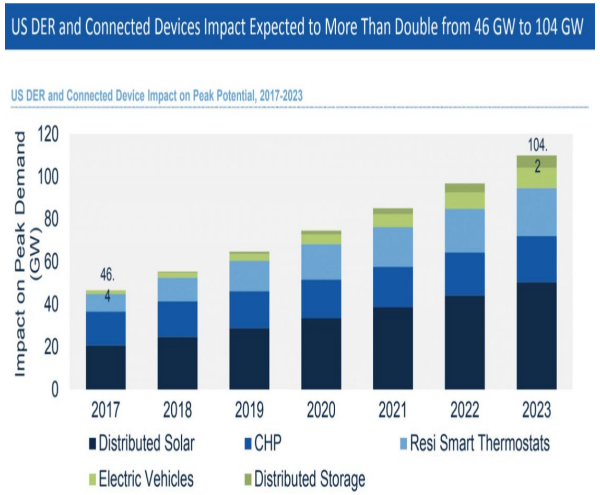


Image Source: California Senate





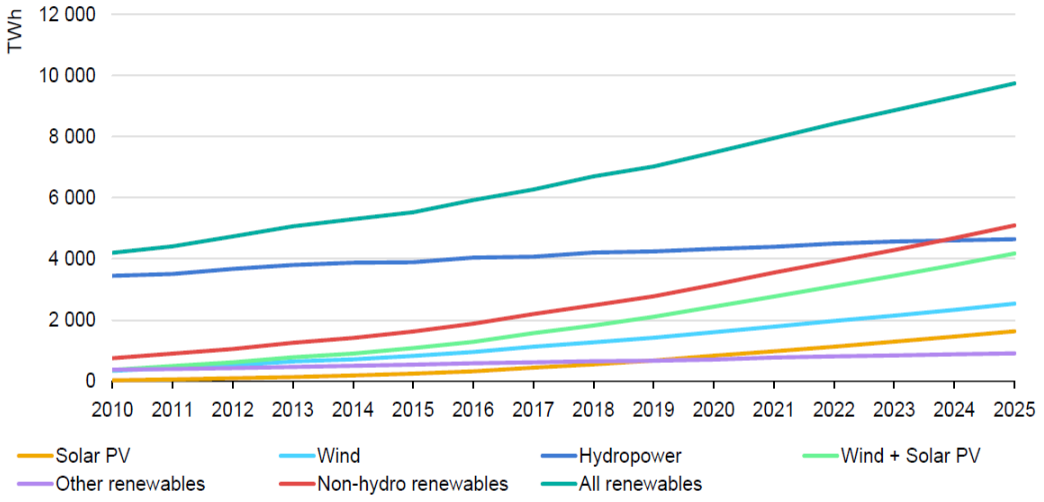
Source: GTM Research and US DOE

- Generation is becoming distributed
- Almost all states have Net Metering programs
- California, Hawaii, New Mexico, Washington, and Nevada legislating 100% renewable energy in the next 20-30 years.

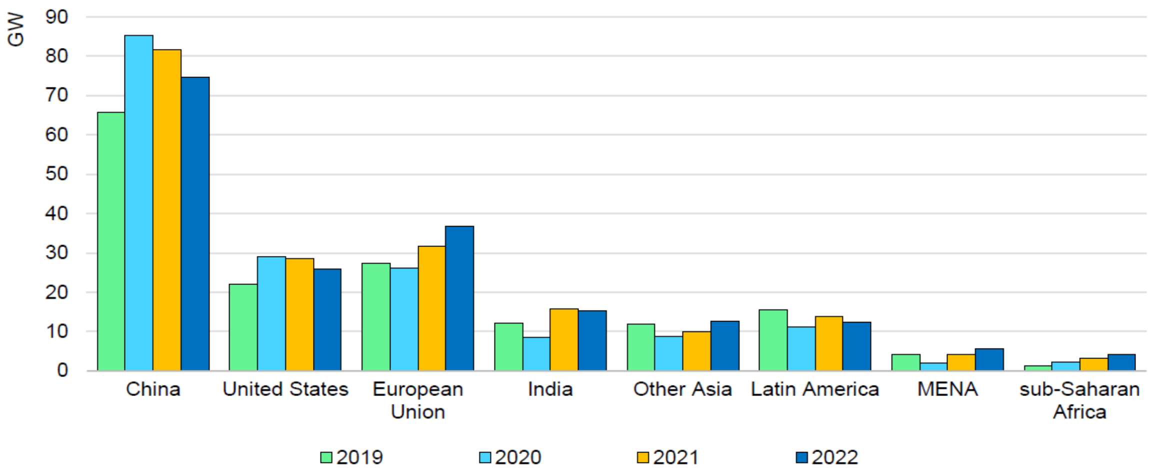
Increasing Adoption of Renewable Energy Resources

- Current trends:
  - Accelerating retirements of coal fired power plants
  - Stalled replacement/expansion of nuclear generation
- Growth of net renewable electricity capacity, mainly from wind, utility-scale PVs; and hydro in some locales
- Share of renewables in electricity grid sector will take the largest portion, followed by buildings and transport

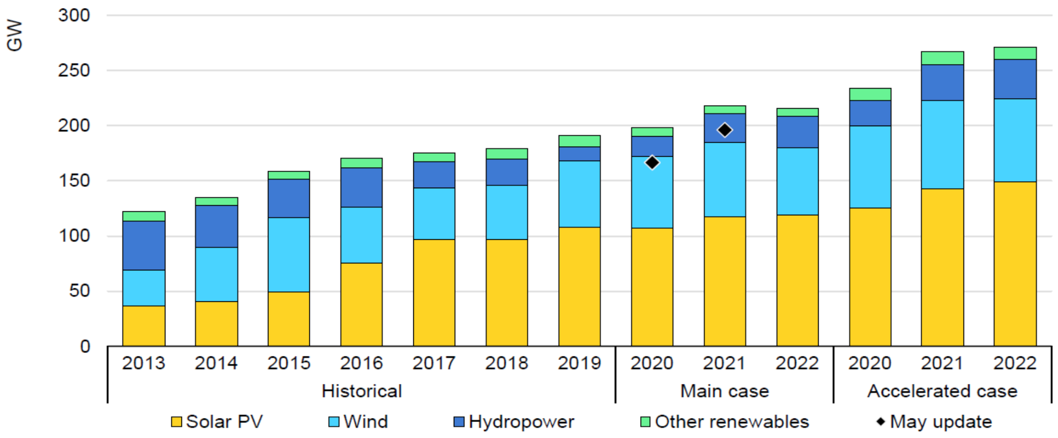
Renewable generation 2010-2025



Renewable capacity addition by country 2019-2022



Renewable capacity addition by technologies

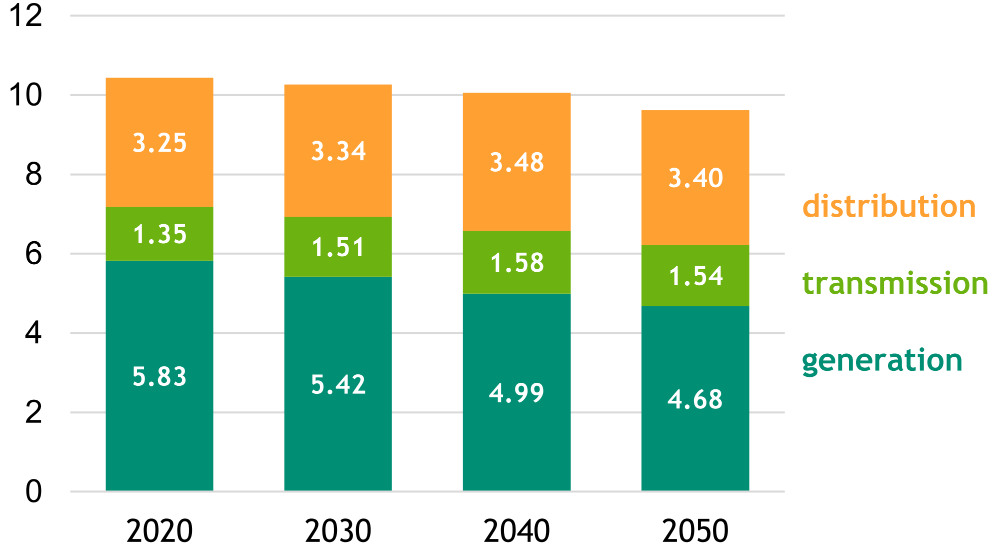


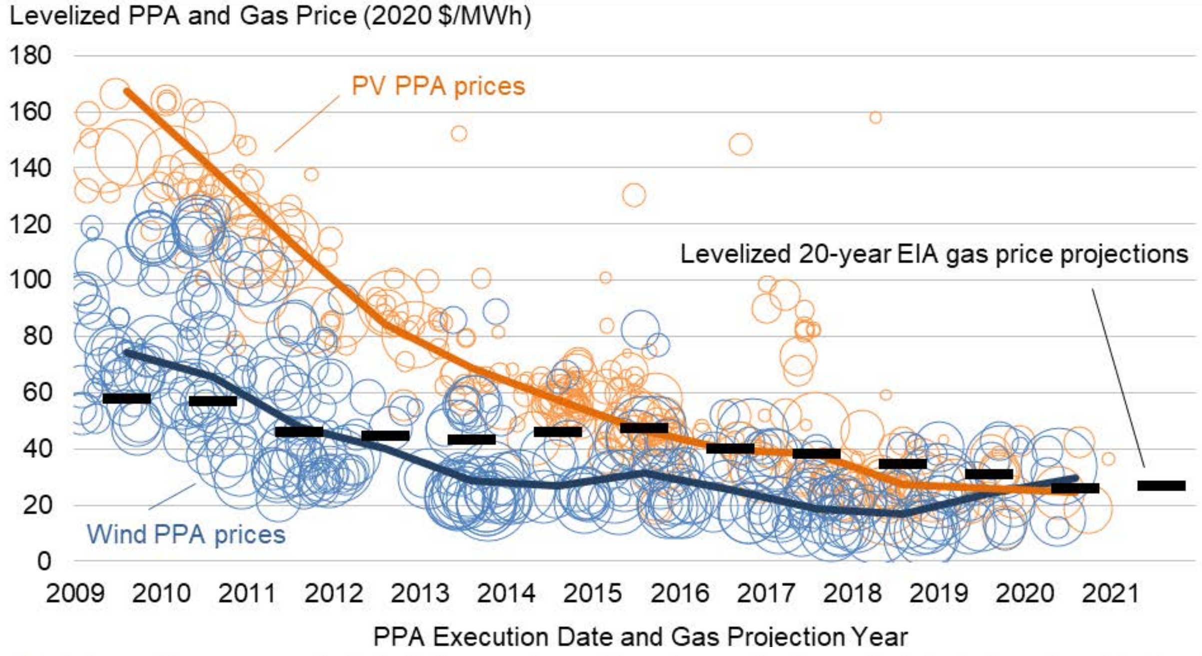
Source: IEA Renewables 2020

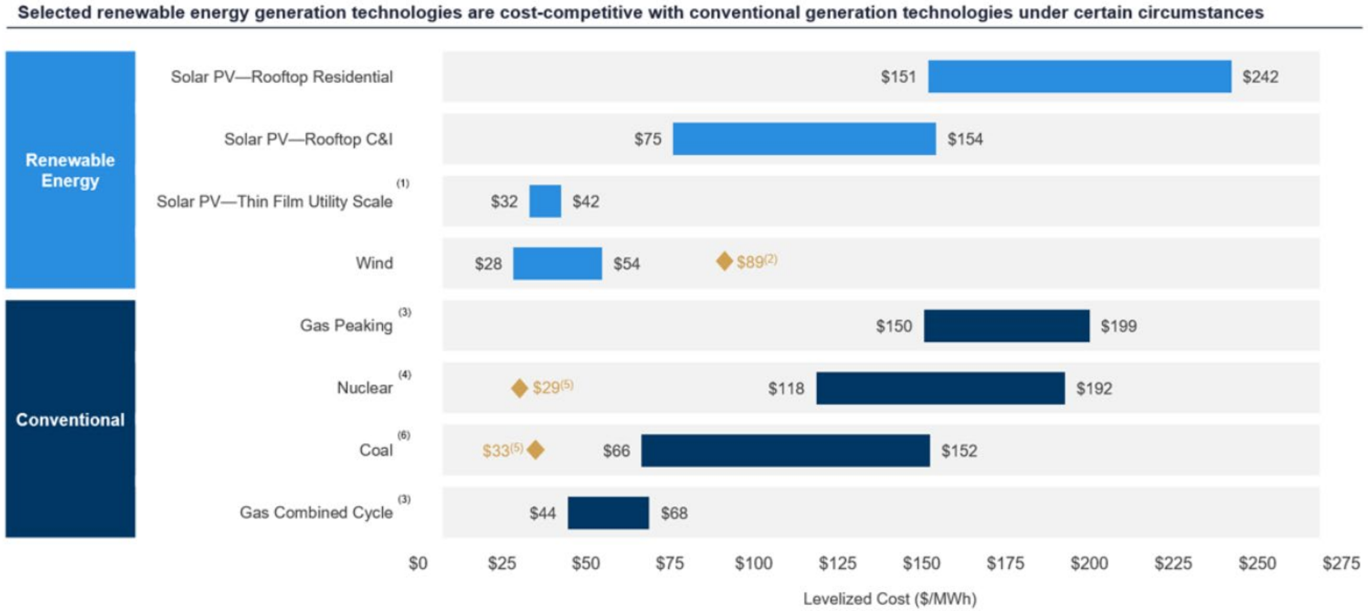
Decreasing cost of Renewable Generation

- Becoming cheaper
- At parity with traditional generation

Components of U.S. Electricity Prices AEO2021





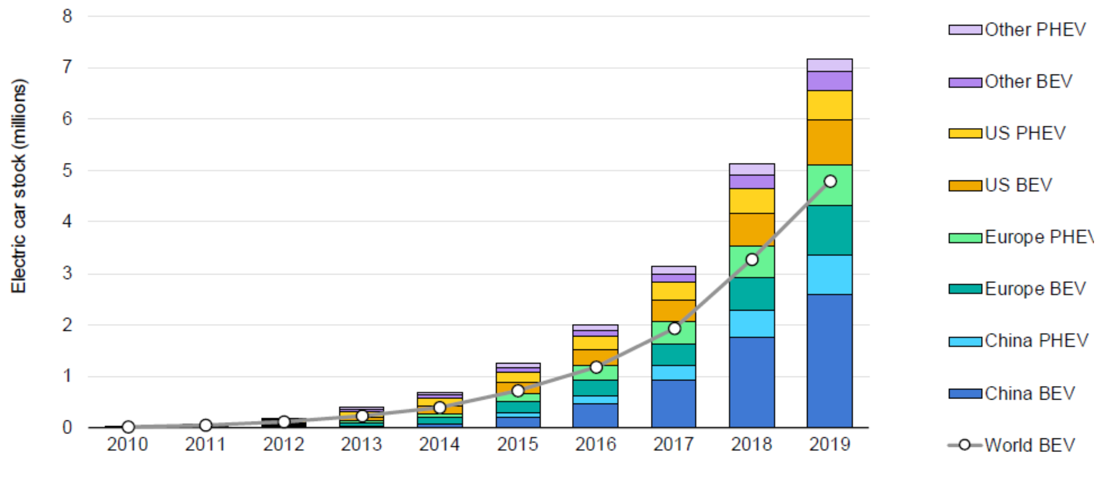


https://www.lazard.com/perspective/lcoe2019

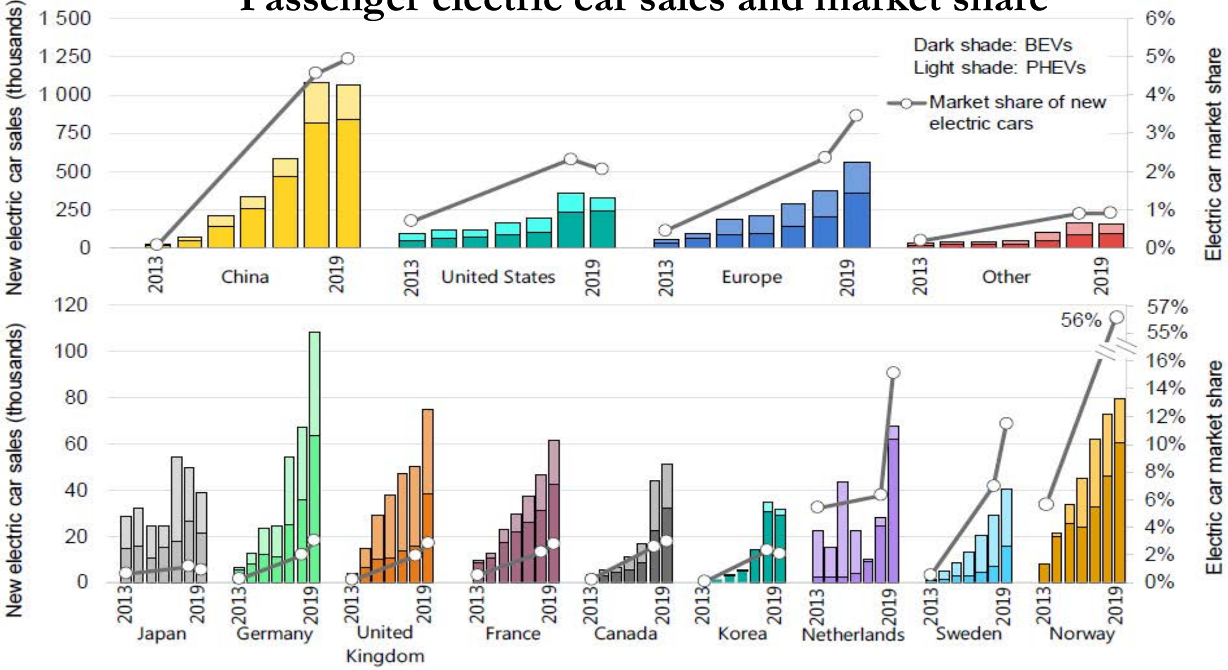
Zero Emissions and Electrification

- **Transport Electrification**
  - Transport will undergo electrification to reduce transport emission (e.g., 33% rise in 2050 REmap)
  - Battery storage for electric vehicles will increase significantly, causing major changes in electricity grid due to charging infrastructure
- **Buildings**
  - Despite improved efficiency, electricity demand in the building sector is projected to increase by 70% by 2050, mainly due to electrification of heating systems
- **Industry**
  - Industry sector is second largest CO_2 emission source, mostly due to the demand from high temperature processes
  - Use of electricity will increase to promote low-temperature process, causing electricity demand increase

Global EV car stock

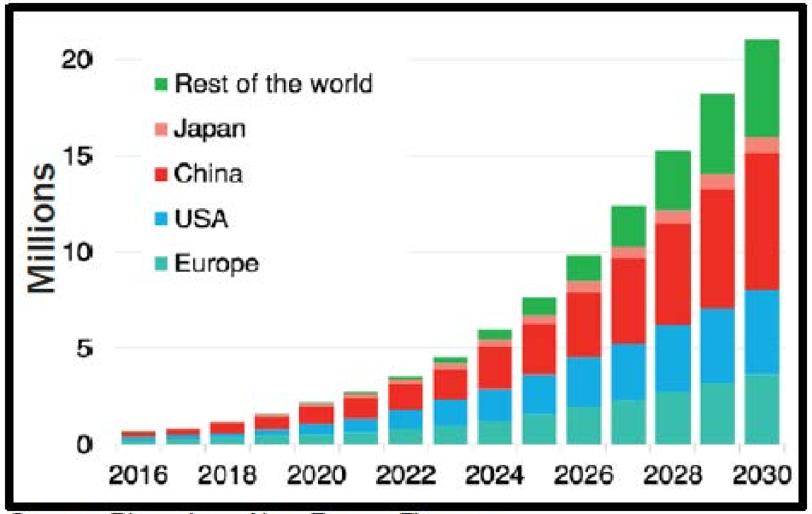


Passenger electric car sales and market share



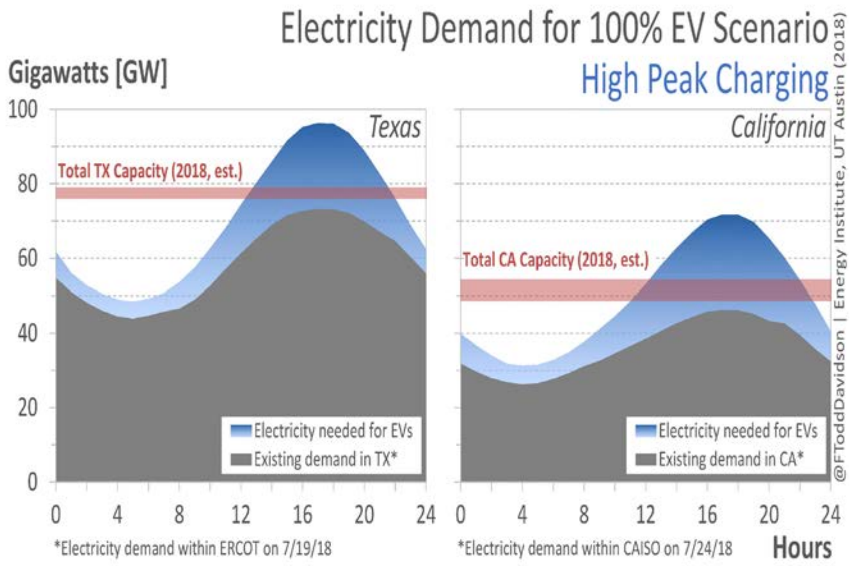
Sources: IEA Global EV Outlook

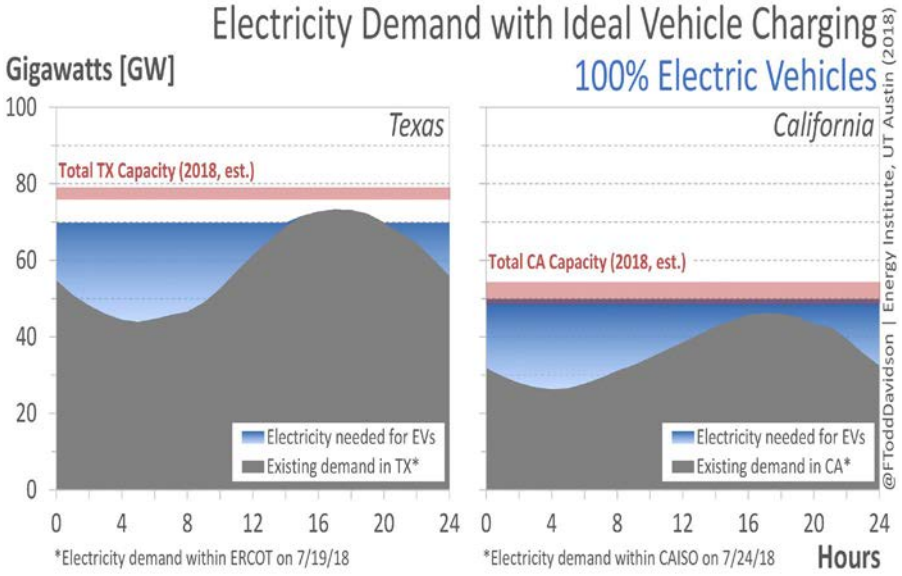
Electrification of Transportation Fleet



Source: Bloomberg New Energy Finance

- Projections for annual production of electric vehicles reaching 20 Million by 2030 and a fleet of 130M (mostly passenger vehicles) on road as base case; 230M vehicles optimistic case (BNEF, IEA, 2018)
- Electrification will drive demand growth, overloading distribution systems and causing transmission congestion. Total load may double.
- Needs major T&D upgrades if EVs are mainly charged from the grid.





Disruptions at the Grid Edge

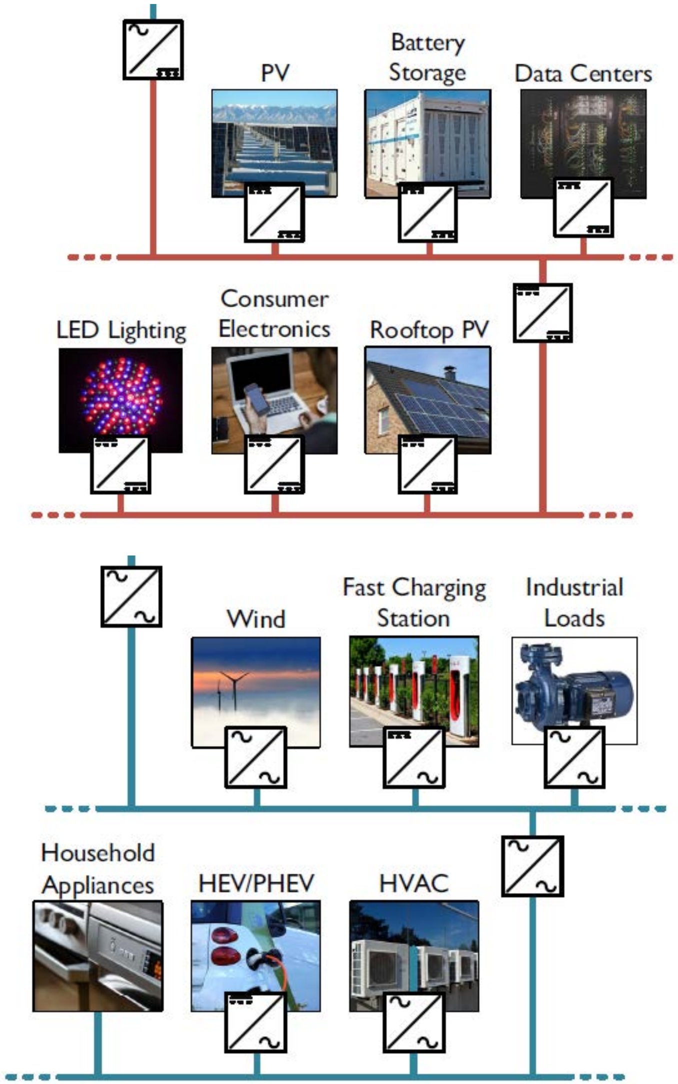
Electrification of the Transportation Sector
- EV charging infrastructure and fast charging
  - Ensure stability of the power grid
  - Accommodate large loads
  - Provide grid services and infrastructure for transactive energy

Behind-the-meter solar and energy storage

Rapid evolution of off-grid and micro-grids
- Potential to disrupt existing electricity market structures

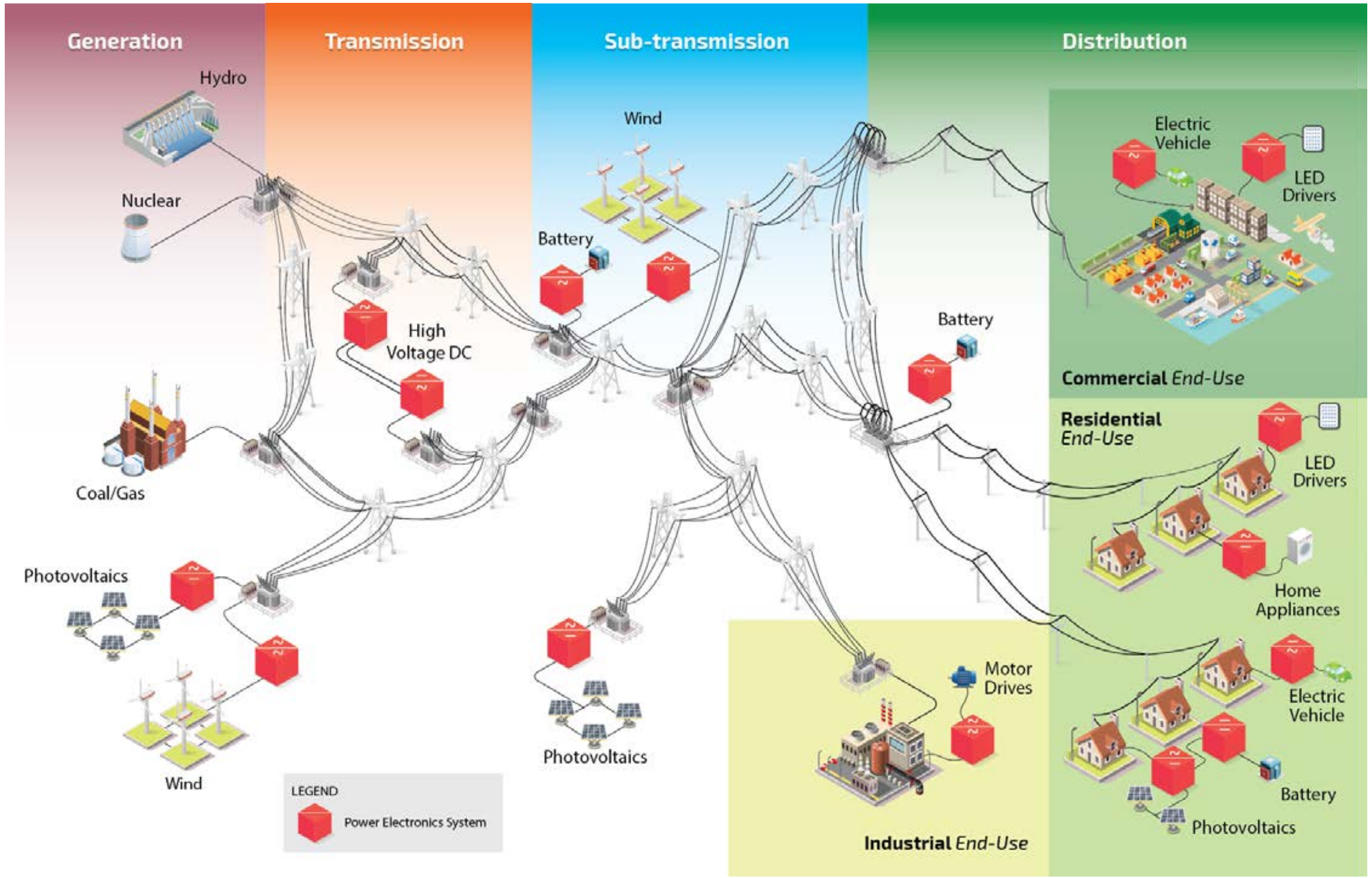
Behind-the-meter technologies with bi-directional communication
- Smart meters, smart loads, rooftop solar, electric vehicles, battery storage

Computation challenges associated with distributed sensing, control, and big data



Increasing Role of Power Electronics in Electricity Infrastructure

The power conversion system is at the center of DER, Energy Storage, and EV infrastructure



Source: K. Cheung, US DOE

Approximately 30% of all electric power currently generated uses PE somewhere between the point of generation and distribution.

By some estimates, 80% of energy will flow through power electronics.

Cost reductions in power electronics and power conversion systems has been slow to come.

- Bringing in WBG devices can make format factor smaller, reducing thermal management issues
- New magnetics and high temperature capacitors can make the systems more compact and robust

Evolution of the Grid

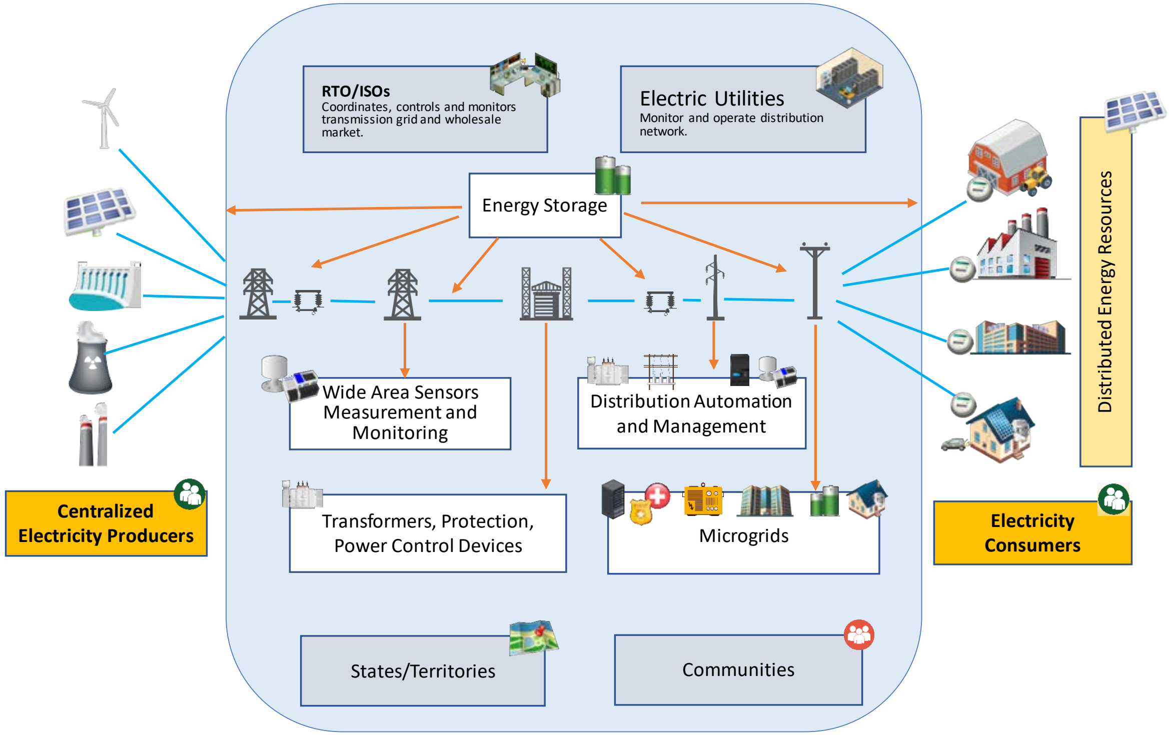
We are beginning to see existing business models not keeping pace with changes

Conservative regulated utility industry
- Not open or reluctant to change business models
- IOUs and PUCs struggling to adapt to rapid change

Flat to declining electricity sales in OECD markets
- Investors struggling with poor returns due to long adoption cycles. $2 Tn Asset Base in the US alone

Rapid change is bottom-up, with major transformation at the grid edge
- EVs, DER, Smart metering, microgrids, demand response, energy efficiency

Changes cut across technology, economics, policy, and markets



Source: US DOE Office of Electricity

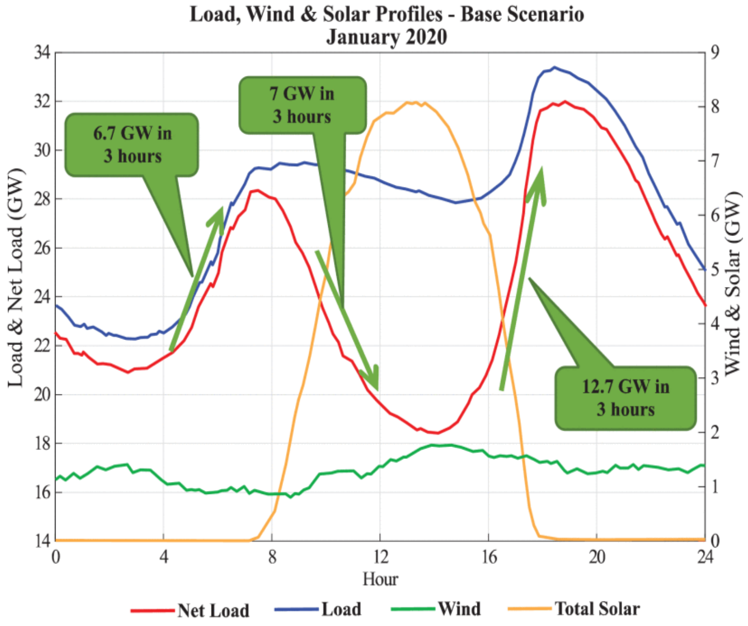
Energy Storage, Electric Vehicles, Power Electronics, and Communications at the center of grid modernization

Maintaining Grid Reliability

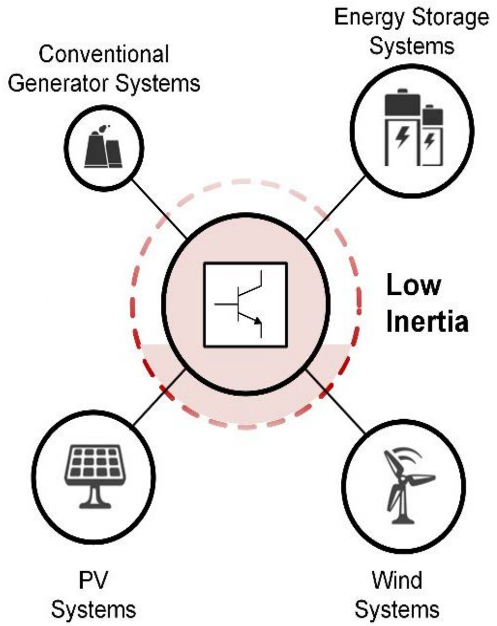
Must have sufficient generation and transmission capacity to meet peak demand

Able to maintain steady system frequency

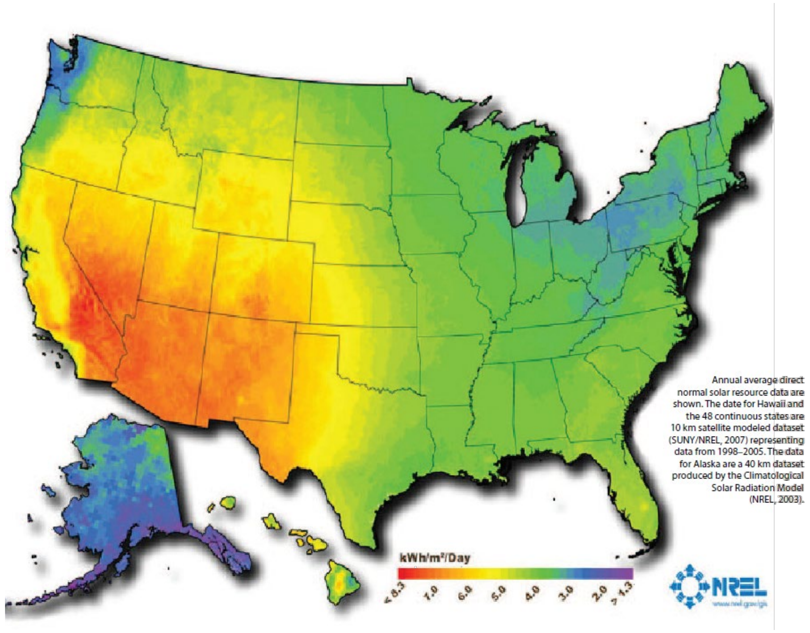
Must be able to maintain steady local voltages



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

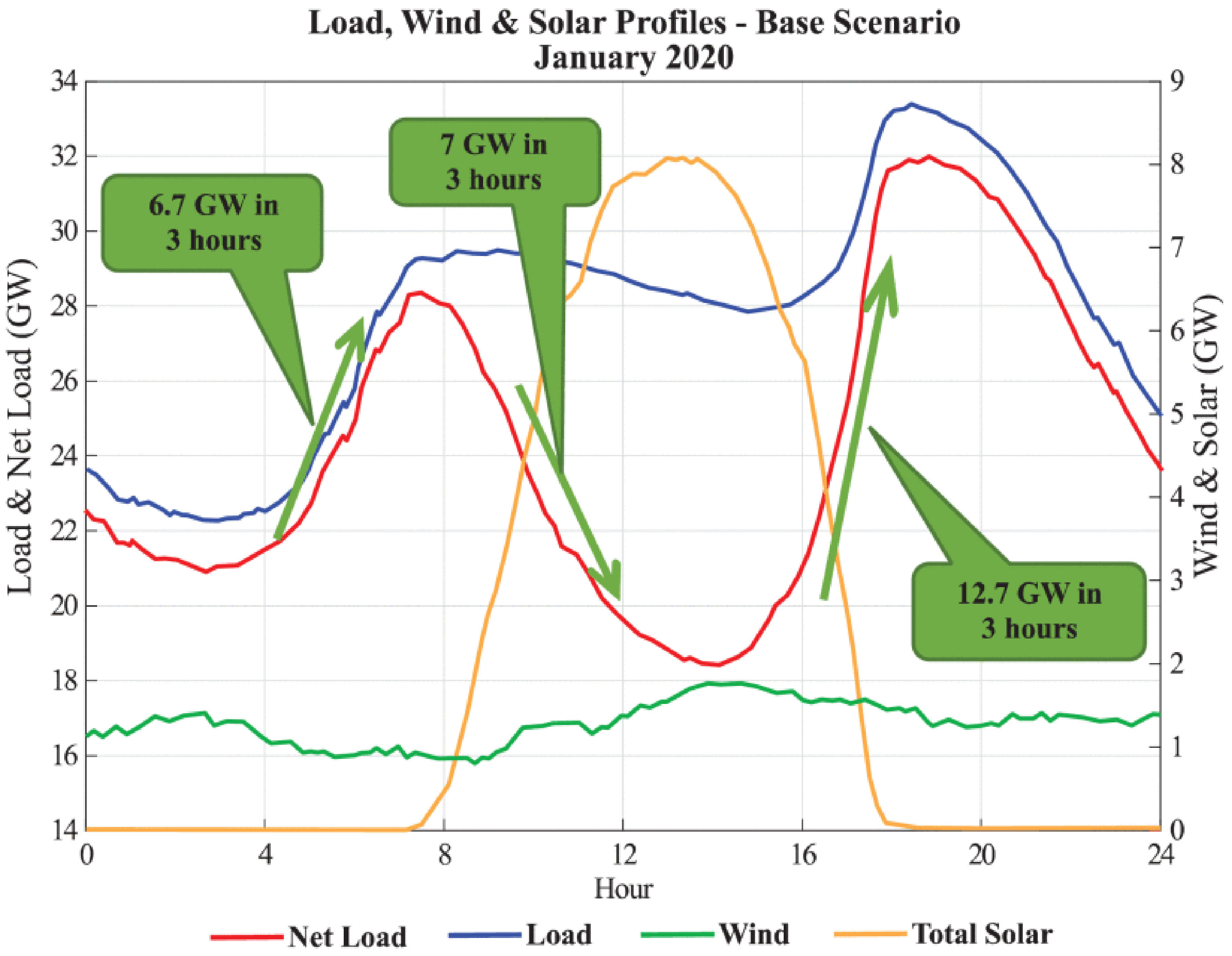
Zero Inertia Grid

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

Transmission Infrastructure

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

High Variability And Uncertainty



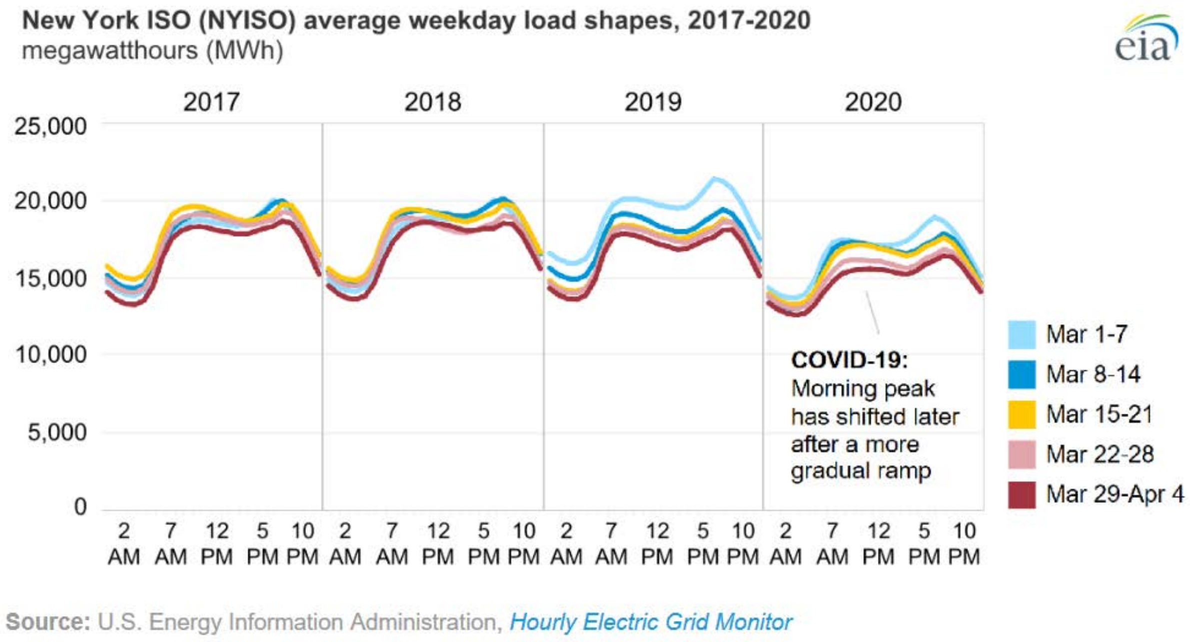
Source: CAISO, Jan. 2020

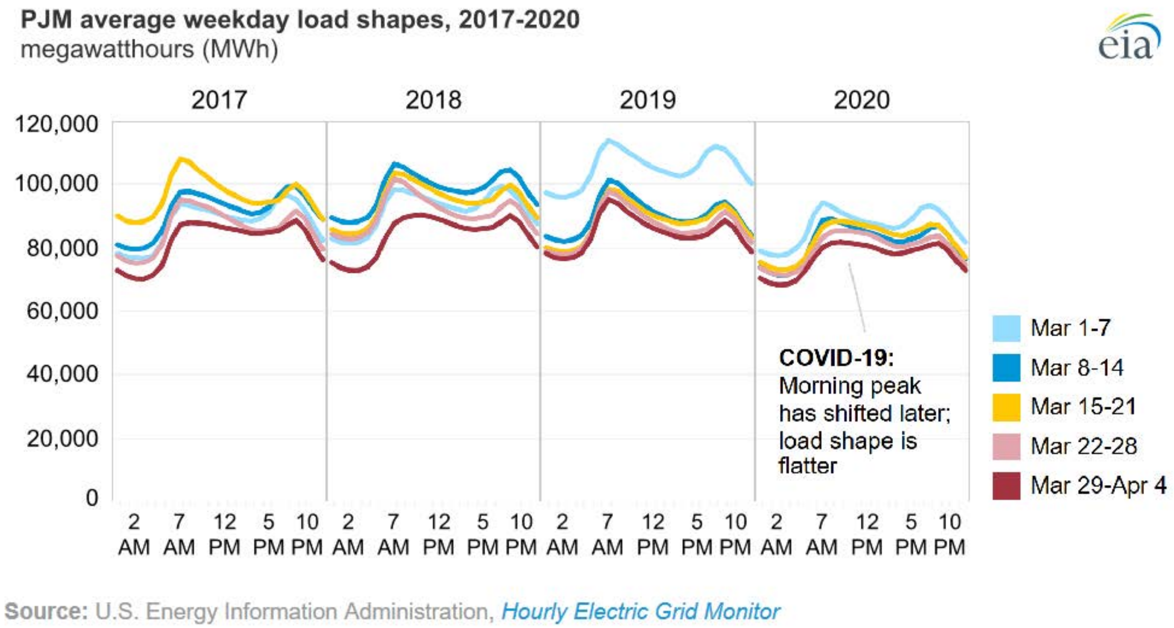
- Solar PV creates larger ramps since a large amount of energy is produced only during daytime, which is not coincident with the peak load.
- Wind generation tends to be larger during nighttime, which also create ramps.
- Renewable plants are often oversized to deal with weather variability and uncertainty.

Resource Adequacy with Renewable Generation

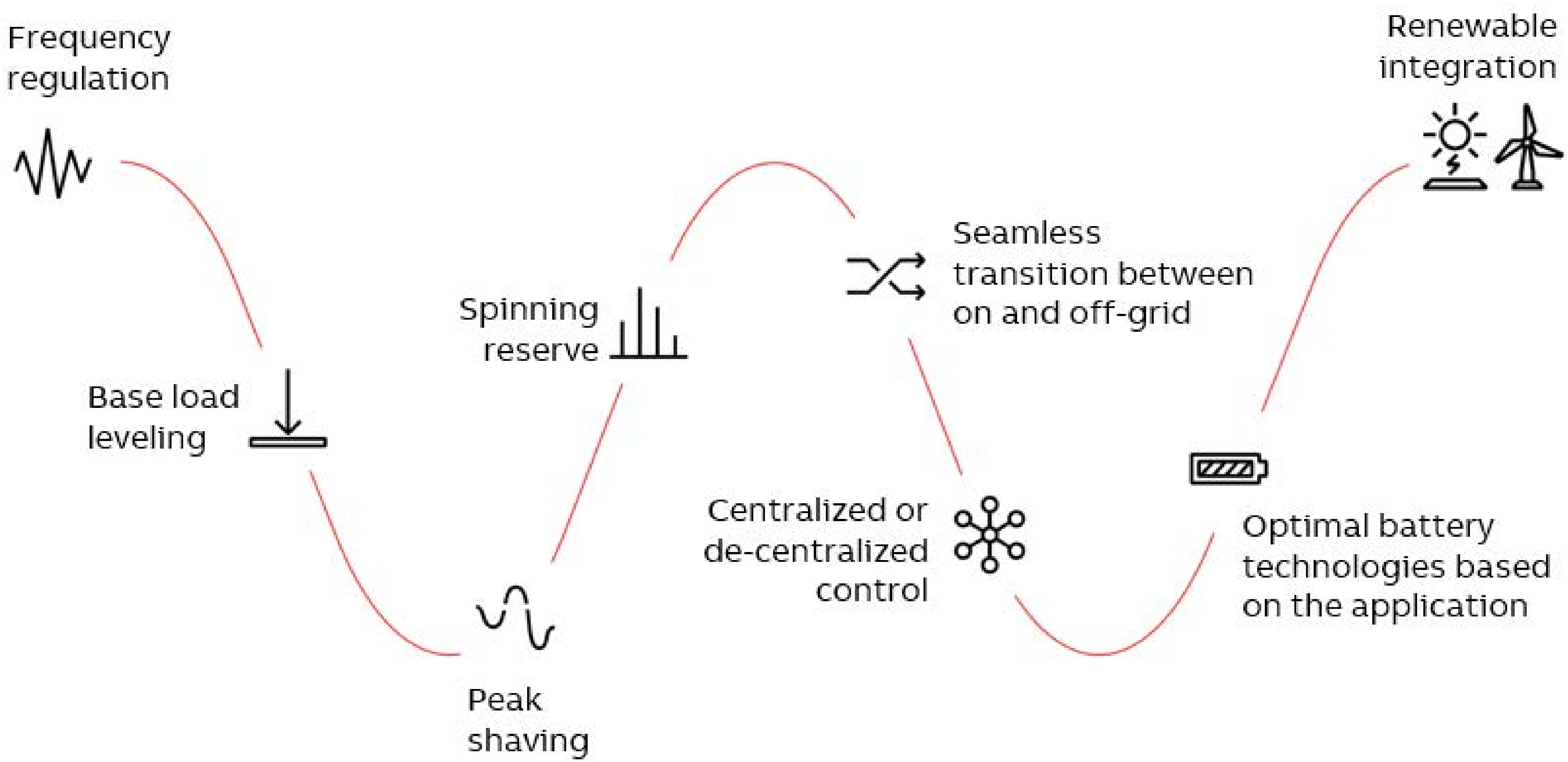
Grid should have adequate generation capacity to meet peak demand, considering:

- High variability and uncertainty from renewable energy generation
- Resources becomes much more distributed
- Customers not only consume but also generate power





Maintaining Frequency

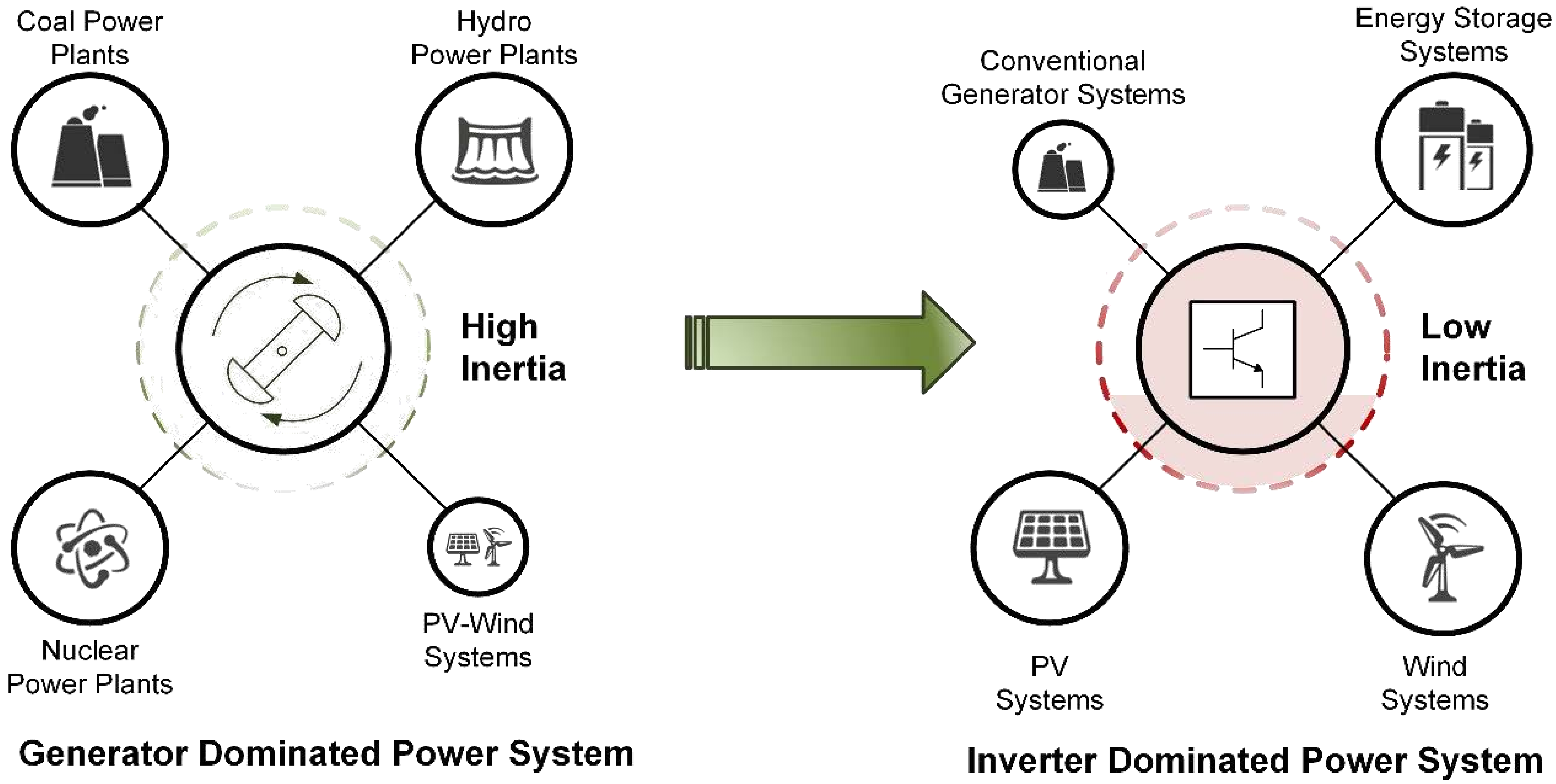


Sources: Hitachi ABB Power Grid

- Employ operating reserves able to respond to unplanned events
- Automatic control and protection (e.g., under-frequency load shedding)
- New options: demand response, DER, energy storage

Low Inertia

- The power conversion system is at the center of DER, Energy Storage, and EV infrastructure
- System will operate with much lower inertia – energy buffer provided by kinetic energy will decrease



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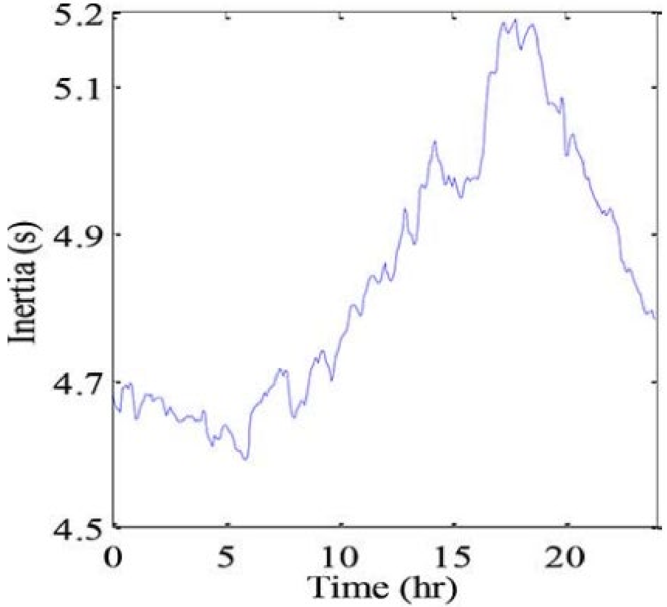
Effect of Renewables on Frequency Stability

Photovoltaic Power Plants
No Rotational Energy
No Inertia

Wind Power Plants
Coupled through power electronic converters
Limited Inertia

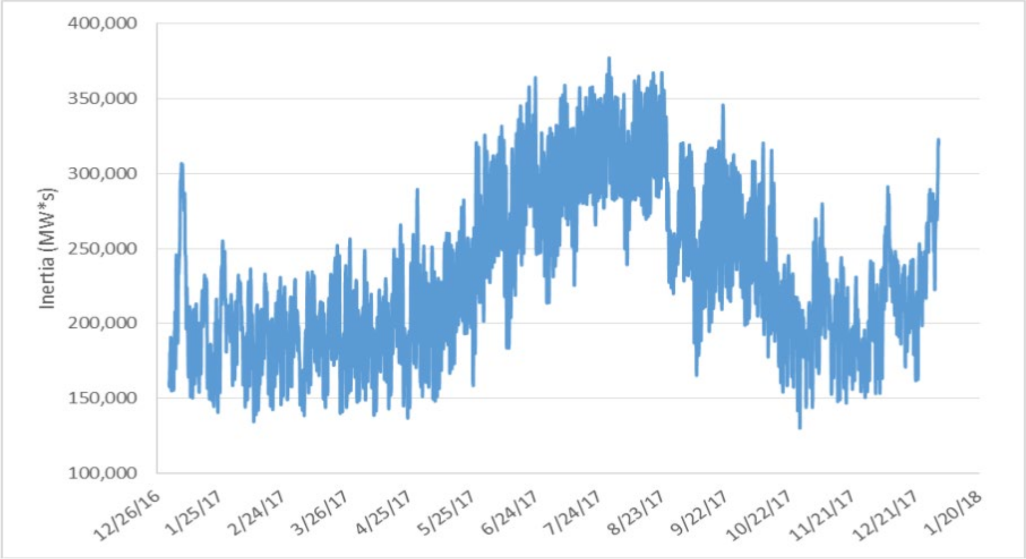
- Displacement of conventional generation leads to frequency stability issues
  - Large frequency deviations and Rate-of-Change-of- Frequency (ROCOF)
  - Under Frequency Load Shedding (UFLS) relays can be triggered
  - Causing cascaded tripping

Uncertainty in Grid Inertia with Renewables



Daily inertia variations from the UK grid

*Source: X. Cao, B. Stephen, I. F. Abdulhadi, C. D. Booth and G. M. Burt, "**Switching Markov Gaussian Models for Dynamic Power System Inertia Estimation**," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3394-3403, Sept. 2016.*



Seasonal variation in inertia of ERCOT

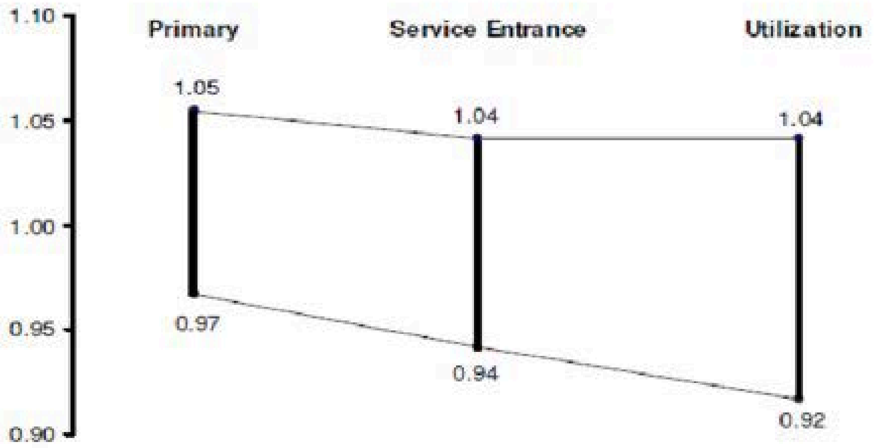
*Source: ERCOT. (2018) **Inertia: Basic Concepts and Impacts on the ERCOT Grid**. http://www.ercot.com/content/wcm/lists/144927/Inertia_Basic_Concepts_Impacts_On_ERCOT_v0.pdf*

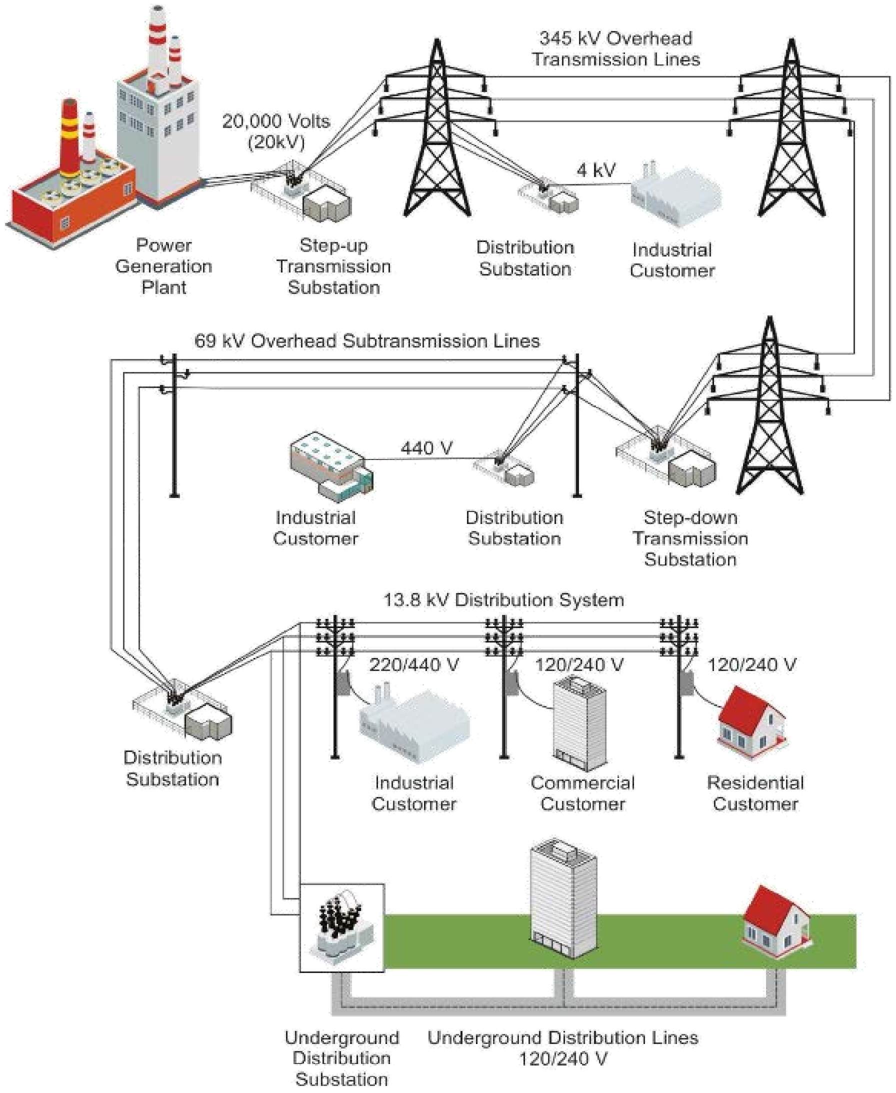
- Inertia dependent on the number of synchronous generations at any given time
- Inertia variability more pronounced in microgrids
- Design of controllers and protection systems becoming challenging

Maintaining Voltage

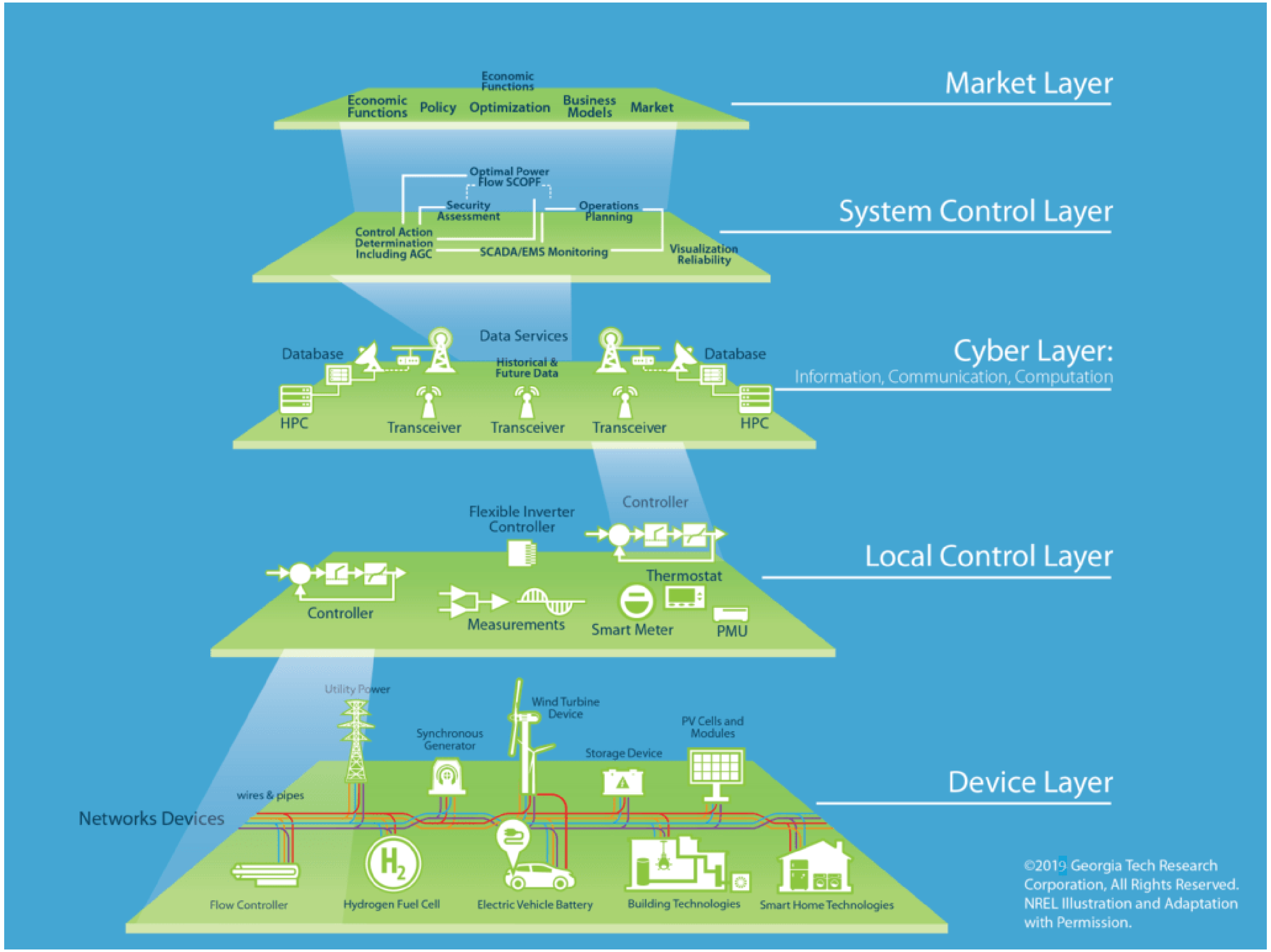
- Power electronic interfaced devices can create a big problem in coordinating multiple voltage regulators in order to maintain grid voltages.

	Service		Utilization	
	Min	Max	Min	Max
Range A (normal)	-5%	+5%	-8.3%	+4.2%
Range B (emergency)	-8.3%	+5.8%	-11.7%	+5.8%





Communication and Control



Sources: E&E News, Georgia Tech ACES

- Smart grid control and monitoring require fast, reliable and secure communication between all components.
- Large amount of networked device increases connectivity of grid assets, but creates a great challenge for cyber security as target domain for attack increases.

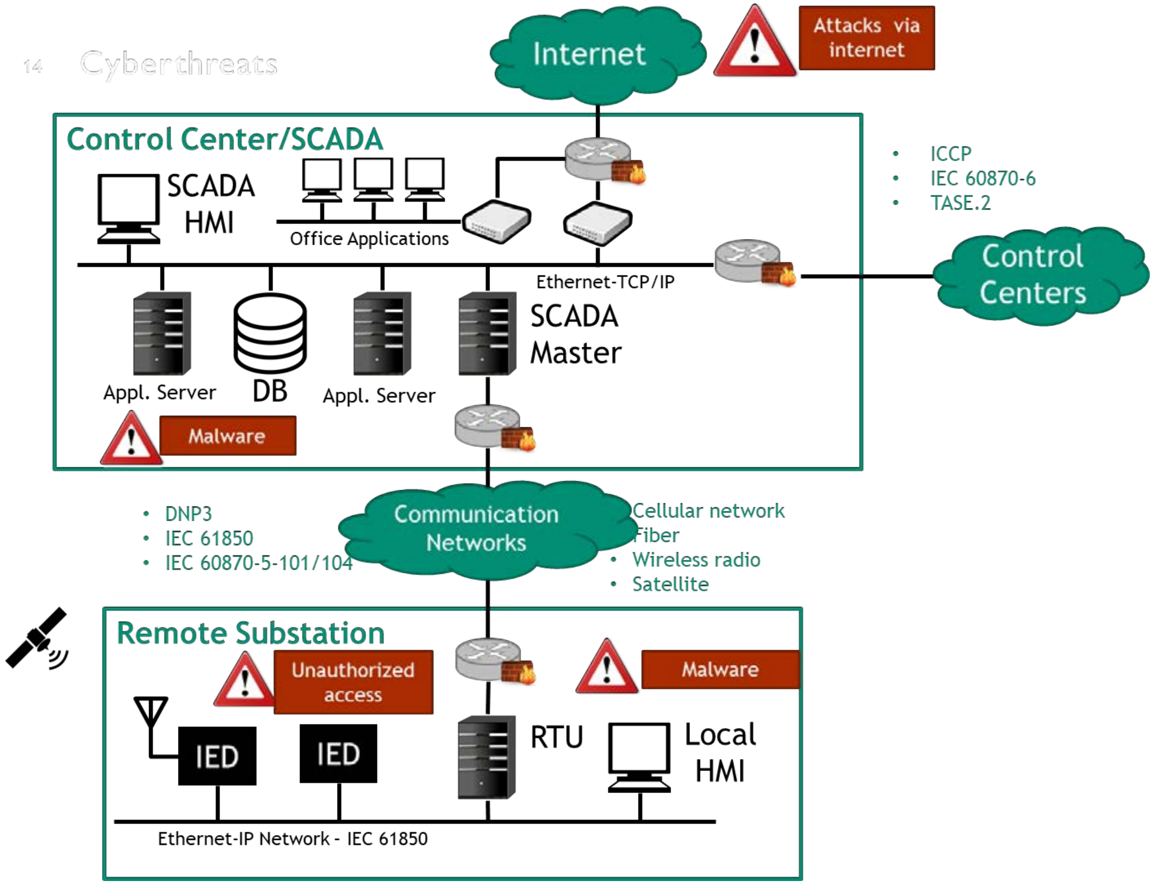
Cybersecurity and Physical Security

Electronic T&D Grids are Communications Intensive
- Pervasive communication systems with low latency and high bandwidth
- Sensors with high sampling rates in great numbers
- Response to fast grid dynamics, IP-based communications
- More fiber optics and cellular network links (LTE, 5G)

Change of paradigm from centralized to decentralized
- Agents that participate actively in power grid will be more granular
- Coordinated participation of DER will require fast and reliable communications

Cybersecurity will be a challenge with active DER
- Increased connectivity can improve its performance
  - Associated risks of communications
- Coordination between electric vehicles
- Communication over public networks

Physical Security
- EMP, GMD, and other large scale disturbances
- Weather related



Grid Resiliency

- Electricity interruptions cost Americans ~$150B/yr
- For every $1.00 spent on electricity, we spend at least another $0.50 to cover the cost of power failures.
- The concept of Reliability and associated metrics are becoming inadequate.
- Resiliency becoming important in operations planning
  - Encompass reliability
  - Include natural and manufactured threats
  - Include consequences of grid disruption
  - Inform operations in real time
  - Provide guidance for investment decisions

Grid Modernization - Challenges

- What is the impact of climate change on different renewable technologies in different regions, whether grid-scale or distributed?
  - Climate change forecasting as reported focuses on temperature, sea level, and severe weather, but cloud cover and wind speeds are also critical.
- How does renewable production variability change?
- How will renewable forecast accuracy change?
  - These answers have implications for amounts of operating reserves needed, and for how to incorporate "reasonable worst case" figures instead of means in planning.
- How will T&D investment decisions and incentives factor into the relative adoption of different renewable technologies – PV versus wind, grid scale versus distributed, remote versus local?
  - What are the "best" mixes given all costs and performance?

Grid Research & Development Needs

Electric systems	Traditional Grid	Development Trends and Needs	Future Grid
Generation	• Large centralized power plants • Dispatchable generation • Mechanically coupled • Minimal DER	• Growing role of DER • Energy storage • New planning tools to handle RE • Control coordination • NG replacing coal plants	• Hybrid control architectures • Bidirectional power flows and stochastic loads • Power electronic centric infrastructure across the grid
Transmission	• SCADA for status visibility • Operator-based controls • Aging infrastructure. Low peaking capacity utilization. • Threats/vulnerabilities not well defined	• VDC transmission • Growing dc loads • Improving EMS • Integrated planning tools • Growing security awareness • Increasing role of storage	• Wide-spread PMU deployment • Coordinated sensing and control infrastructure • System-wide dynamic power flow management • Resilient and self healing
Distribution	• Minimal to non-existent sensing and automation • Radial design and one-way power flows • Aging distribution infrastructure	• Deployment of ADMS • FACT/inverter enabled voltage regulation • Early adoption of storage in distribution systems	• Truly bi-directional power flows and large scale DG • Pervasive sensing and communications • Local, autonomous coordination • Asynchronous networks
Consumption	• Regional, location and customer specific rate structure • Uniformly high reliability • Predictable behavior based on historical needs and weather • Reliable, yet inflexible	• Customer-determined reliability/power quality • Real time pricing, time of use rates, demand charges • Improved utility communications • Behind-the-meter storage	• Autonomous microgrids • Advanced EMS • Widespread DERs and transactive energy • Pervasive sensor environment
Operation/Market structure	• Vertically integrated utilities, wholesale markets	• Market reform to compensate for services provided	• Diversity of energy products and services

Source: DOE Quadrennial Technical Review, 2015

Future Grid Infrastructure Needs

Adaptation to accommodate High Renewables, Electrification and Climate Change

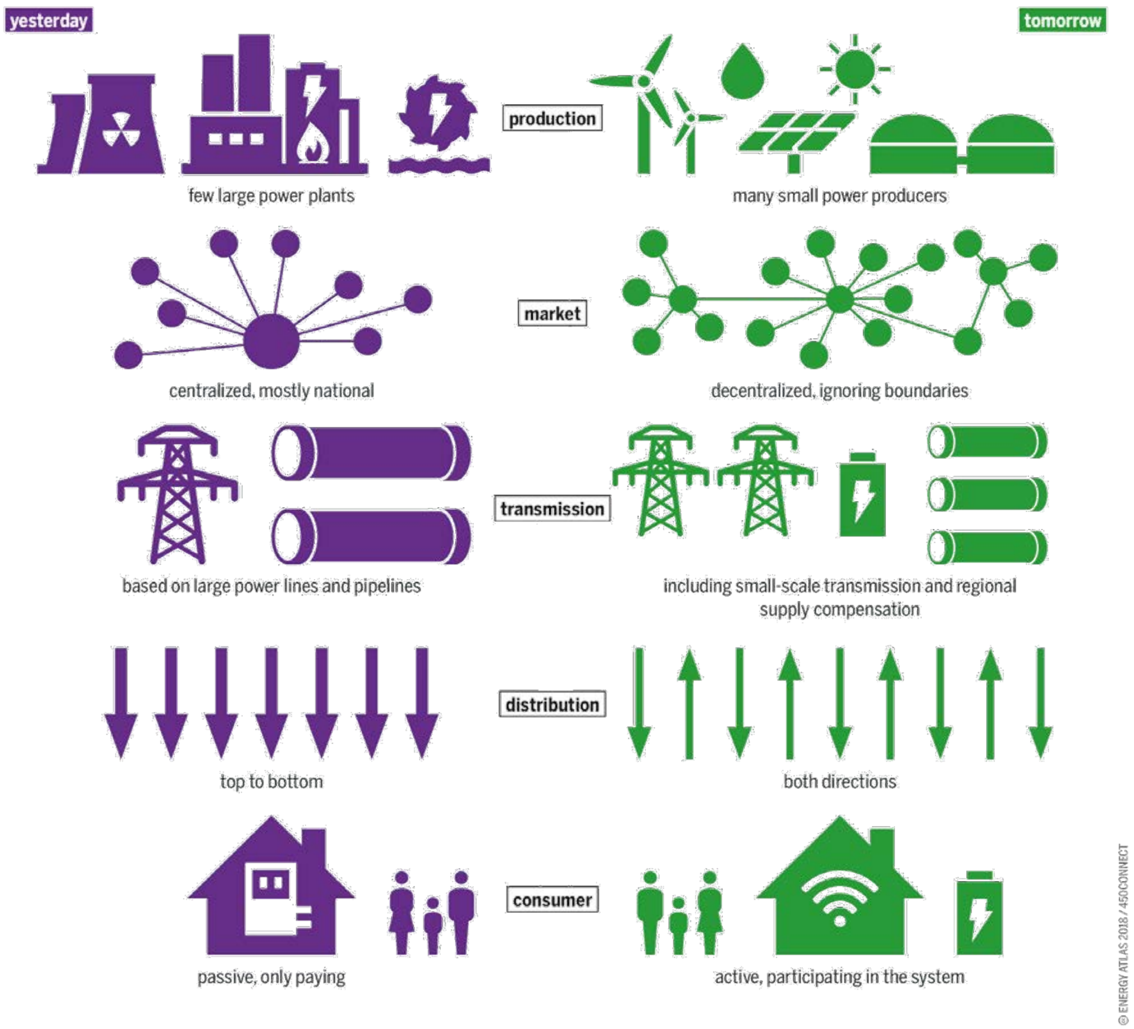
- Flexibility, G-T-D Coordination, Market Design

Handle Increased Resilience

- Weather, Natural disasters, Cyber, Physical attacks

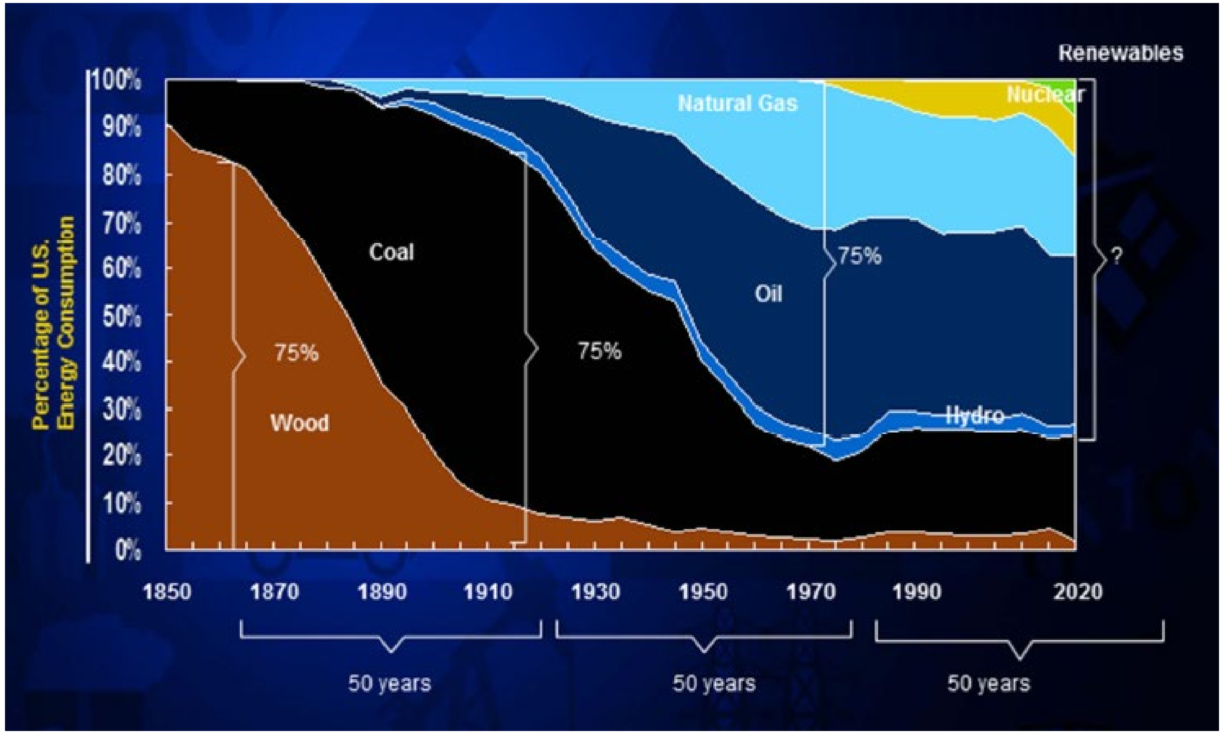
Smarter Grid

- Sensors, Analytics, Automation, IOT, Demand Side Participation, and Secure



Source: DOE Quadrennial Technical Review, 2015

Energy Transition Cycles are Long (50 Year Cycles)



EIA Annual Energy Review 2008

Electric grid is changing rapidly.

change is becoming rapid with decreasing cost of renewable generation, energy storage and power electronics

Future Grid needs lots of Energy Storage

Major Takeaways

The 100+ year old grid is evolving rapidly

- Increased renewable generation and distributed energy resources
- Increasing deployment of inverter-based resources (load and generation) and smart grid functionality
- Increased concern about resilience to natural and manmade events
- Increased concern about cyber security vulnerabilities
- Continued deregulation and evolution of energy markets

Major research challenges

- Designing for resilience, especially factoring in interdependencies between critical infrastructure (e.g., electricity, gas, water, etc.)
- Improved operation with increased variability from renewable generation
- Grid controls to improve stability, reliability, and resilience
- Low cost energy storage solutions
- Big data approaches for improving grid operations based on ubiquitous sensors
- Cyber security – guarantee confidentiality, integrity, and availability of the electric grid

Acknowledgements

The Energy Storage program at Sandia is supported by

DOE Office of Electricity Energy Storage Program

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Grid Energy Storage

Supporting Grid Modernization, Renewable Integration and Electrification

Babu Chalamala, Ph.D.

Sandia National Laboratories

5th International Summer School on Materials for Energy Storage and Conversion

September 10, 2021

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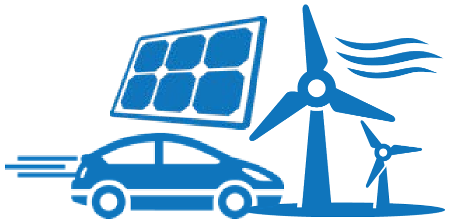
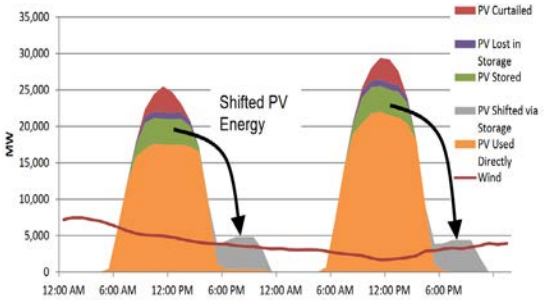
Role of Energy Storage in the Grid

- 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.

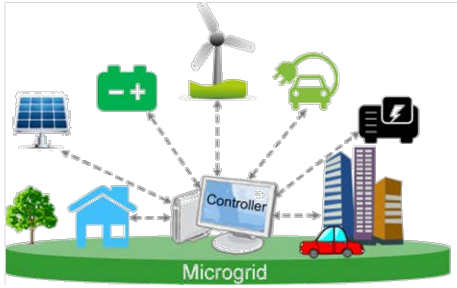


Balancing renewable variability



Peak shaving and energy shifting

Regulation/contingency reserves



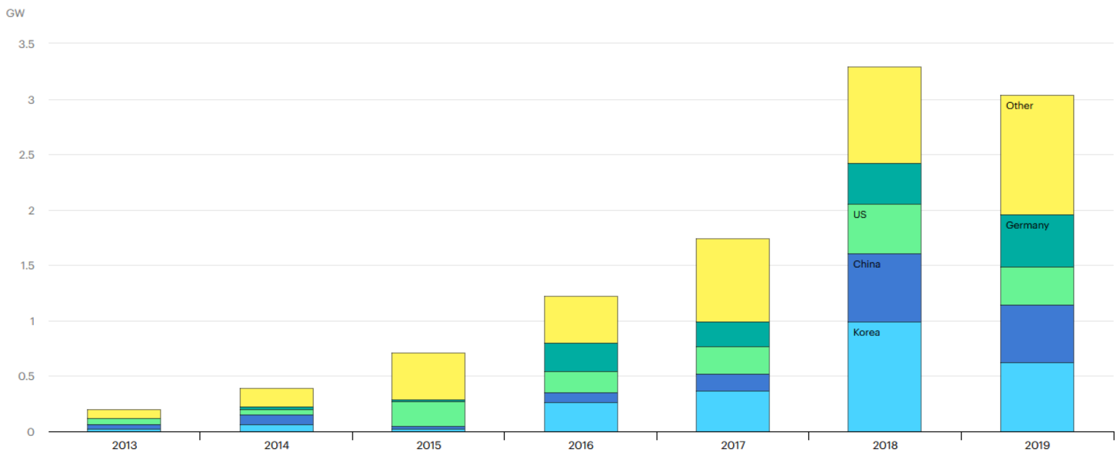
Microgrid

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 throughout the United States
  - 1.2 GW large-scale solar-plus storage in India
  - Post-2025 target 200 MW of storage in Singapore
- Battery energy storage is the majority of new capacity installed, benefitting from the spill-over of EV technology development to grid-scale batteries.
  - 2 GW BESS installed capacity in 2018 in the U.S., the rest is mostly pumped hydro
  - 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)

Energy Storage in the Grid Today

Grid-Scale Energy Storage < 0.1% of U.S. Generation Capacity

US installed energy storage capacity of 32 GW represents ~15 min ride through

BESS reached 2GW in installed capacity in 2018, rest is mostly Pumped Hydro.

1.6 GW Raccoon Mountain PHS

100 MWh BESS Plant - Tesla

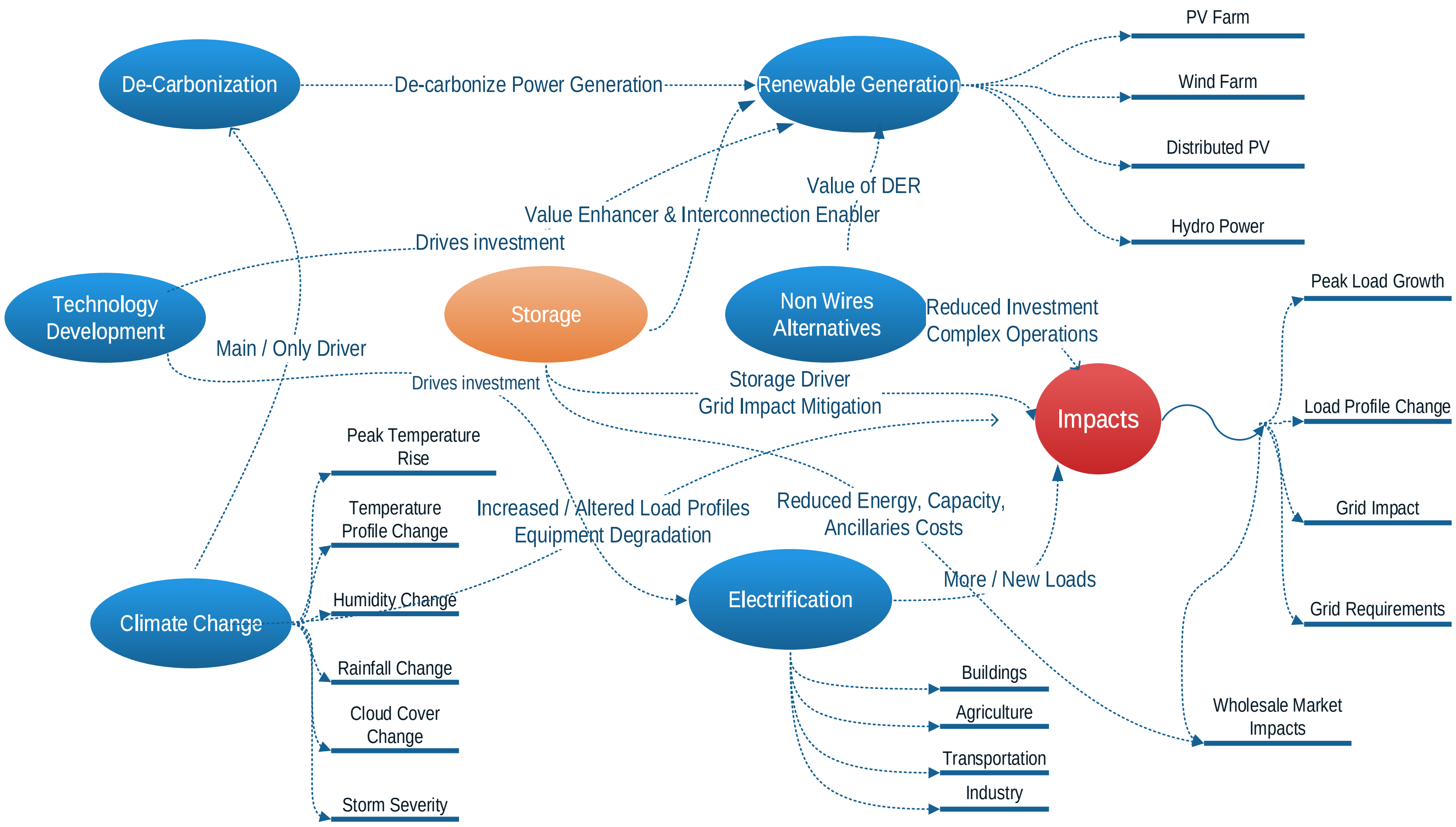
Wood Mackenzie P&R

ESA | U.S. energy storage monitor 2018

Compared to the need, the scale of energy storage deployments is insignificant.
With a 1 TW US electric grid, even 1 hr of energy storage means 1 TWh

DOE Global Energy Storage Database, 2018

Role of ES in RE, Electrification and Mitigating Climate Change



Energy Storage is Key to Renewable Integration, Grid Resiliency Decarbonization and Electrification

Adaptation to accommodate High Renewables, Electrification and Climate Change

- Flexibility, G-T-D Coordination, Market Design

Handle Increased Resilience

- Weather, Natural disasters, Cyber, Physical attacks

Smarter Grid

- Demand Side Participation

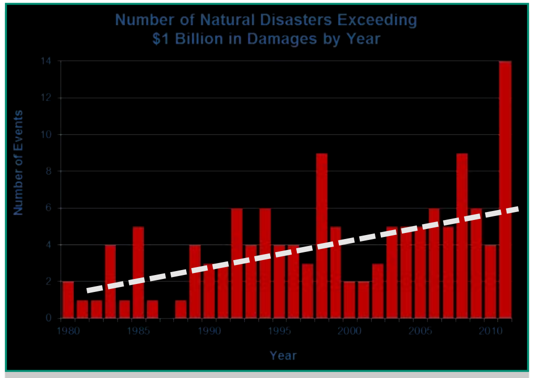
System Needs

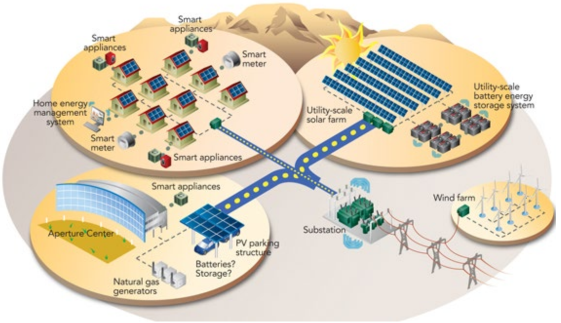
- Capable across energy and time, short duration (power applications), medium duration (energy shifting), and long duration(10+ hours to days) to seasonal

- Scalable Systems – from BTM to T&D applications

- Simple to install, operate, safe and secure

- Needs standardization at all levels





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

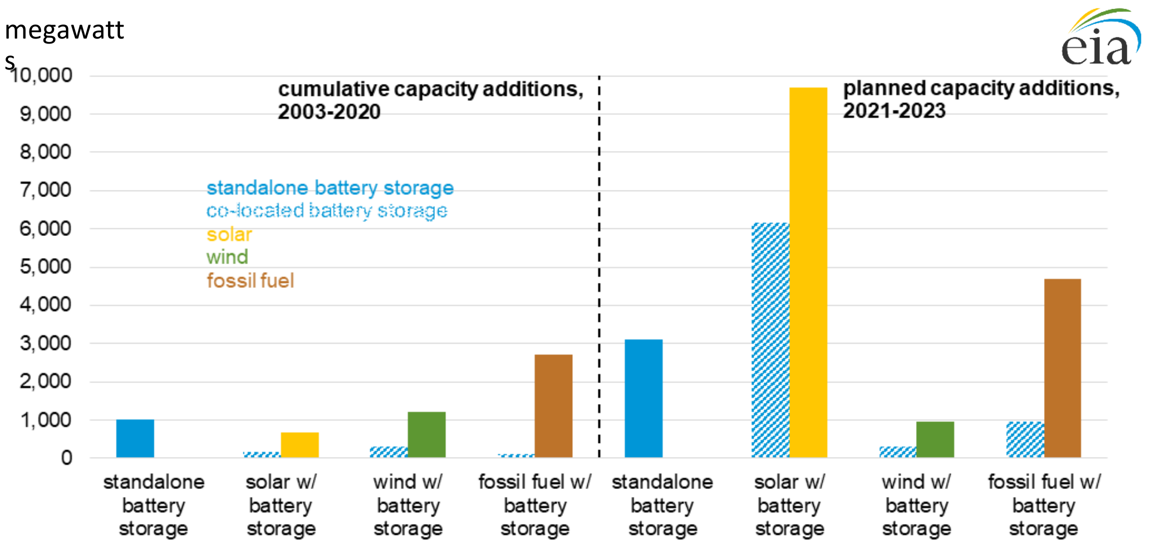
Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

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

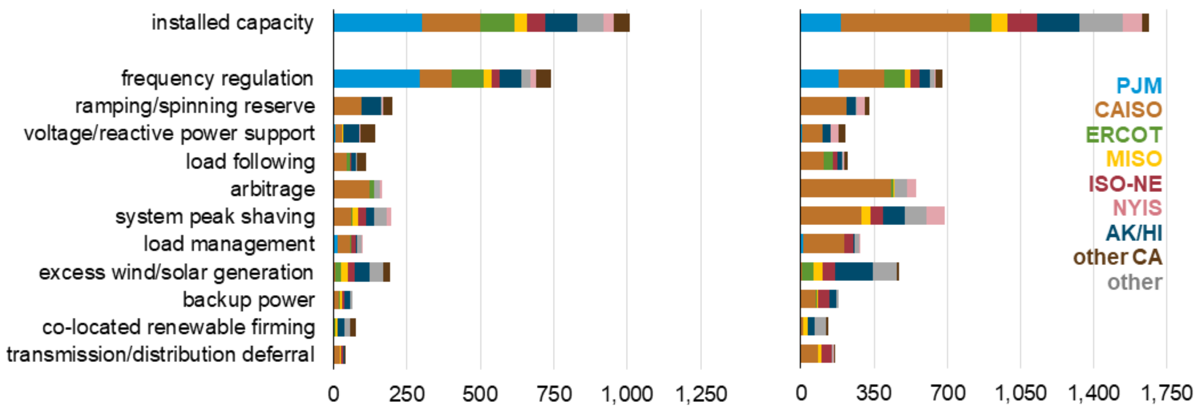
GWh size BESS Plants no longer at the conceptual stage

Images: Company websites and Wikipedia

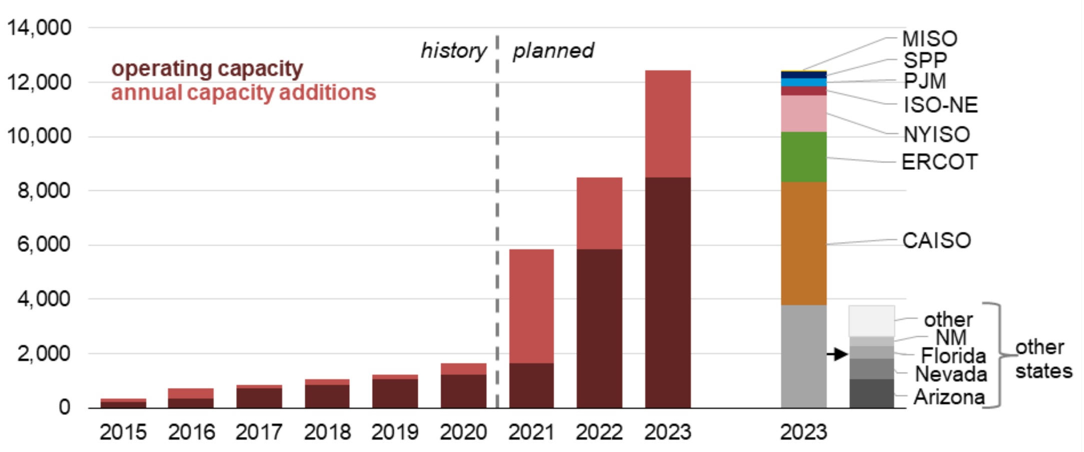
Energy Storage and Renewable Integration



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



Applications served by large-scale battery storage (2019)



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

Most of planned new capacity in the pipeline is hybrids either with solar, wind or NG

Energy markets beginning to open, storage is still expensive for energy applications

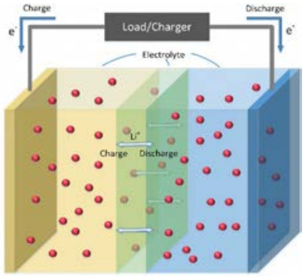
Most ES deployed is Li-BESS

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

Energy Storage is New to Grid Operators
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**



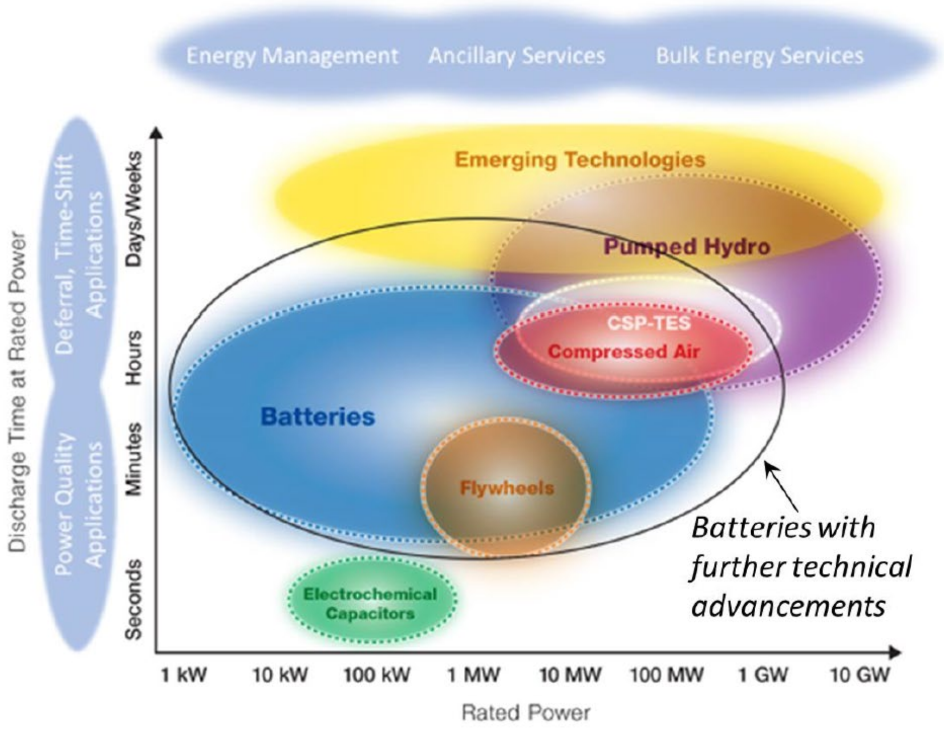
Manufacturing

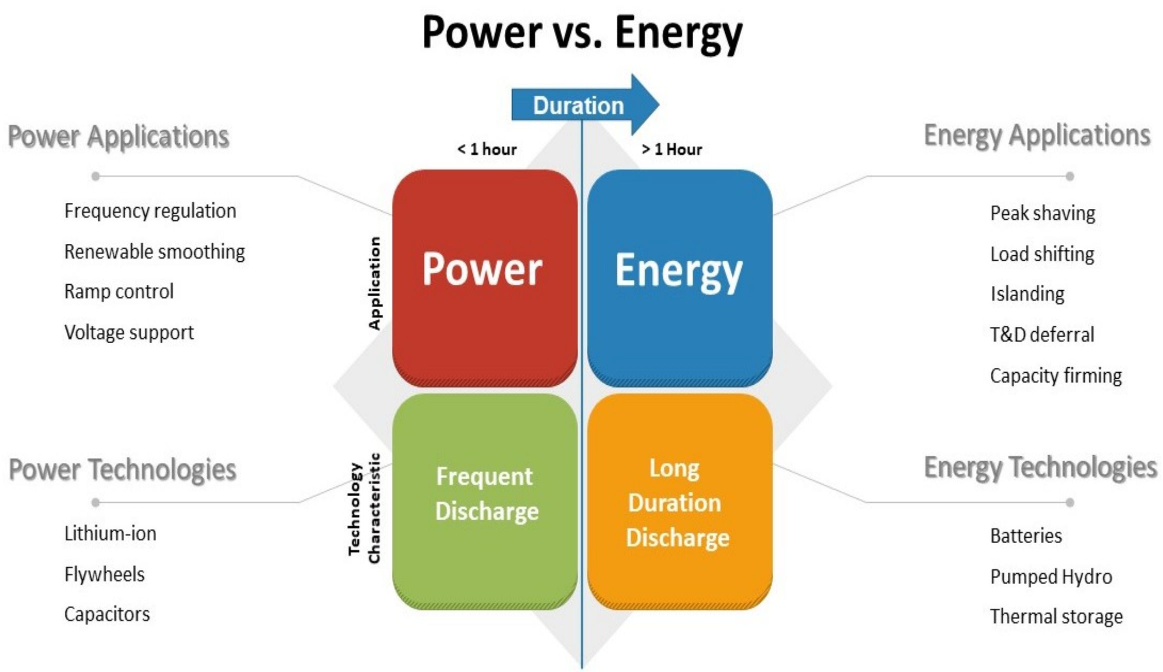
- Industry needs cycles of learning – manufacturing scale through deployments
- Project finance – bankable, warrantees, performance guarantees, risk management
- **Standardization – equipment, permitting, construction processes**

Grid Operation

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

Range of Technologies and Applications





Source: Potential Benefits of High-Power High-Capacity Batteries, DOE Report, Jan 2020

Source: Energy Storage Primer, IEEE Power and Energy Society, 2020

Range of battery technologies for short duration energy storage, seconds to days

Pumped hydro and CAES for hours to day long energy storage

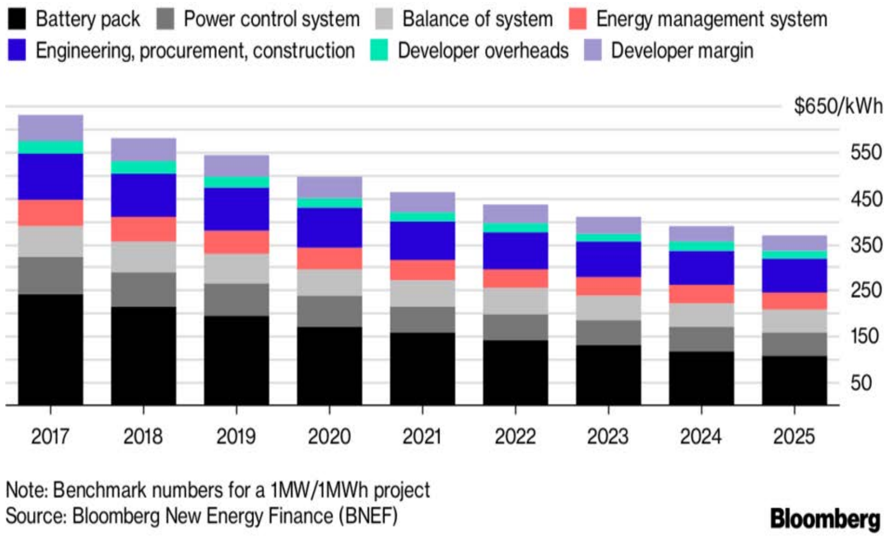
No ready solutions for real long duration and seasonal storage needs

"Energy" applications: slower times scale, large amounts of energy

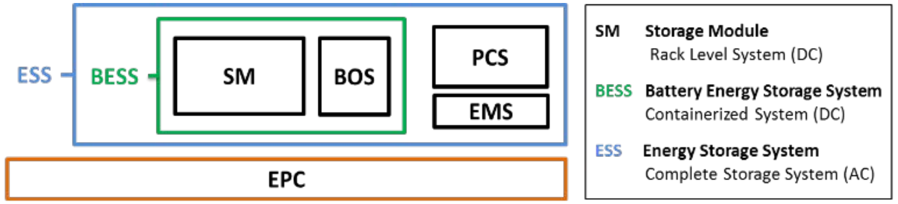
"Power" applications: faster time scale, real-time control of the electric grid

Battery Energy Storage is not just about Batteries …

- Integration costs are significant to meet safety and performance requirement
- Performance of battery energy storage systems are not sorely 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

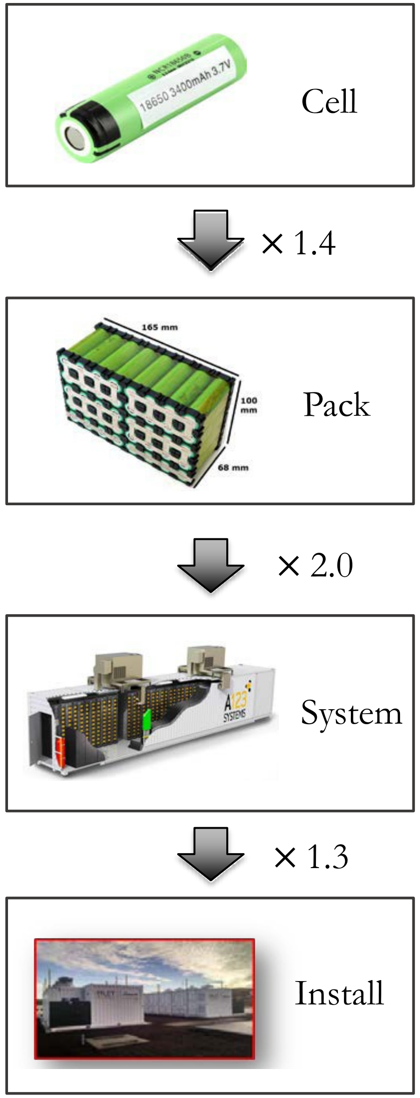


Integration costs increase as cell → battery → Storage System. For example, doubling in cost, $250/kWh battery leads to $500-$700/kWh at the system level.



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

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 Technologies

Market drivers

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

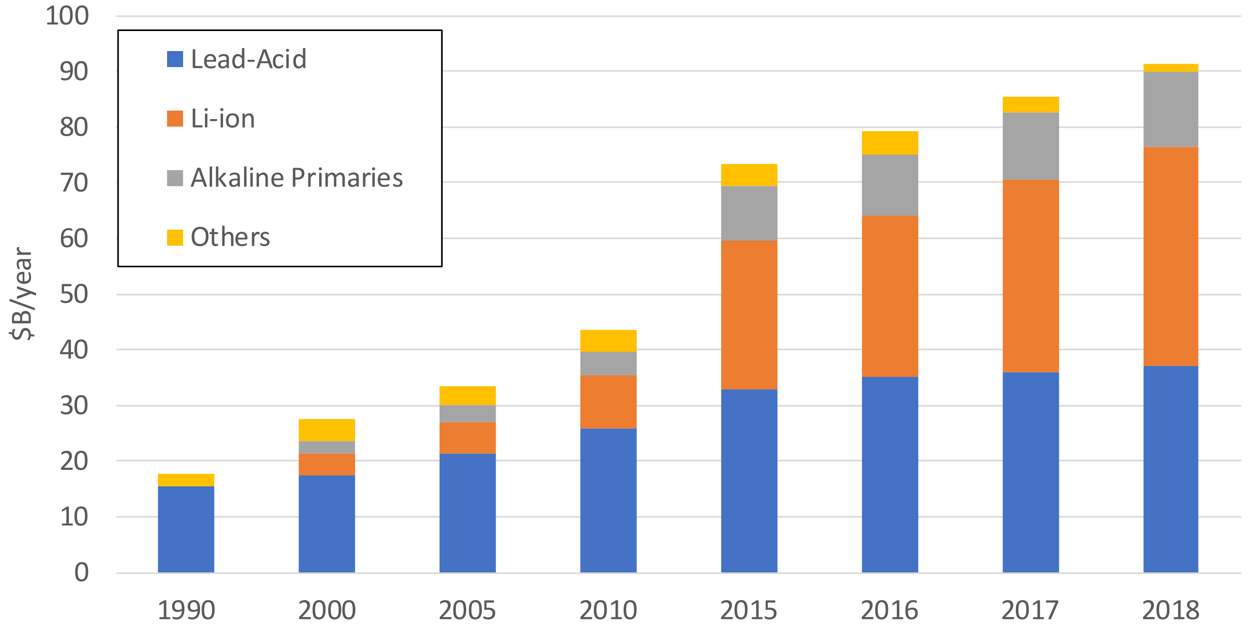
Traditional Batteries
e.g. Lead-acid, Ni-Cd, Ni-MH, Zn-MnO$_2$

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

Global Battery Sales



- Lead-Acid: 350 GWh production capacity, $38B/yr
- Li-ion: over 300 GWh and growing capacity, $40B/yr
- Primary cells: $13B/yr

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

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

Li-ion Batteries

Family of electrochemical systems

Positive electrode
- Metal-oxides (e.g. LCO, NMC, NCA)
- Phosphates (e.g. LFP)

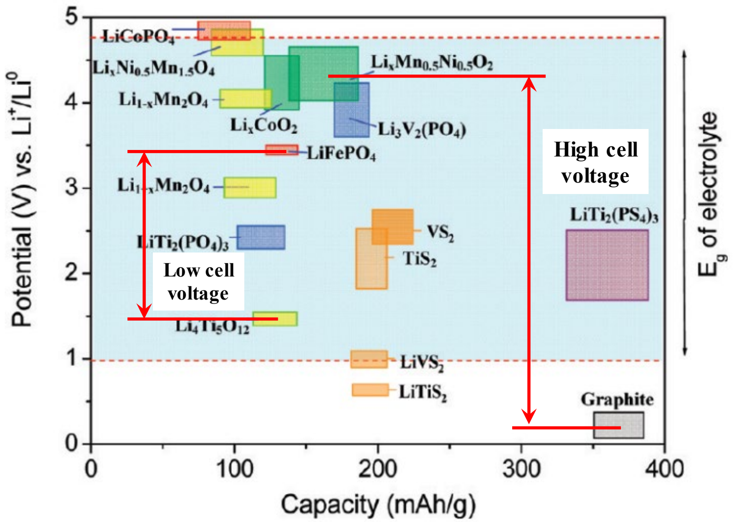
Negative electrode
- Graphite and other carbons
- Lithium titanate

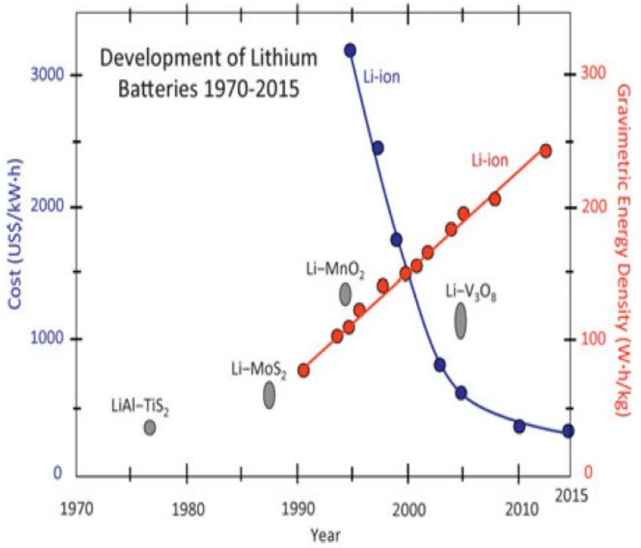
SOA EV batteries - Specific energies near 250 Wh/kg

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

Li-ion Batteries – Challenges for Grid Applications

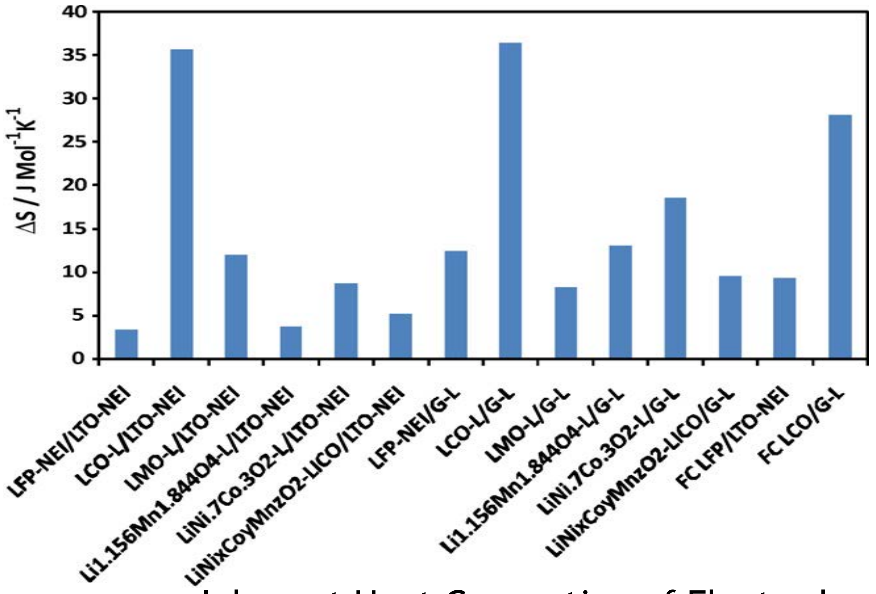
Battery safety is very important for applications where high power is required.

Heat generation during high power usage must be managed
- Dictates smaller form factor
- Higher production costs

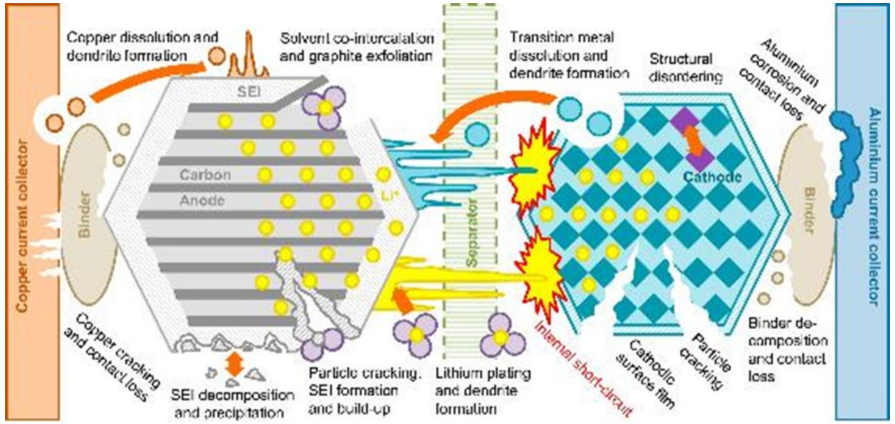
High Temperature
- Typical operating window 0-50°C
- Operation above this temperature can lead to organic electrolyte decomposition and flammable gas, rapid internal pressure build-up

Overcharging
- Overcharging can lead to Li metal plating on anode, potential for short

Need better understanding of the degradation pathways and engineering to control thermal runaway

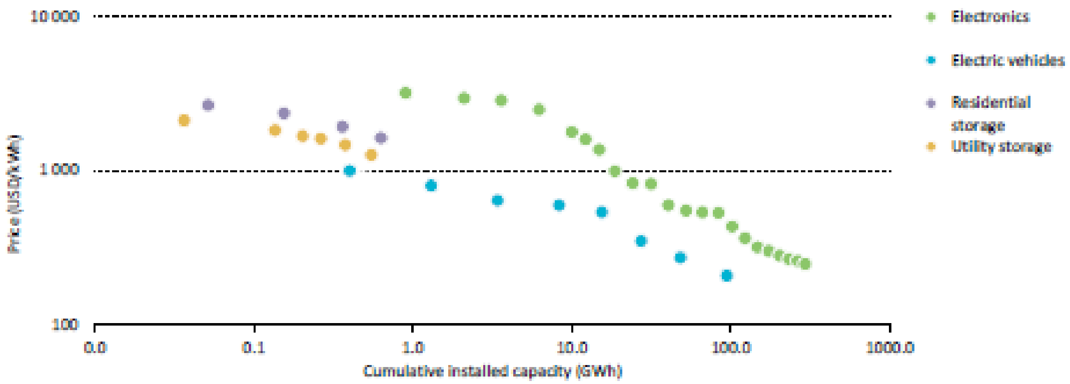


Inherent Heat Generation of Electrodes



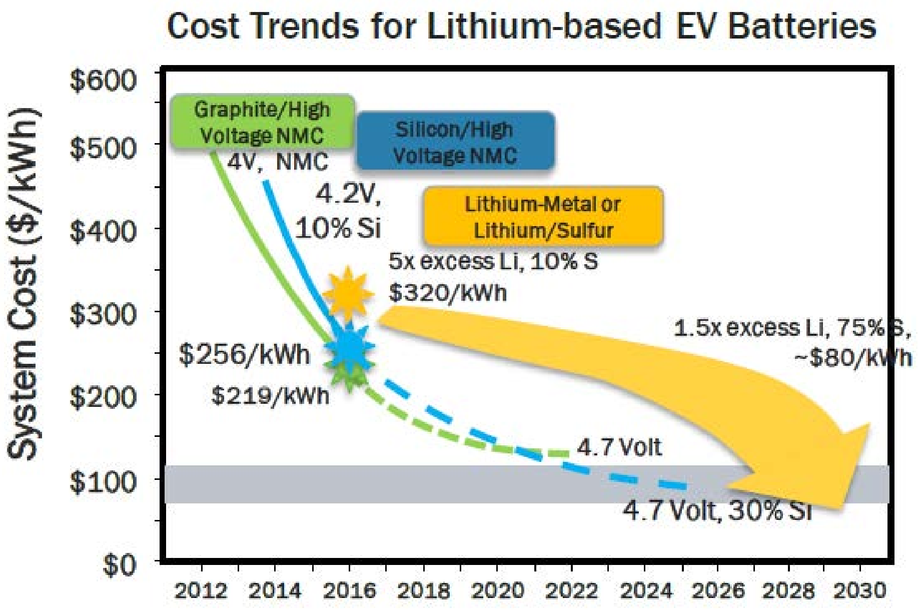
J. Power Sources, **2017**, 341, 373

Manufacturing Scale and Cell/System Costs



Li-ion storage technology price with manufacturing volume
Source: IEA, 2018

Future cost projections predicated on stable commodity prices, significant improvements in energy density and cell performance



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

Lead-Acid Batteries

Sealed lead-acid
- Gel and Absorbed Glass Mat (AGM)
- More temperature dependent

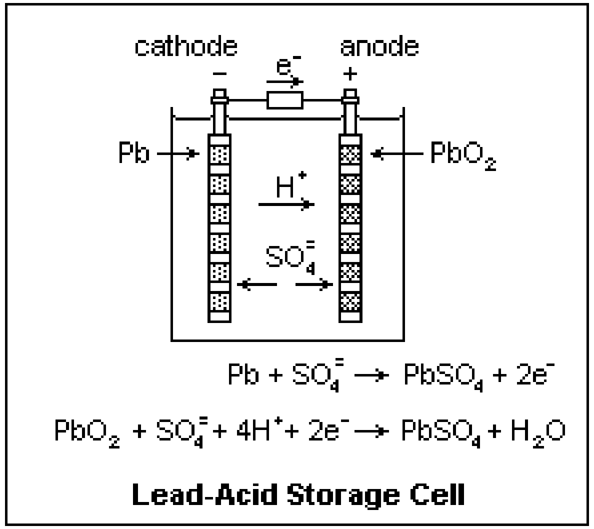
Advanced Lead Acid Energy Storage
- Carbon plates significantly improve performance

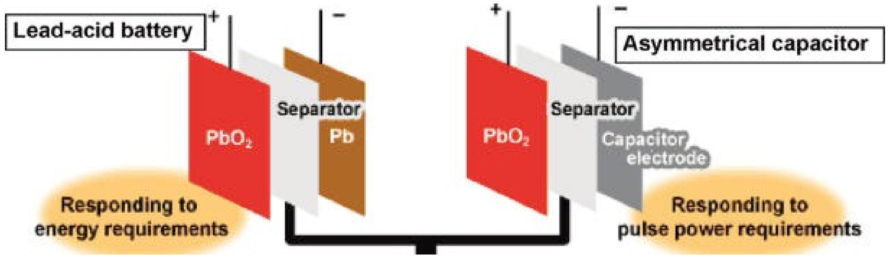
Mature technology

High recycled content

Good battery life

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





http://www.ultrabattery.com/

Lead Acid Batteries – Deployment for Grid Services

3 MW/3 MWh advanced lead acid battery system for utility applications (Source: EastPenn, East Lyons, PA)

Solar plus ultrabattery storage (Source: PNM Albuquerque, NM

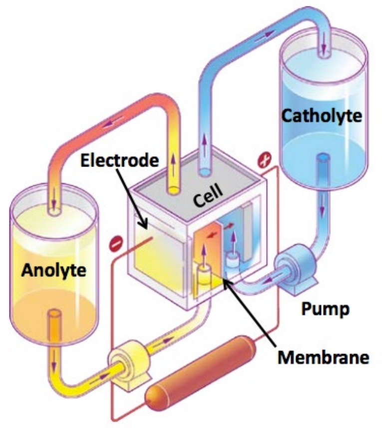
1.3MW/1.9 MWh advanced lead acid battery system providing support for a 68MW solar farm in Alt Daber, Germany (Source: BAE Batteries, 2018)

Redox Flow Batteries

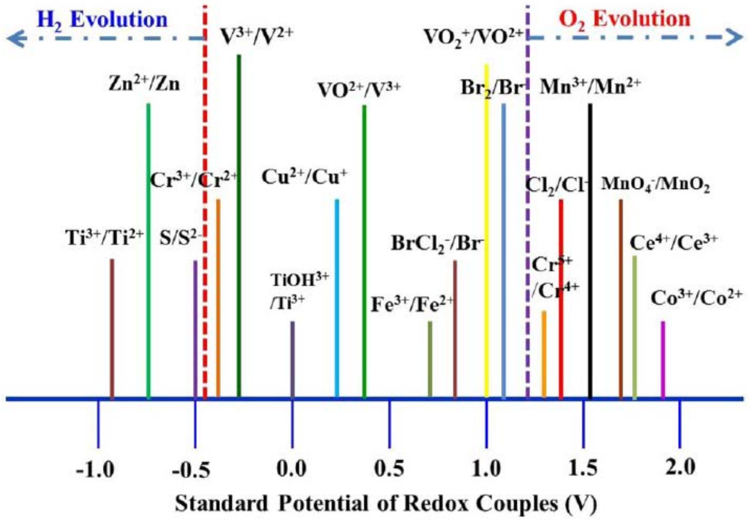
Energy storage technology utilizing redox states of various species for charge/discharge purposes

Key Aspects
- Power (kW) and energy (kWh) separation
- Greater flexibility and safety
- Modular and scalable across a wide range of power and energy
- Long cycle life
- Low energy density ~ 30 Wh/L

Range of redox chemistries
- Fe-Cr, Zn-Br, V-V are most studied and large systems demonstrated
- Most large commercial flow batteries are based on V-V chemistry, and Zn-Br



Source: Travis Anderson, Sandia National Laboratories, 2013



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

Redox Flow Batteries – Technical Challenges

Low energy density

- Limited voltage window of aqueous electrolyte solutions (< 1.5 V)
- Large form factor/footprint

Limited electrolyte stability

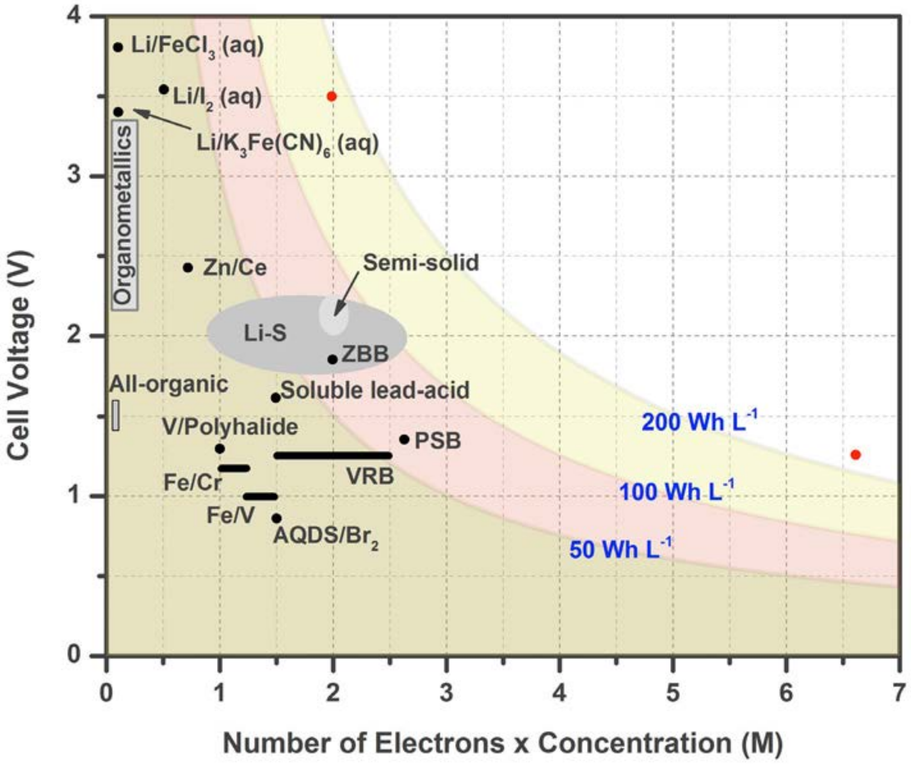
- Low solubility of redox species in aqueous electrolytes
- Capacity decay during cycling
- Narrow temperature range

Corrosion of membranes and electrode materials by acidic electrolyte solutions

- Long-term reliability

Opportunities to Reduce Materials Cost

- New redox chemistries, new electrolytes under development
- Lower cost of membranes
- Increased current density and lower cost stack design



Wei Wang, et. al., Adv. Funct. Mater., , **23**, 970, 2013

RFB Stack Sizes Continue to Grow – Large Plants being built

Rapid progress in the development of large utility class redox flow battery systems

Rapid development of new electrolytes to replace Vanadium species

Further potential to reduce the size of the stacks and to increase energy density

Containerized Systems

UniEnergyTechnologies, 1MW/4MWh

32 KW Stack
Rongke
Power/UET
120 mA/cm2
Meter size
stack

Flow battery power plants

Sumitomo Electric, 15MW/60MWh

Stack room

NaS Batteries

Most widely deployed of long duration batteries

NaS first developed by Ford Motor Co. in 1960's

- Commercialized by NGK in Japan
- 530 MW/3700 MWh of installed capacity, primarily in Japan

NaS battery

- 2Na + xS → Na2Sx (x = 3~5)
  - E = 2.08~1.78 V at 350°C

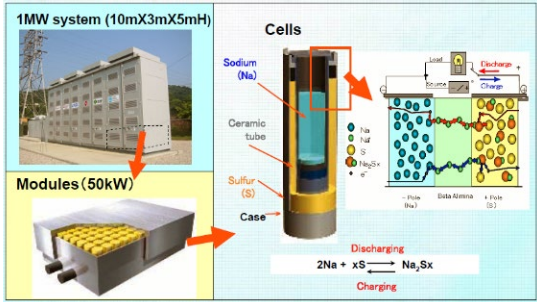
Applications

- Power quality, Congestion relief
- Renewable integration

Challenges

- Battery is assembled fully charged, presents a major safety/handling issue
- System needs to be maintained at temperature
- High temperature operation, safety and containment challenges
- Relatively expensive

NGK is the only committed manufacturer



Source: NGK

34MW /245 MWh NAS at a wind farm Rokkasho, Aomori, Japan (Source: NGK, 2017)

Los Alamos, NM. 1 MW, 6MWh

$NaNiCl_2$ Batteries

NaNiCl2 battery

- 2Na + NiCl2 → 2NaCl + Ni
  - E = 2.58V at 300°C

Large cells and stable chemistry

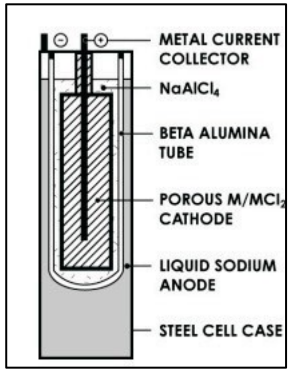
- Lower temperature than NaS
- Cells loaded in discharge mode
- Improved safety compared to NaS. Addition of catholyte $NaAlCl_4$ leads to a closed circuit on failure

High efficiency, low discharge

Long warm up time (16 hr)

Supply chain concerns. Only one manufacturer FIAMM. GE no longer in this business

- Limited deployments



FIAMM 222-kWh System Duke Energy Rankin Substation

Molten Na Batteries - Engineering Challenges

Low cost active materials, but challenging systems engineering

- Need for high temperature operation, kinetics driven by the solid ceramic electrolyte
- Typical operating window 250-350^{o}C. Need for continuous thermal management even when not in use. At lower T, Na metal freezes out, degree of distortion to cell dictated by SOC of battery
- Safety concerns related to membrane rupture. In NaS, failure can lead to exothermic reaction
- Need hermetic seals
- Charging/discharging limitations

Engineering cells that operate at lower T (150^{o}C or lower) remains a challenge. Low Temperature Operation of a Molten Na Battery is Tremendously Enabling

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

Rechargeable Alkaline Batteries

Range of alkaline battery chemistries

- NiMH, Ni-Fe, Ni-Cd, Zn-Ni, Zn-MnO2

Zn-MnO_2 shows most promise for grid storage

Cost

- Traditional primary batteries, low cost ($18-20/kWh primaries)
- Low-cost materials and manufacturing
- Established supply chain

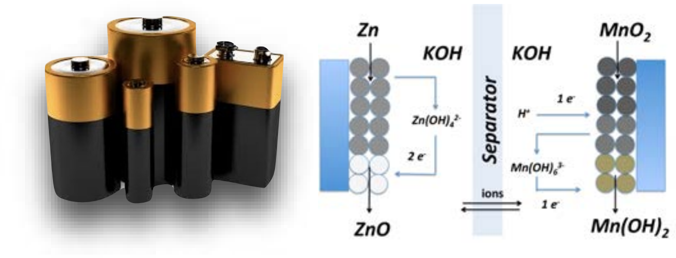
Safety

- Aqueous chemistry
- Non-flammable
- EPA certified for landfill disposal

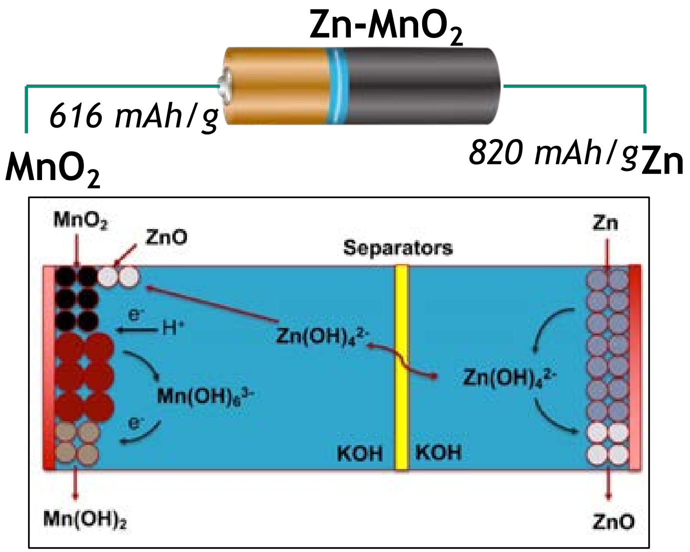
Reliability

- Long shelf-life
- Limited thermal management required

Reversibility and cycle life have been the primary technical challenges



Single-use Alkaline Battery $25/kWh



Source: S. Banerjee, CUNY Energy Institute

Full Utilization of 2e

On the MnO_2 Cathode

- Regeneration of cathode structure on solution/dissolution/precipitation cycle
- Formation of Inactive phases
- Reducing susceptibility to Zinc poisoning

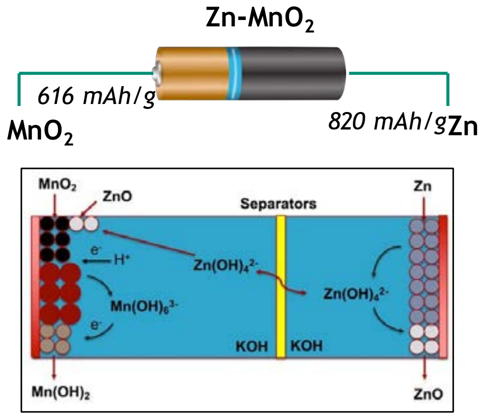
Separator

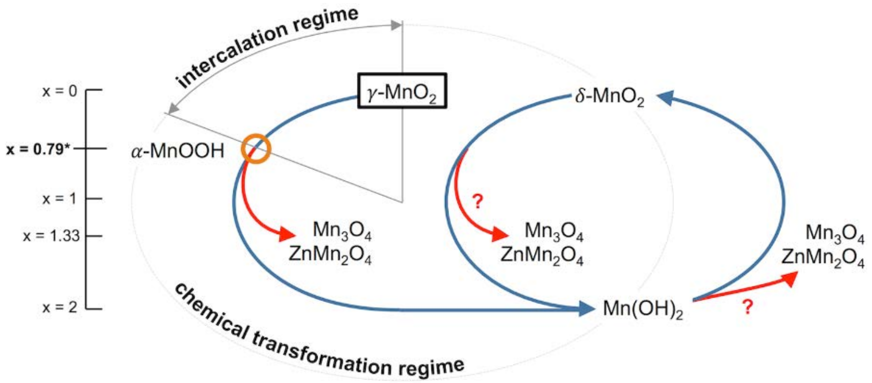
- Reduce Zincate crossover

On the Zn Anode

- Control shape change
- Passivation
- Reduce dendrite formation

Need improvements in materials utilization, process optimization and engineering of large format cells



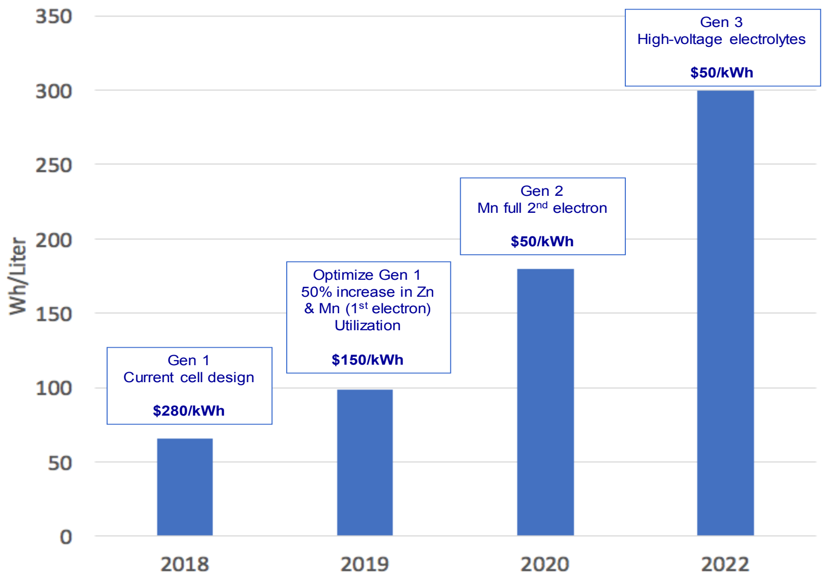


Failure Mechanisms of Cathode

Instability of Mn(III) resulting in formation of irreversible Mn_3O_4
Zn poisoning forming irreversible $ZnMn_2O_4$

Potential for Zn-MnO_2 Cells <$50/kWh

- Recent breakthroughs in making MnO_2 fully rechargeable. Based on the formation of a layered birnessite MnO_2 structure and stabilizing this structure for thousands of cycles.
- Improvement in energy density and cost by improvement in zinc utilization
- Cathode degradation mitigation by improvements controlling Zn migration across separator
- Potential for $50/Wh cells with high cycle-rechargeability of Zn-MnO_2



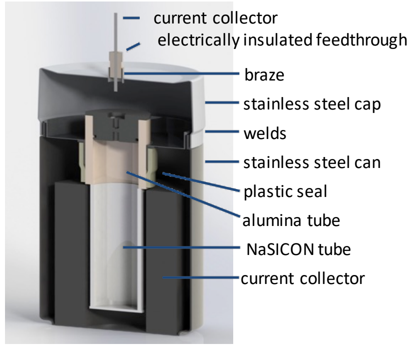
Source: CUNY Energy Institute

Grid Storage needs Large Format Cells

Engineering costs are significant for small format cells. Large format cells are needed to reduce overall system costs.

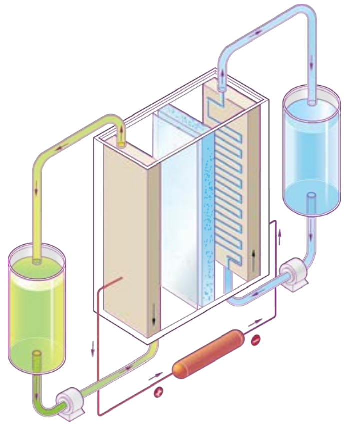
Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

High Conductivity Separators for Low Temperature Molten Sodium Batteries



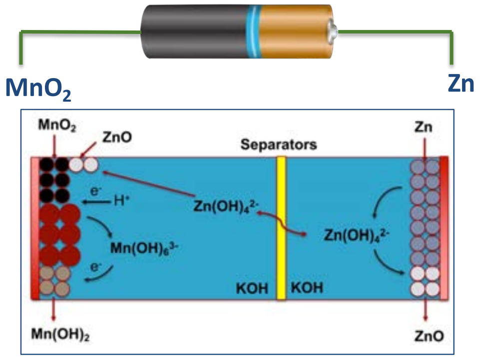
Robust ceramic separators exhibit low Na^+ conductivity at lower, more cost effective temperatures (120-180 °C).

Crossover in Redox Flow Batteries



Cross over of the electroactive species through the separator leads to severe capacity decay in flow battery systems.

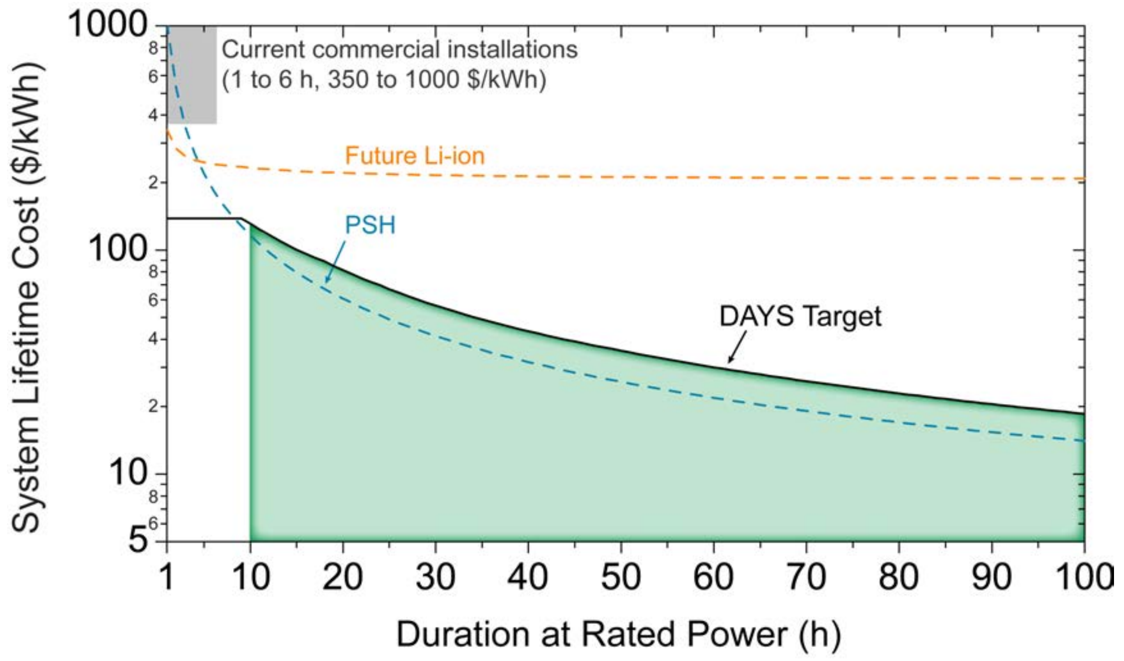
Zincate poisoning of MnO_2 in Zn/MnO_2 Batteries



Zincate diffusion and subsequent poisoning of MnO_2 impairs reversibility and significantly decreases lifetimes.

Long Duration Energy Storage is a Major 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 larger to justify lower system costs.



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

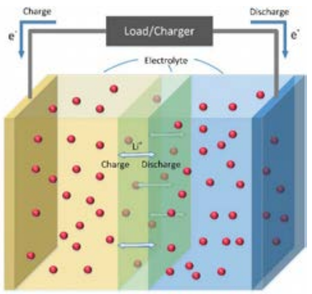
Storage Technology	Advantages	Challenges
Pumped Hydro	▪ Mature technology ▪ Demonstrated large capacity (~GWh); >90% of U.S. grid energy storage ▪ Good reliability	▪ Unique geologic resources ▪ Water availability and evaporation
Compressed Air	▪ Demonstrated capability at large scales ▪ Moderate round-trip efficiency ▪ Good potential for long-duration storage	▪ Unique geologic resources ▪ Well integrity ▪ Repository integrity
Hydrogen	▪ Large-capacity, long-duration storage ▪ Can be used for both grid and transportation ▪ Environmentally friendly	▪ Low round-trip efficiency of hydrogen production and storage ▪ High cost ▪ Leakage and safety of hydrogen gas
Thermal (Sensible)	▪ Mature technology ▪ Demonstrated large capacity with concentrating solar power (~GWh) ▪ Low cost	▪ Heat loss ▪ Heat exchanger performance and reliability

Source: Cliff Ho, Sandia National Labs
Long Duration Energy Storage Workshop, March 2021

Making Energy Storage Mainstream

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**



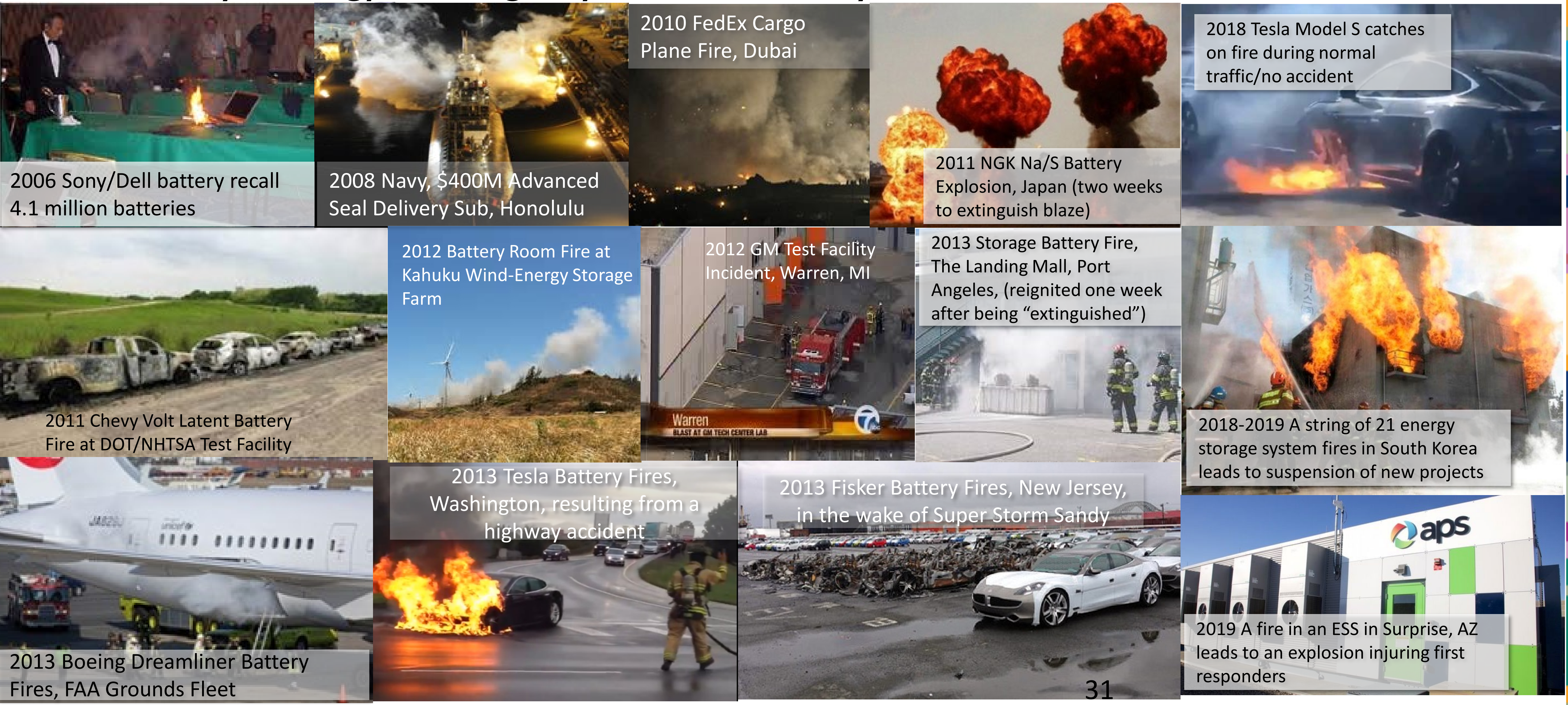
Manufacturing

- 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

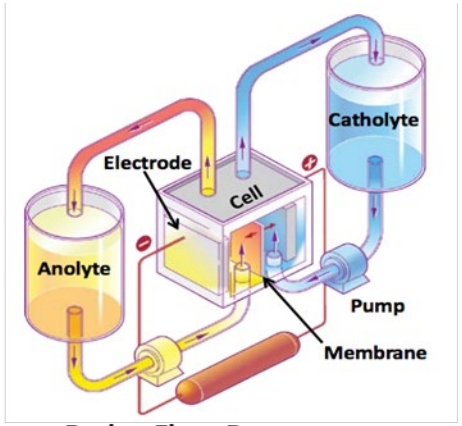
Battery Energy Storage Systems – Safety Concerns



Safety R&D is largely focused on Li-ion BESS

- Li-ion batteries: knowledge base mostly form consumer electronics, safety issued adequately addressed.
    - Safety issues for larger size (EV, grid) just beginning to be dealt with
- New technologies are being introduced
    - Is testing adequate to new technologies?
    - Li-ion – High energy anode materials
    - Li metal
    - Advanced aqueous batteries
    - Molten salt batteries
- Large storage systems targeting non-traditional locations, and areas near populations
- 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?


Subway regen system, SEPTA



Redox Flow Battery

SAFT 10 MWh storage system


US Marine Corps FOB, Afghanistan

What is needed?

How can we adequately prepare for new technologies to enable their rapid adoption?

Are we adequately addressing current gaps in safety research?

What gaps still hinder lithium-ion adoption? How best to ensure stakeholders are adequately informed of the risk they accept?

Is full-scale testing necessary, and if so, is there lab capacity to adequately perform it.

Do we have appropriate standards to ensure safety?

Do first responders have adequate training/resources to handle incidents?

Ensuring Safety – Codes and Standards

Safety standards are developed through a consensus-based development process with diverse stakeholder participation.

Advantages:

- Broad agreement in the field
- Good at learning from past accidents

Disadvantages

- Slow to change (3-10 year revision schedules)
- Bad at preventing accidents before they happen

A few prominent examples are:

- IFC – defines what safety standards shall be used in regions that have adopted it
- UL 9540 – provides a hierarchy of safety standards for energy storage components, tests, and system integration
- NFPA 855 – covers: installation, commissioning, O & M, emergency response, and decommissioning

Energy Storage Safety Codes and Standards Update

Publication released quarterly

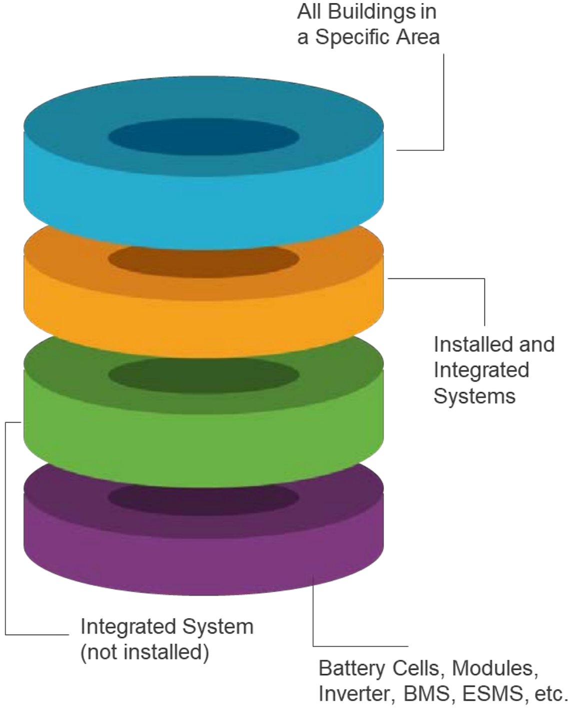
[Available: https://www.sandia.gov/energystoragesafety-ssl/](https://www.sandia.gov/energystoragesafety-ssl/)

4 **Built Environment**
International Codes – IFC, IRC, IBC
IEEE – C2, SCC 18, SCC 21
NFPA 5000, NFPA 1, ISA

3 **Installation / Application**
NFPA 855, NFPA 70, IEEE C2, IEEE 1635/ASHRAE 21, IEEE P1578, FM Global 5-33, UL 9540A, NECA 416

2 **Energy Storage Systems**
UL 9540, MESA
ASME TES-1, NECA
NFPA 791

1 **System Components**
UL 1973, UL 1974, UL 810A, UL 1741, CSA 22.2 No. 340-201, IEEE 1547, IEEE 1679



Lower Cost Power Electronics and Modular Coverters

Power conversion system is a significant cost of grid energy storage systems

Cost reductions in power electronics and power conversion systems has been slow to come.

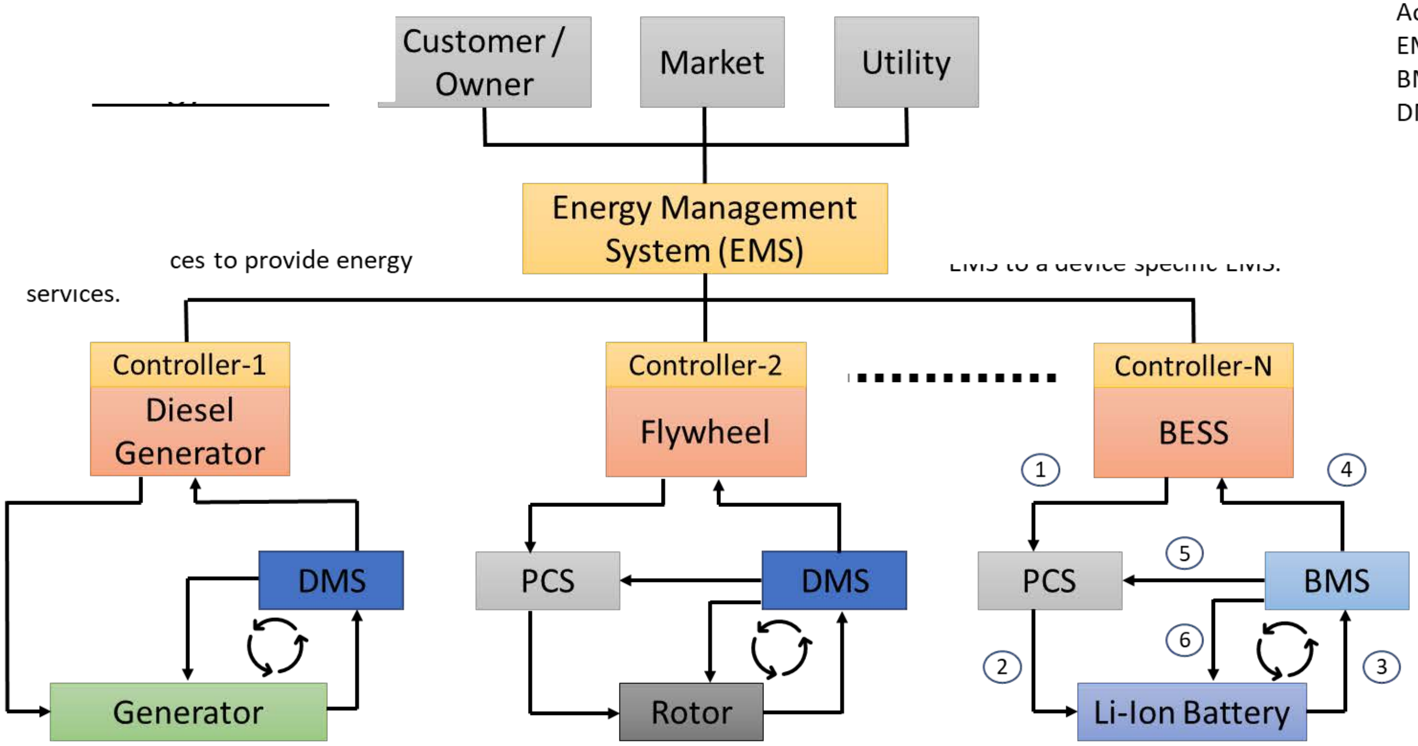
- Bringing in WBG devices can make format factor smaller, reducing thermal management issues
- New magnetics and high temperature capacitors can make the systems more compact and robust

Module converters are not fully commercial

No standardization, systems are custom designed and integrated

Robust Energy Management Systems

Acronyms:
EMS – Energy Management System
BMS – Battery Management System
DMS – Device Management System
ower Conversion System



1. Control Commands
2. Control Implementation
3. Sensor Measurements
4. Feedback Data (Alarms)
5. Safety Limits
6. Safety Disconnect

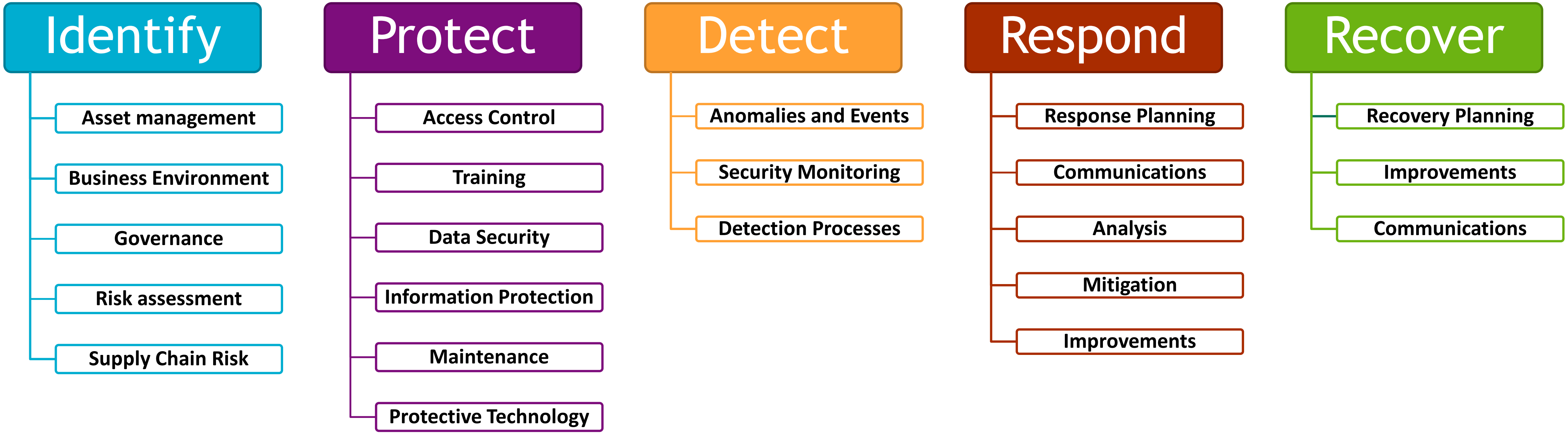
Source: D. Rosewater, IEEE Working Group 2686 - Battery Management Systems in Energy Storage Applications, 2021

Multi-scale storage systems are difficult to assemble

- Hybrid systems use fragmented control systems that are prone to latency, expensive integration, and cybersecurity attacks
- Control systems are proprietary and expensive
- Systems are integrated on the AC side. Multiple Power Converters are needed, although they don't always operate

Energy Storage – Security (cyber and physical 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:



Growth of the Energy Storage in the Grid

Pace of deployments of energy storage picking up

- Grid reliability, solar + storage, resiliency applications

Large new manufacturing capacity for Li-ion batteries primarily for EVs coming up fast

- 2 TWh of new manufacturing capacity projected for 2030
- Spill over into grid energy storage applications

Refurbishment of existing pumped hydro storage fleet to become more flexible

Other technologies such as flow batteries, alkaline batteries continue to be interesting

Power conversion system remain expensive

Critical gaps in analytical tools and models

Long duration storage is a challenge

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.

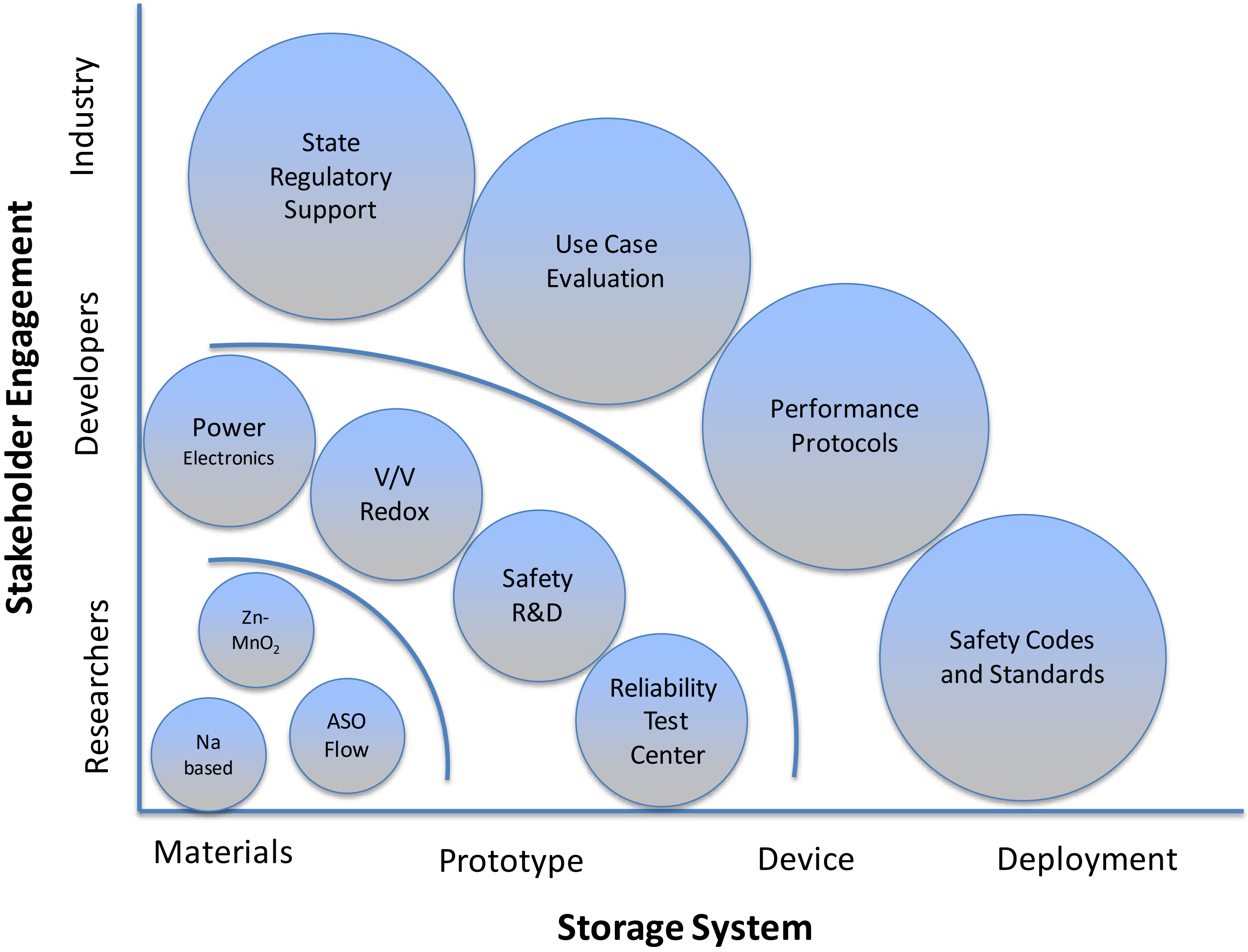
DEMONSTRATION PROJECTS
Work with industry to develop, install, commission, and operate electrical energy storage systems.

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

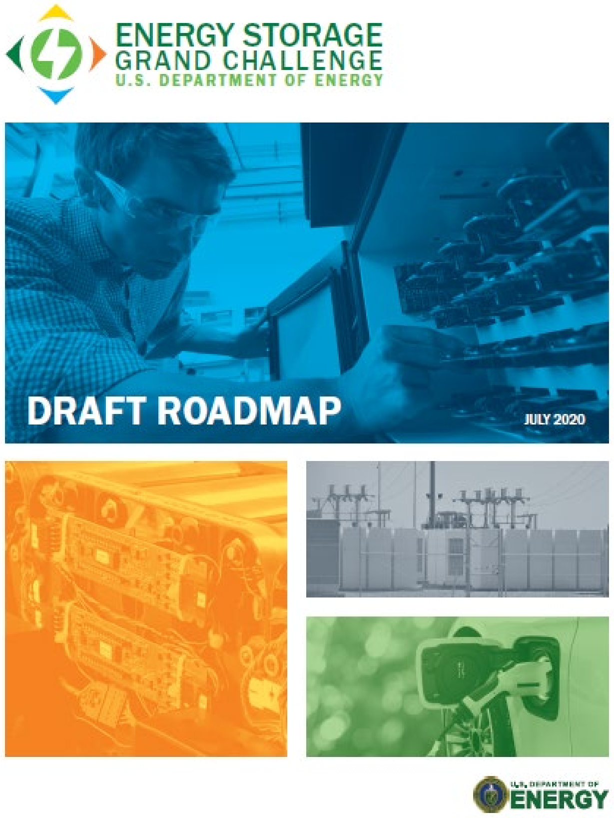
DOE Office of Electricity - Energy Storage Systems Program



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 earthshots U.S. DEPARTMENT OF ENERGY | Storage™

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

DOE Hydrogen Earthshot

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

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Hydrogen for

Announced by Secretary Granholm, June 6, 2021

Acknowledgements

The Energy Storage program at Sandia is supported by

DOE Office of Electricity Energy Storage Program

U.S. DEPARTMENT OF ENERGY

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