Introduction to Grid Energy Storage

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Sandia National Laboratories

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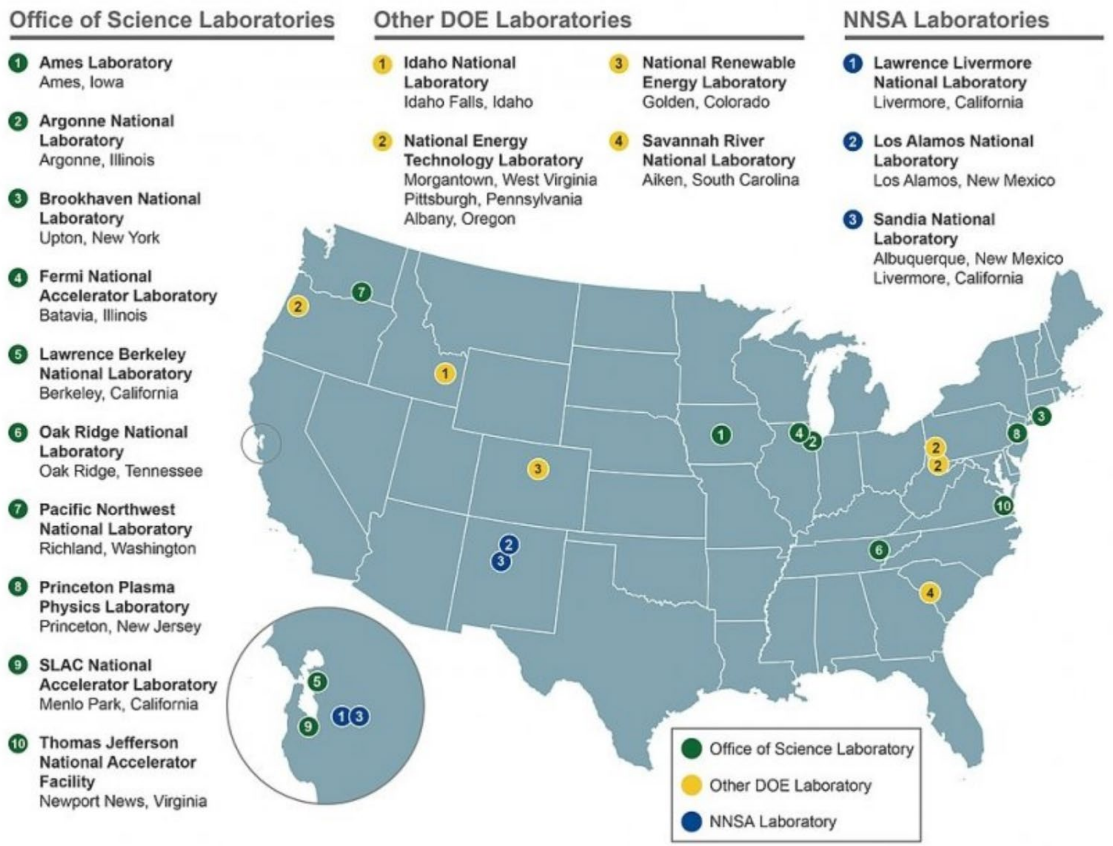
US Department of Energy: National Laboratories



Office of Science Laboratories

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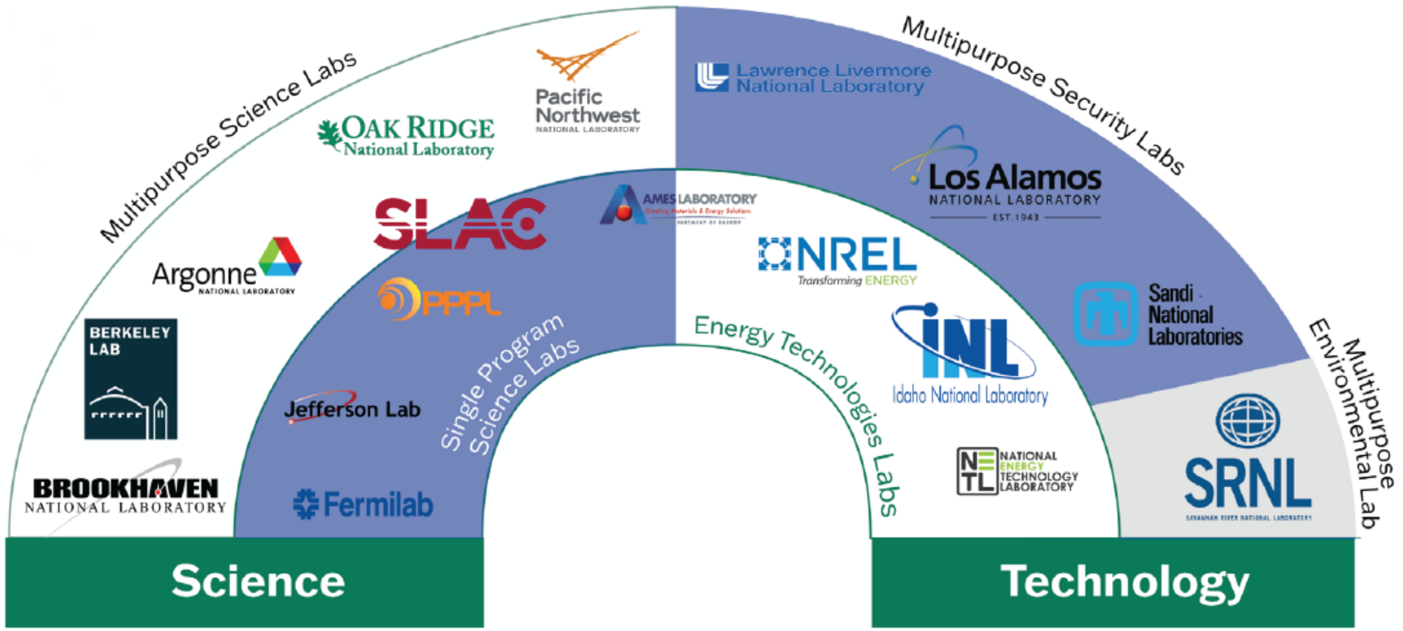
17 National Laboratories - Basic sciences, Engineering and Technology Development



Sandia National Laboratories

Activity locations

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

Main sites

- Albuquerque, New Mexico
- Livermore, California

15,000 staff, $4.4B in 2023

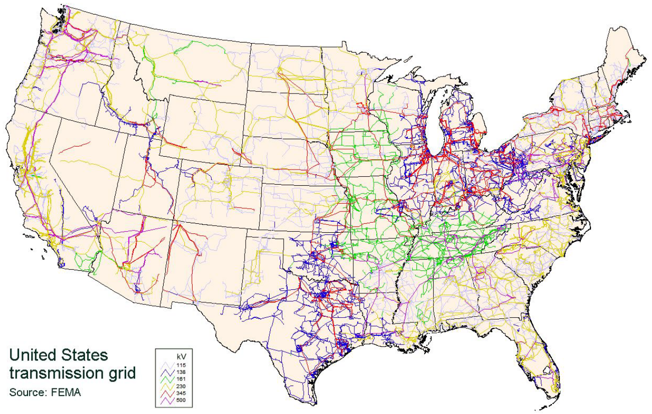
U.S. Electric Grid

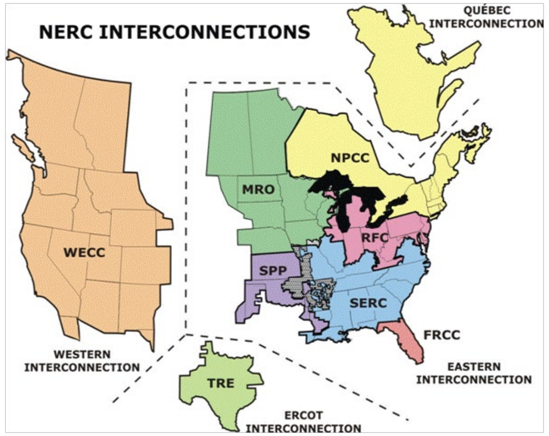
Big interconnected system with ~850GW baseload, 1250 GW summer peak, 7,000 operational power plants

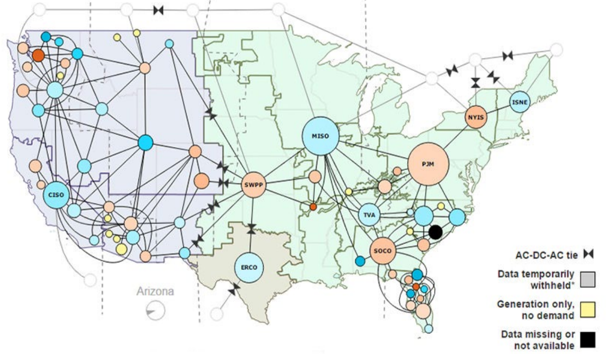
- 3,200 utilities, 60k substations, 642k miles of HV transmission lines, 6.2 million miles of distribution circuit, 159 million customers.
- 4,000 TWh of generation (2020)
- Revenues reaching $400 B, ~10.42 c/kWh avg

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



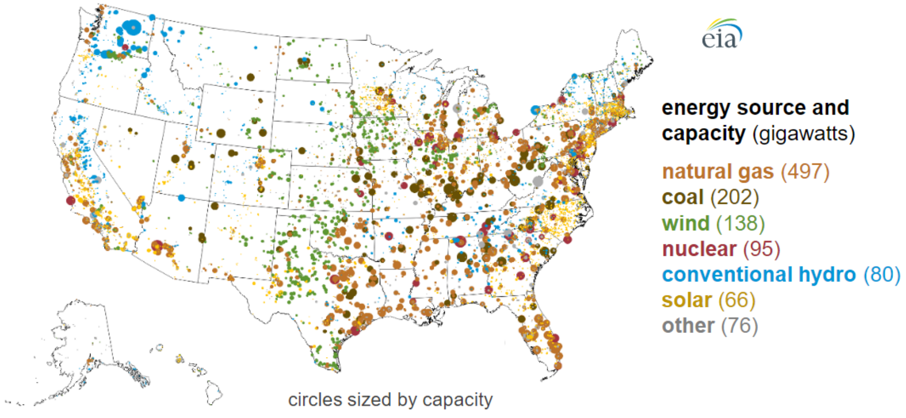




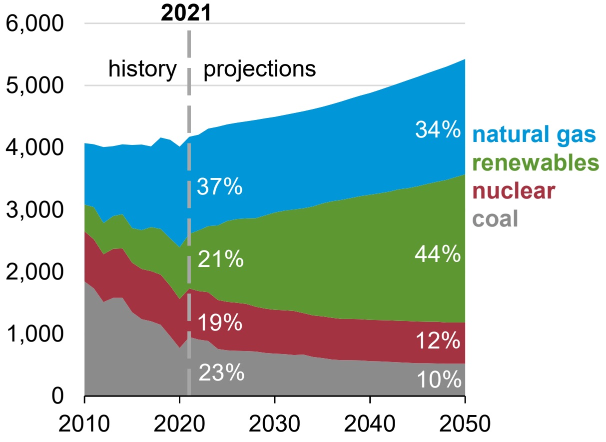
Sources: EIA, EEI, FEMA and NERC http://www.nerc.com

US Electric Grid: Generation

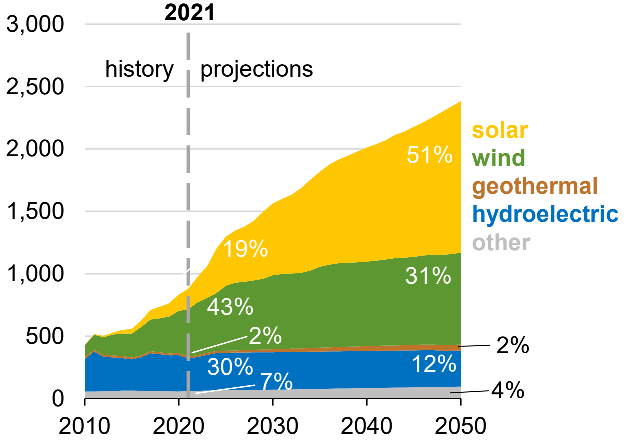
Operable utility-scale generating units (June 2022)



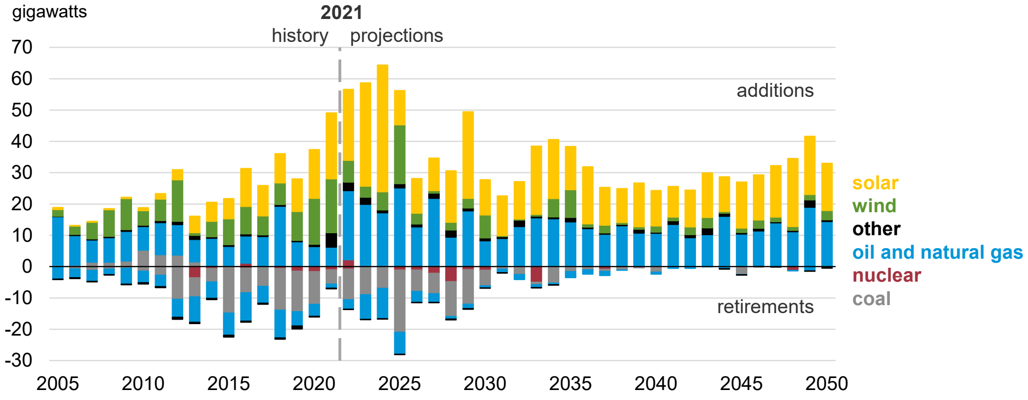
U.S. electricity generation from selected fuels
AEO2022 Reference case
billion kilowatthours



U.S. renewable electricity generation, including end use
AEO2022 Reference case
billion kilowatthours

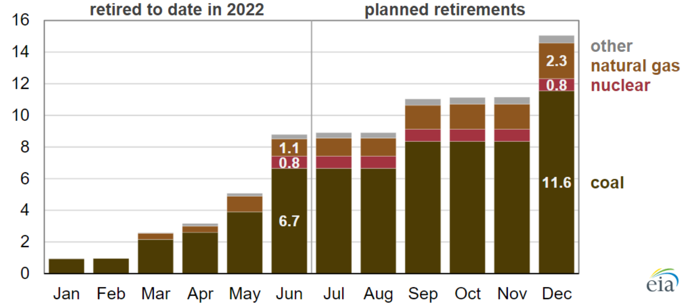


Annual electricity generating capacity additions and retirements
AEO2022 Reference case
gigawatts

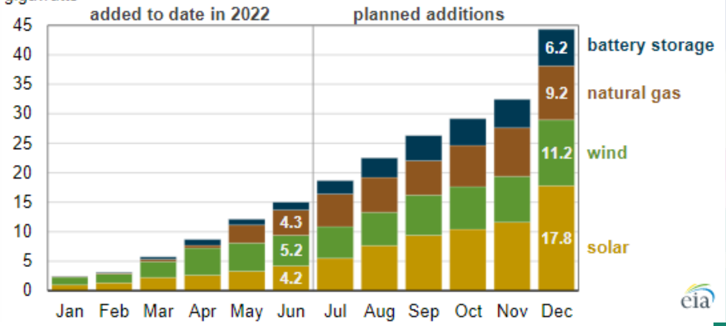


Source: Form EIA-860M, *Monthly Update to the Annual Electric Generator Report*, August 2021

Cumulative utility-scale electric generating capacity retirements (2022)
gigawatts



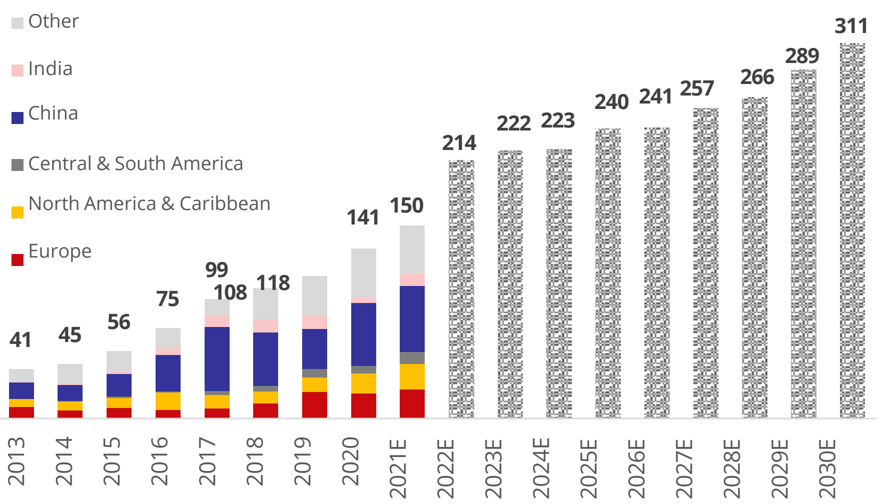
Cumulative utility-scale electric generating capacity additions (2022)
gigawatts



- Mostly large centralized generators (natural gas, coal, Nuclear, hydro)
- Accelerating retirements of coal fired power plants
- Increasingly amounts of renewables: 42% of generation by 2050 (EIA)
- Rapid growth of storage deployment, coupled with renewables

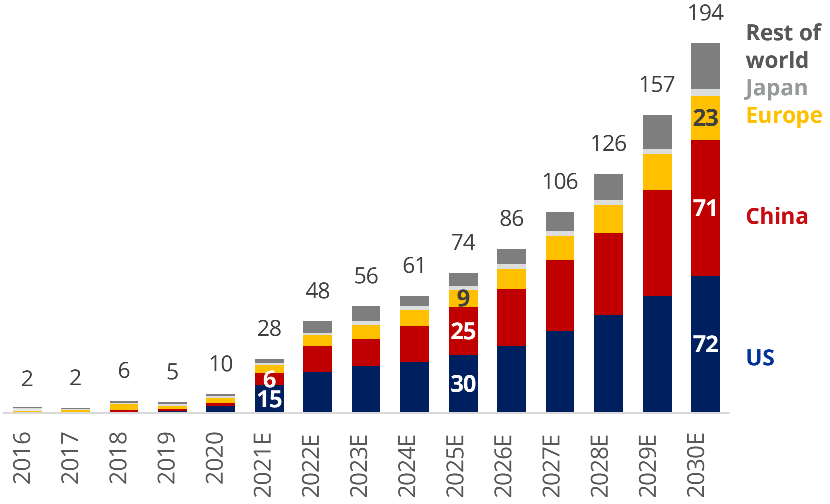
U.S. Energy Information Administration, Annual Energy Outlook 2022 (AEO 2022)
EIA-860M, 'Monthly Update to Annual Electric Generator Report', October 2022
www.eia.gov

Grid Evolution: Rapid Growth of DERs, Energy Storage, EVs



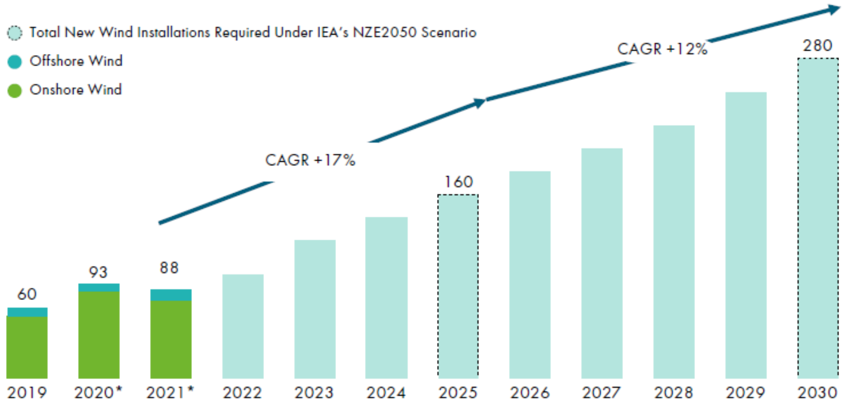
Global Solar PV Annual Installations, GW

Source: BNEF, Wood Mackenzie estimates (2021)



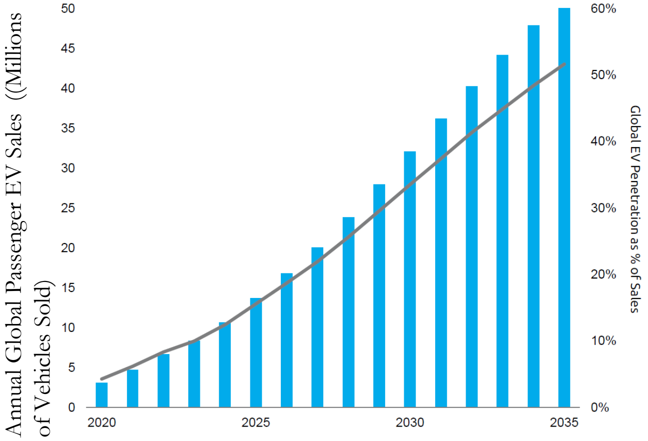
Projections for Energy Storage Annual Capacity Additions, GWh

Source: BNEF, Wood Mackenzie estimates (2021)



Global Wind Energy Report 2021

Source: Global Wind Energy Council (GWEC, 2021)

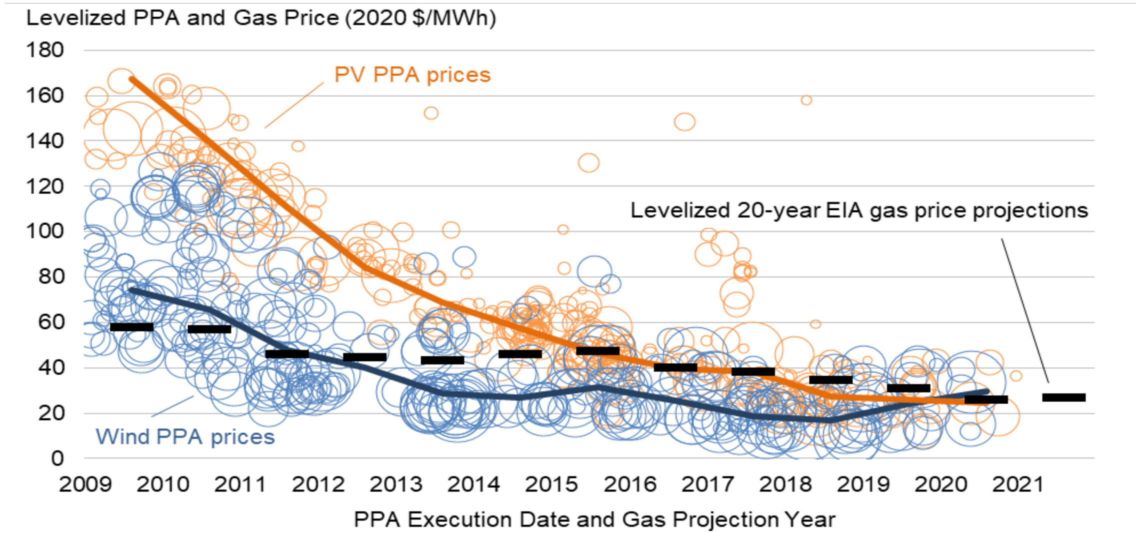


Annual Sales of Battery EVs and Plug-in Hybrid Electric Vehicles

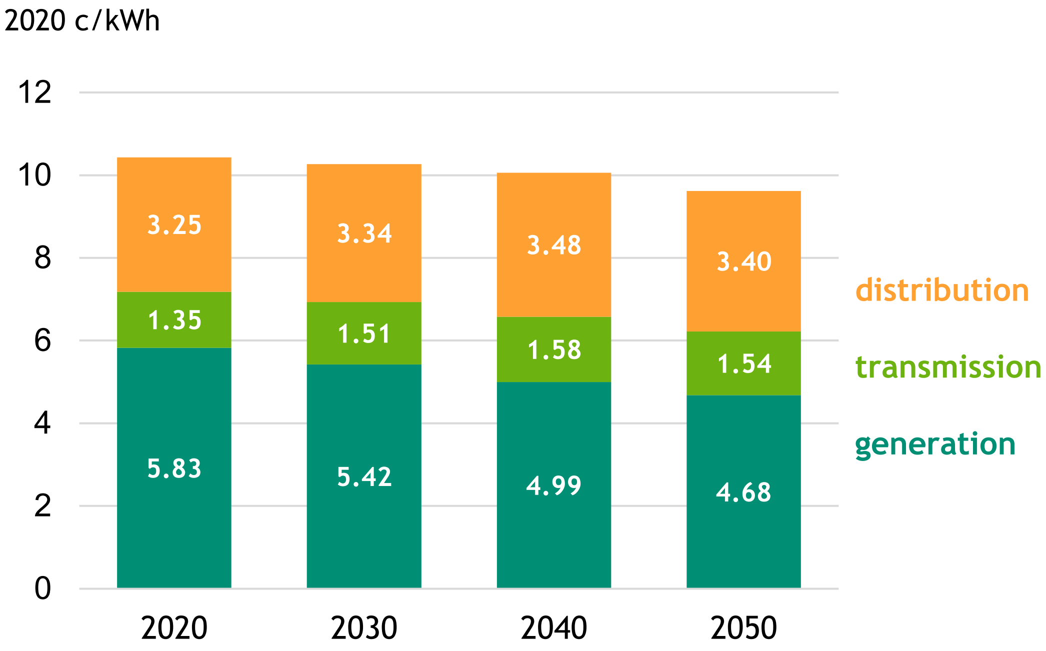
Source: Bloomberg New Energy Finance BNEF, 2021

Renewables at Parity with Combined Cycle Gas

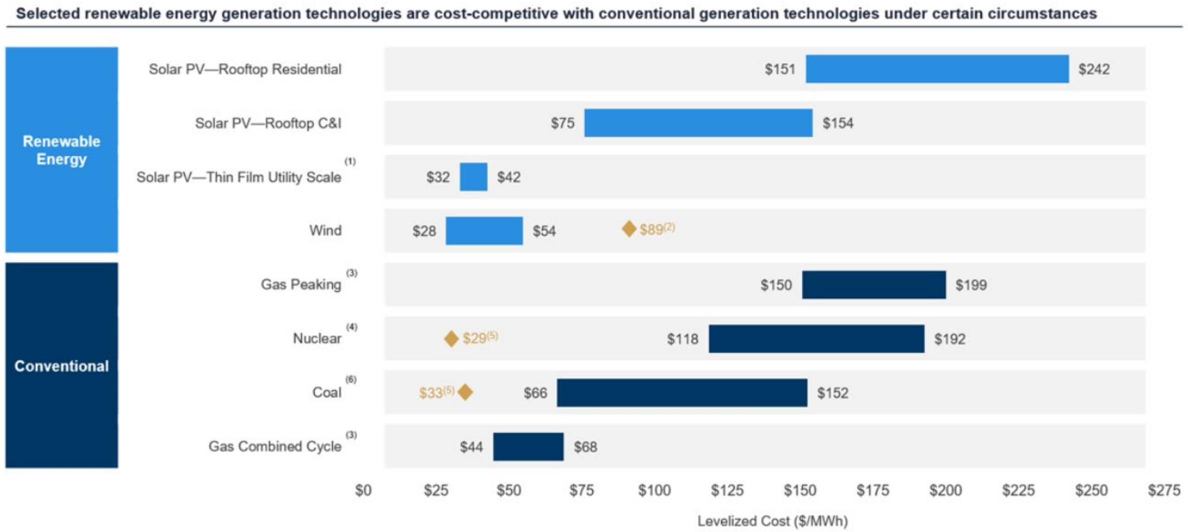
PV and wind have reached economies of scale
Becoming cheaper, at parity with traditional generation.
Major challenge - making renewables firm power



Source: Berkeley Lab, FERC, EIA. Note: Smallest bubble sizes reflect smallest-volume PPAs (<5 MW), whereas largest reflect largest-volume PPAs (>500 MW).



Components of U.S. Electricity Prices (DOE, EIA, AEO2021)



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

Grid Edge: Changing Rapidly

Rapid growth of behind-the-meter technologies

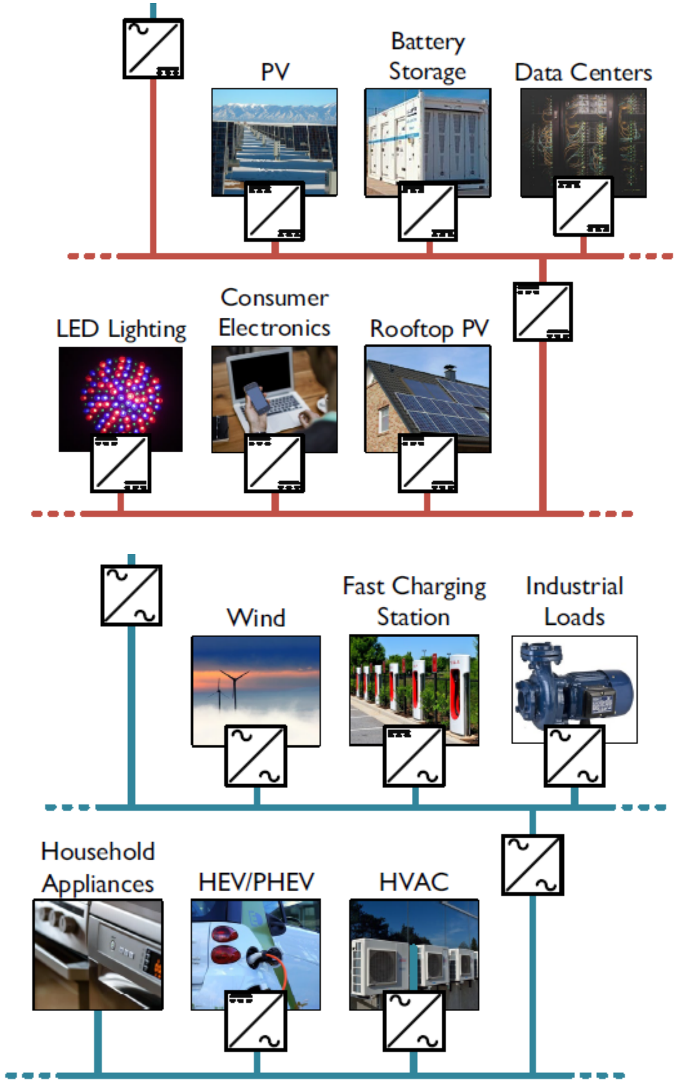
- Rooftop solar, battery storage, smart meters, smart loads
- Managing power flows, protection

Electrification of the Transportation Sector

- Infrastructure bottlenecks, especially in dense urban areas
- Distribution systems are not ready for fast charging
- Ensuring stability of grid, capacity constraints for large loads
- Infrastructure for transactive energy

Rapid evolution of off-grid and micro-grids

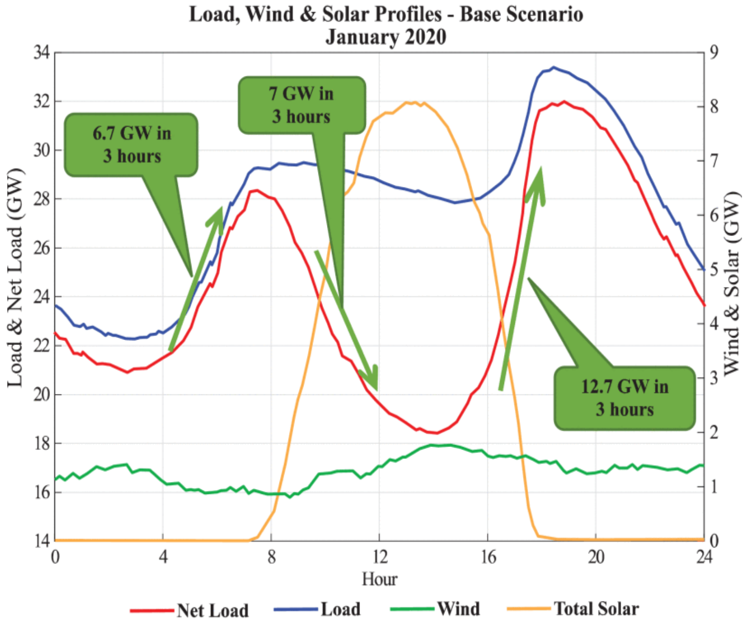
Computation challenges associated with distributed sensing, control, and big data



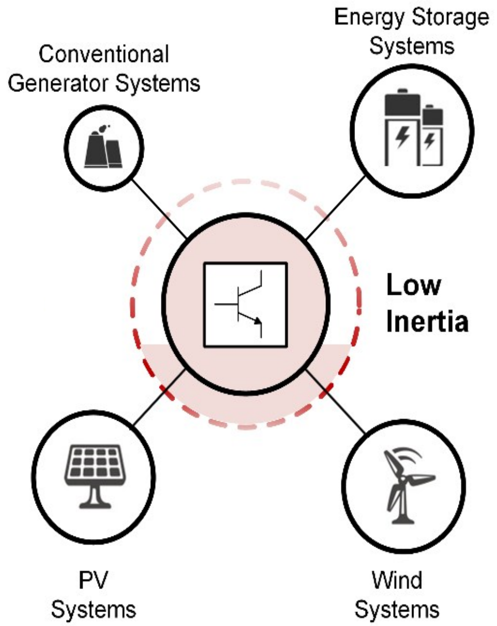
Maintaining Grid Reliability

Maintaining system frequency; voltage stability, low inertia

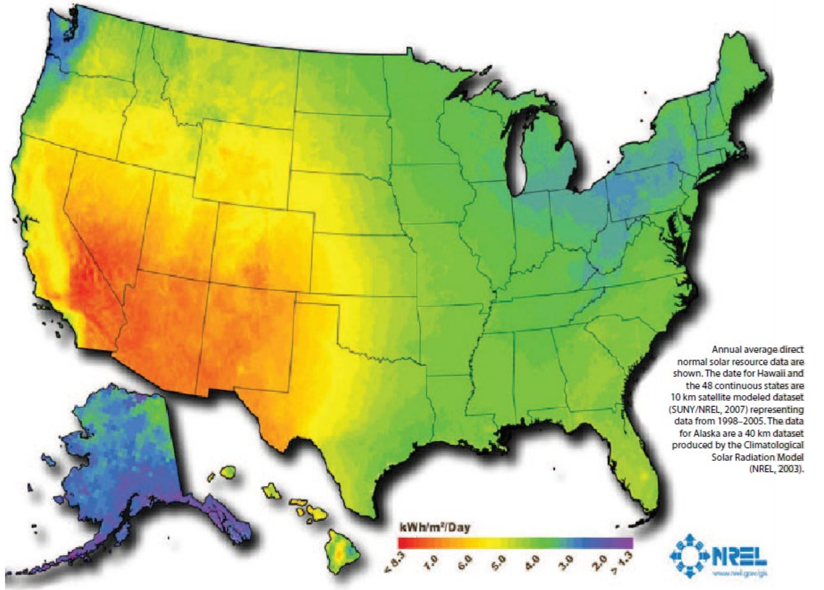
Resource adequacy and transmission capacity to meet peak demand



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.



Annual average direct normal solar resource data are shown. The date for Hawaii and the 48 continuous states are 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998–2005. The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

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.

Grid Resiliency

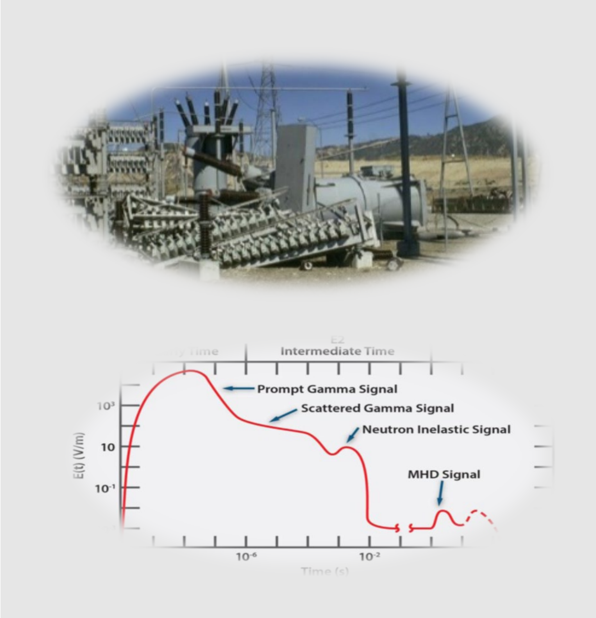
Estimated cost of electricity interruptions in the US: ~$150B/year

For every $1.00 spent on electricity, $0.50 is spent to cover the cost of power failures.

Natural phenomena:
- "The New Normal" of more extreme weather events (i.e., hurricanes, torrential rain, wind-storms, wildfires)
- Space weather events

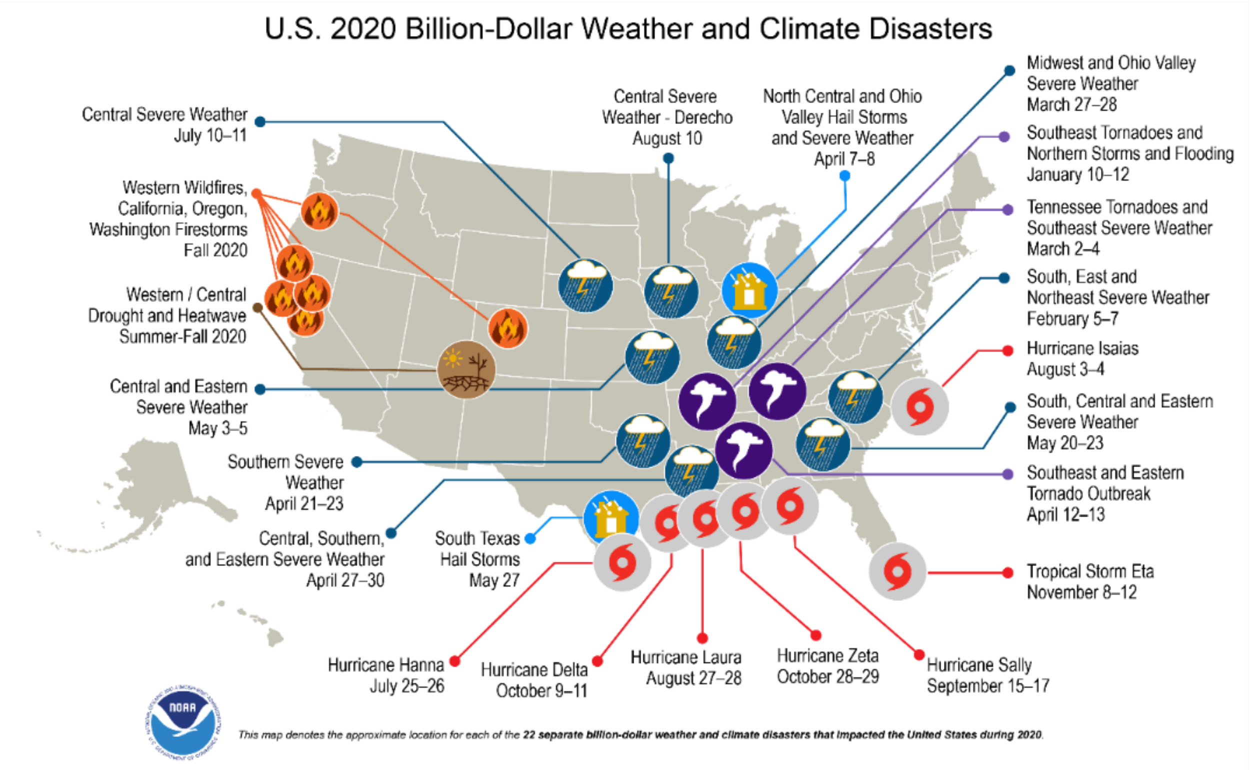
Man-made:
Cyber and physical security, EMP

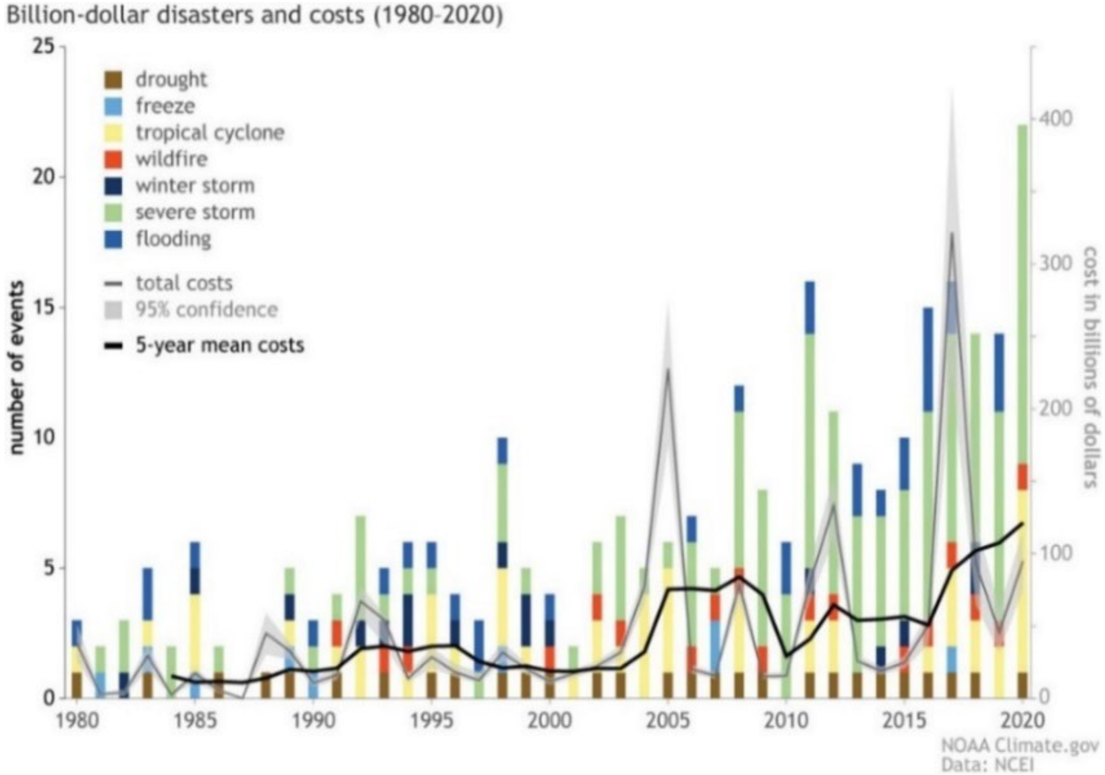
System design, aging, and human error:
Equipment tripping, power system islanding, voltage and angular instability



Importance of T&D Grid Modernization to Mitigate Impacts from and Adapt to Climate Change, IEEE PES Technical Report TR93, February 2022

Climate Change: Increasing Impacts on Grid Operations





Billion-Dollar Weather and Climate Disasters in the U.S. in 2020 (NOAA, 2021) https://www.ncdc.noaa.gov/billions/

U.S. Economic Losses Due to Natural Disasters Exceeding $1B in Damages per Year
A.B. Smith, 2020 U.S. billion-dollar weather and climate disasters in historical context, January 8, 2021. https://www.climate.gov/disasters2020

Importance of T&D Grid Modernization to Mitigate Impacts from and Adapt to Climate Change, IEEE PES Technical Report TR93, February 2022

Electrification and Deeper Decarbonization: Societal Goals

Targets

- **Increased decarbonization**
- **Clean energy to support public health**
- **Reliable and resilient energy delivery**
- **Maintaining affordable electricity prices**

New York's Clean Energy Standard:

- Reduce greenhouse gas 85% by 2050
- 70% renewables by 2030; 100% carbon-free by 2040
- Energy storage: 1.5 GW 2025; 3 GW 2030
- Doubling energy efficiency by 2025

Germany	2020	2030	2050
Greenhouse gas reduction (1990)	40%	55%	80%
Renewable energy share	18%	30%	60%
Energy efficiency increase (2008)	20%		50%

Present cost of generation is affected by regulatory policies

US: ~10¢/kWh
CA: ~15¢/kWh
EU: ~27¢/kWh
GE: ~36¢/kWh

Energy solutions

Energy/fuel transformation

- Renewable generation (i.e., solar, wind, etc.)
- Electrical energy storage

Energy efficiency and demand response

Electrification

- Transportation: light-, medium-, heavy-duty, buses
- Buildings: residential and commercial
- Industrial and agriculture

1891: First successful electric car
1904: ~1/3 cars were electrical

Importance of T&D Grid Modernization to Mitigate Impacts from and Adapt to Climate Change, IEEE PES Technical Report TR93, February 2022

Grid Modernization - Infrastructure Challenges

Adaptation to accommodate High Renewables, Electrification and Climate Change

- Flexibility, G-T-D Coordination, Market Design
- Resource adequacy. Large scale integration of energy storage systems.
- Infrastructure upgrades to enable electrification of transportation.

Improve system reliability and resiliency to mitigate and adapt to climate change

- Weather, Natural disasters, Cyber, Physical attacks

Smarter Grid

- Sensors, Analytics, Automation, IOT, Demand Side Participation, cyber and physical security
- Intelligent power conversion systems with advanced circuit topologies and high speed communication infrastructure.

Need significant cost reductions in power electronics. Lower cost, longer duration energy storage

Improvements in safety and reliability of power converters and energy storage systems

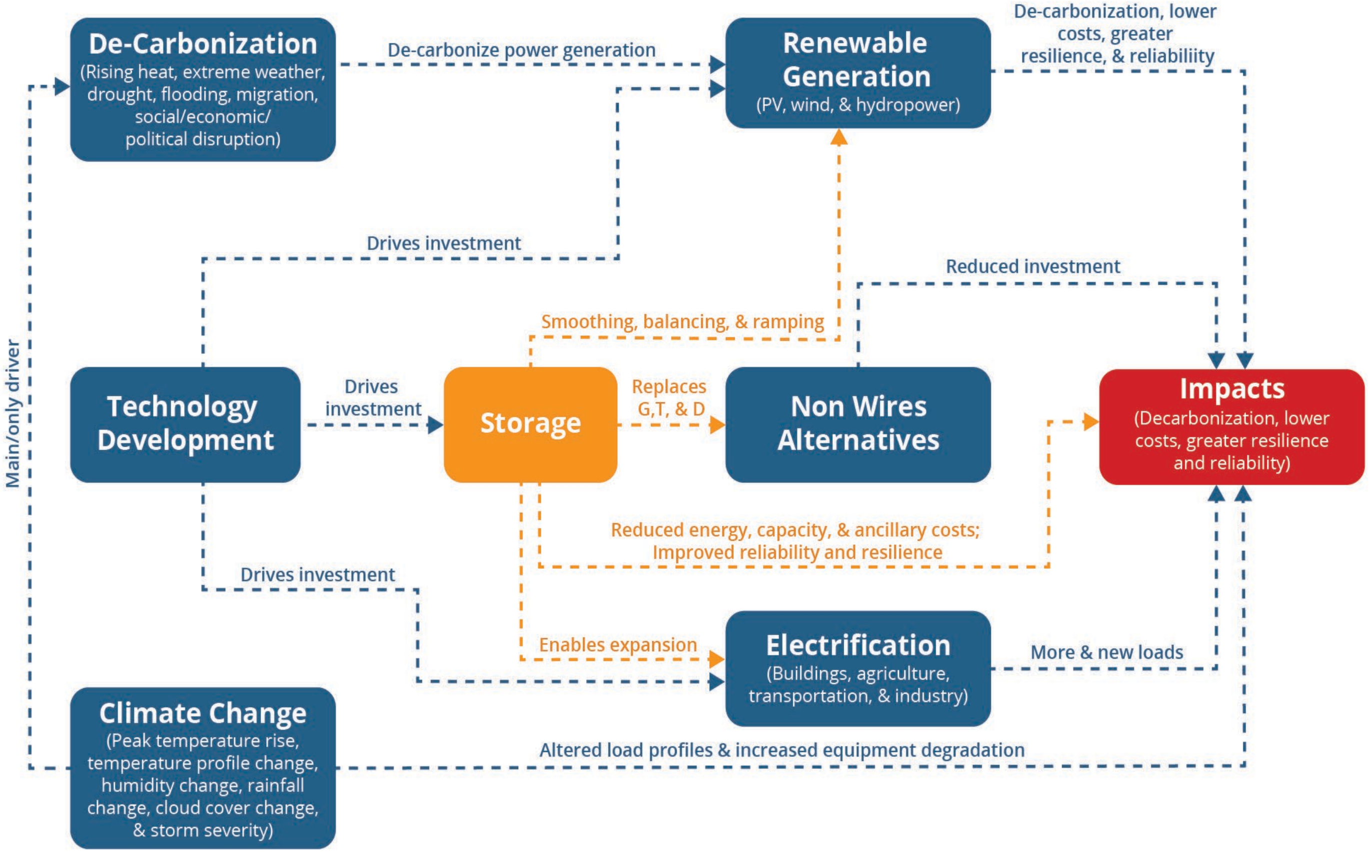
Coordinated sensing and control infrastructure

Black start capability without significant traditional generation assets

Greater understanding of the operational reliability and resiliency of a the new electric grid

Sources: DOE Quadrennial technical review

Energy Storage is Central to Large Scale RE integration and Deeper Decarbonization



De-Carbonization (Rising heat, extreme weather, drought, flooding, migration, social/economic/ political disruption)

Renewable Generation (PV, wind, & hydropower)

Technology Development

Storage

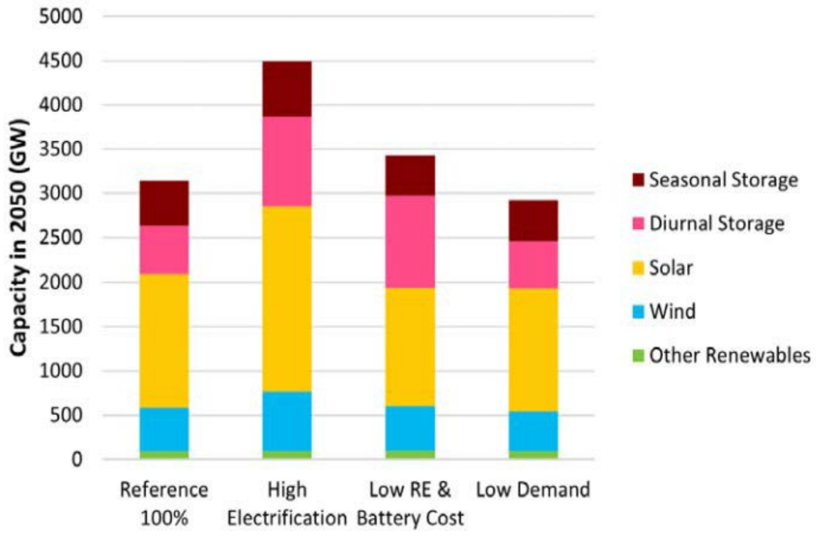
Non Wires Alternatives

Impacts (Decarbonization, lower costs, greater resilience and reliability)

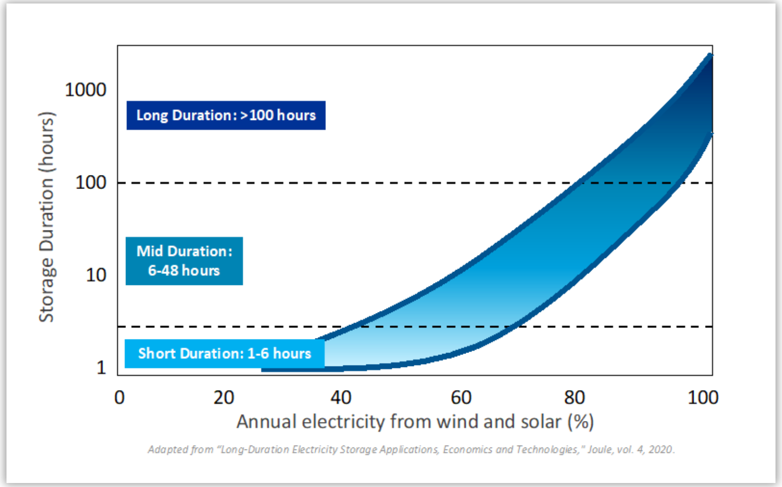
Electrification (Buildings, agriculture, transportation, & industry)

Climate Change (Peak temperature rise, temperature profile change, humidity change, rainfall change, cloud cover change, & storm severity)

Source: R. Masiello, R. Fioravanti, B. Chalamala, and H. Passell, Proc. IEEE, 2022.



Source: N. Blair, NREL Energy Storage Futures Study, 2022.



Adapted from "Long-Duration Electricity Storage Applications, Economics and Technologies," Joule, vol. 4, 2020.

Source: H. Hack, EPRI, 2022.

Energy Storage in the Grid Today

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

US installed energy storage capacity of 29 GW of pumped hydro, 20 GW of BESS (through 2023) represents ~20 min ride through

Pace of deployments of energy storage picking up

- Grid reliability, solar + storage, resiliency applications

1.6 GW Raccoon Mountain PHS

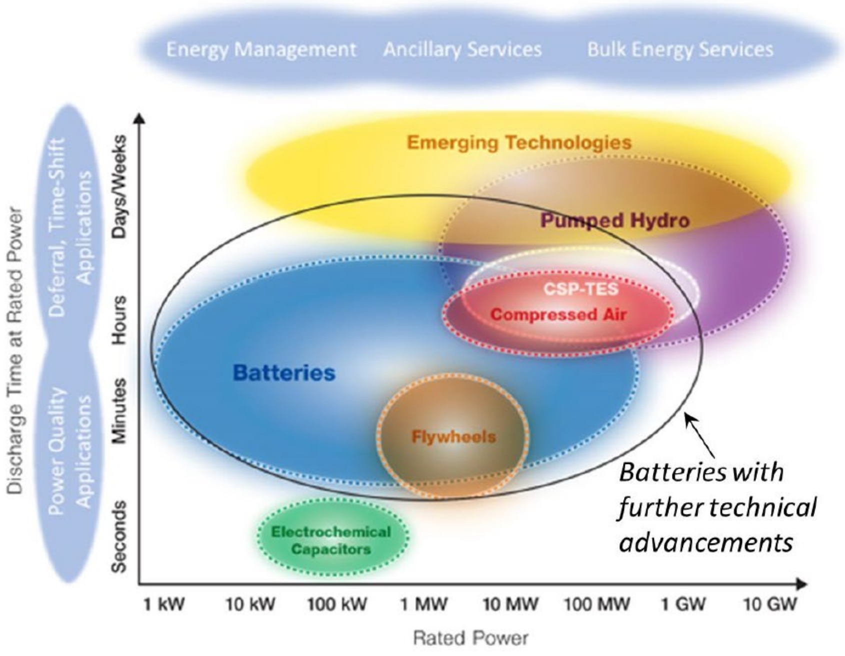
100 MWh BESS Plant - Tesla

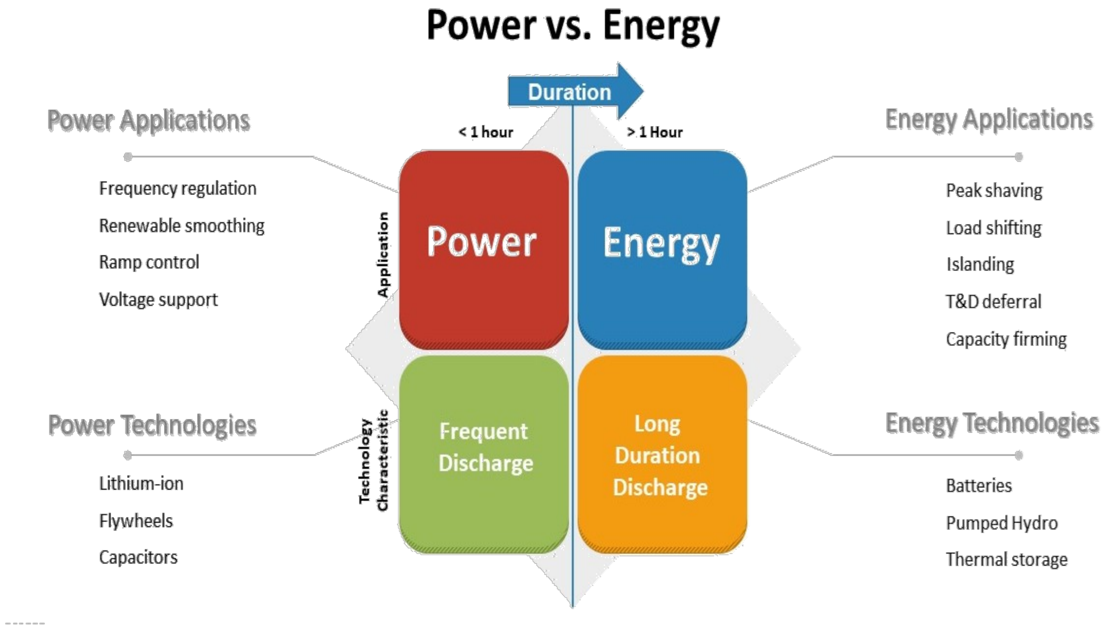
Compared to the need, the scale of energy storage deployments is insignificant.
With a 1 TW US electric grid, even 1 hr of energy storage means 1 TWh

DOE Global Energy Storage Database, 2021

Grid Energy Storage: Range of Technologies and Applications

- Range of battery technologies for short duration energy storage, seconds to days
  - Pumped hydro and CAES for hours-to-day long energy storage
  - No ready solutions for real long-duration and seasonal storage needs
- Applications of energy storage systems
  - "Energy" applications: slower time scale, large amounts of energy
  - "Power" applications: faster time scale, real-time control of the electric grid





Power vs. Energy

Duration

< 1 hour | > 1 Hour

Application

Technology Characteristic

Power | **Energy**

Frequent Discharge | Long Duration Discharge

Power Applications
- Frequency regulation
- Renewable smoothing
- Ramp control
- Voltage support

Power Technologies
- Lithium-ion
- Flywheels
- Capacitors

Energy Applications
- Peak shaving
- Load shifting
- Islanding
- T&D deferral
- Capacity firming

Energy Technologies
- Batteries
- Pumped Hydro
- Thermal storage

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

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

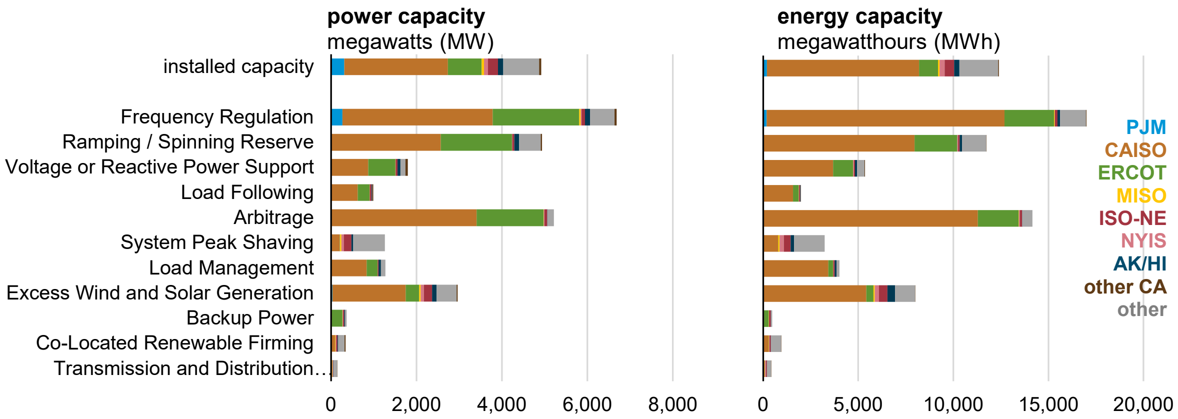

Vistra Energy, Moss Landing, Monterey, CA - 300 MW / 1200 MWh – Peaker Replacement, Grid Reliability

GWh size BESS Plants no longer at the conceptual stage

Images: Company websites and Wikipedia

Battery Energy Storage Deployments

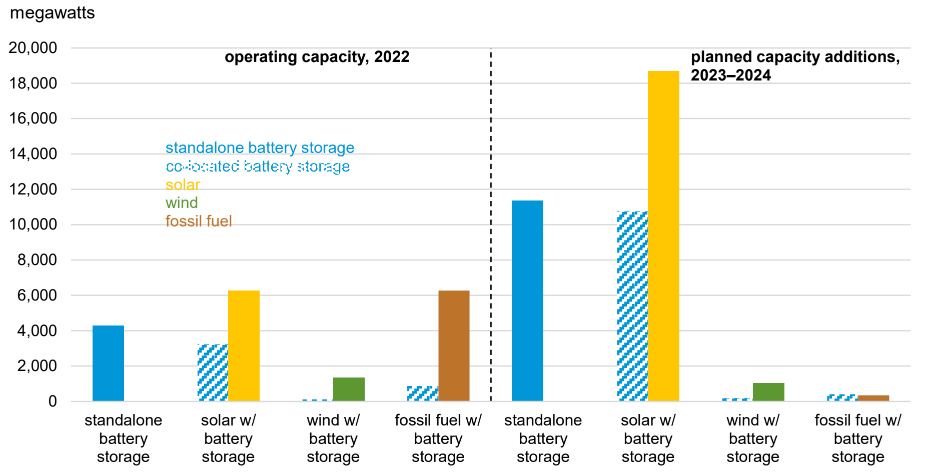
Applications served by large-scale battery storage (2022)



Data source: U.S. Energy Information Administration, *2022 Form EIA-860 Early Release, Annual Electric Generator Report*

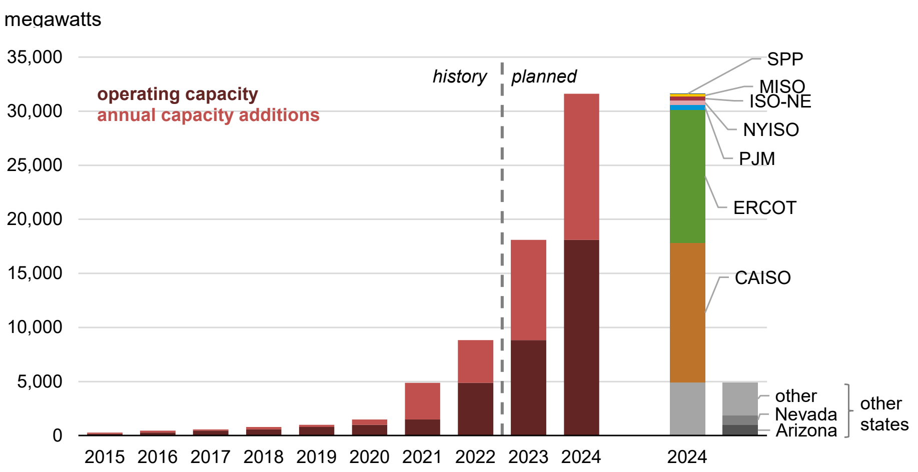
Applications served by large-scale battery storage in the US (2022)

Large-scale battery storage power capacity, standalone and co-located (2022–2024)



Data source: U.S. Energy Information Administration, *2022 Form EIA-860 Early Release, Annual Electric Generator Report*
Note: Solid yellow, green, and brown bars indicate generating total capacity of solar, wind, and fossil fuels that have battery storage on-site.

Large-scale battery storage cumulative power capacity (2015–2024)



Data source: U.S. Energy Information Administration, *2022 Form EIA-860 Early Release, Annual Electric Generator Report*

Early deployments are mainly regulation and ramping services

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

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

Battery energy storage systems are mostly using Li batteries

Electrochemical and Chemical Energy Storage

What do we currently have?

- Lithium battery energy storage systems: mature, majority of currently deployed BESS for most grid storage applications

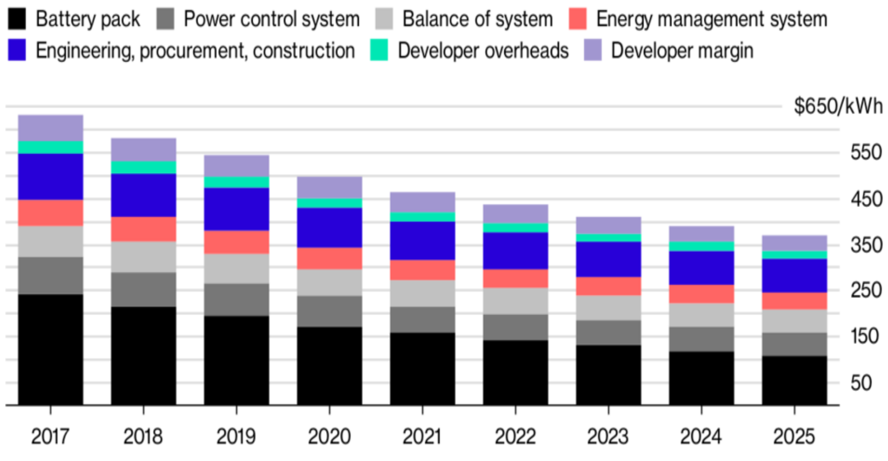
What is on the horizon?

- Range of battery technologies including flow batteries, metal-air batteries
- Hydrogen potentially for longer duration storage
- Liquid fuels and other chemical carriers for even longer durations and seasonal

For shorter duration (up to 8 hours) – Li-ion BESS is the technology of choice. Difficult for other technologies to compete in this market in the near term

Engineering Battery Energy Storage Systems

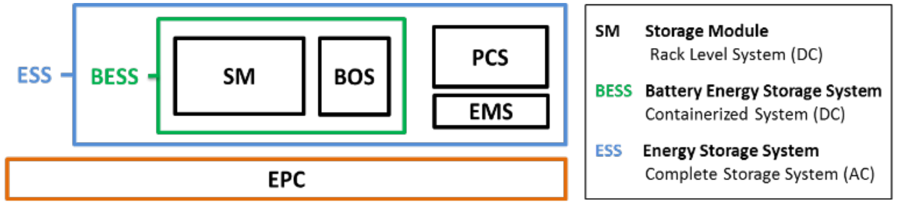
- Integration costs are significant to meet safety and performance requirements
- Performance of battery energy storage systems are not sorely dependent on the cell itself, but in the systems and integration level
  - System-level integration modules, e.g., BMS, PCS, are crucial for the performance,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



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

Bloomberg

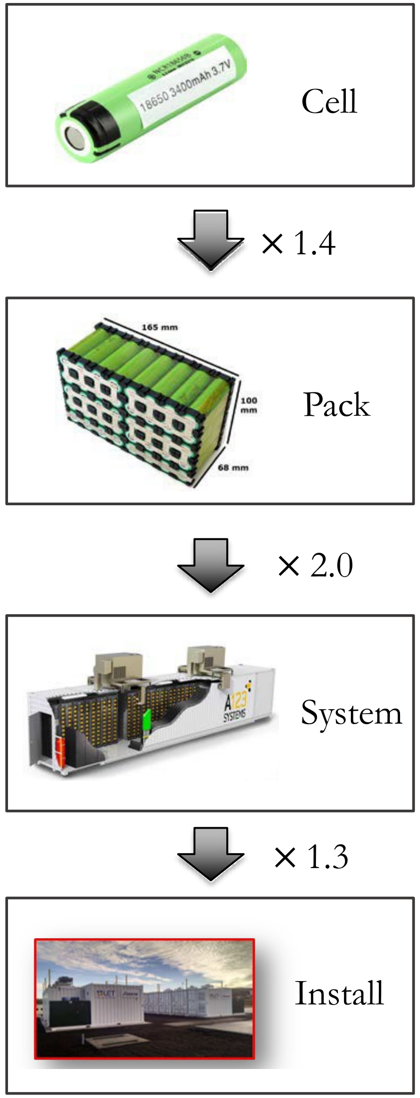
Integration costs increase as cell → battery → Storage System. For example, doubling in cost, $250/kWh battery leads to $500-$700/kWh at the system level.



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

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 Systems – Design and Application Aspects

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

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

- Li-ion batteries: knowledge base mostly 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 , solid state batteries
    - Advanced aqueous batteries
    - Molten salt batteries
- Large storage systems targeting non-traditional locations, and areas near population centers
- Grid-scale systems are complex, including not only a large battery but sophisticated power electronics
    - Qualifying safety? Is full-scale testing necessary?

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

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

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

Standards to Ensure Energy Storage Systems Safety

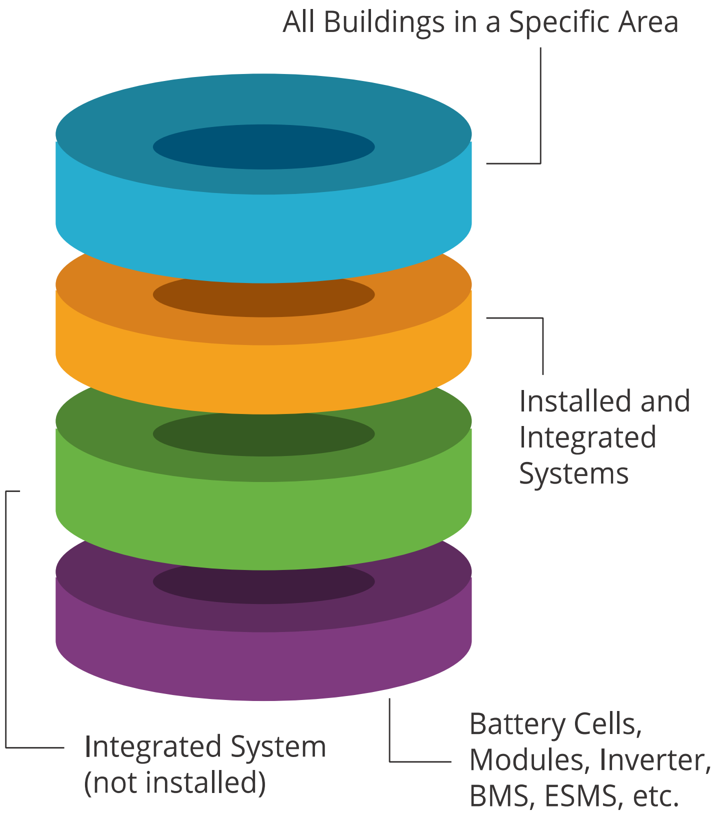
Ensuring safety of battery storage systems remains a major concern
Need significant advances at materials, engineering and systems level

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

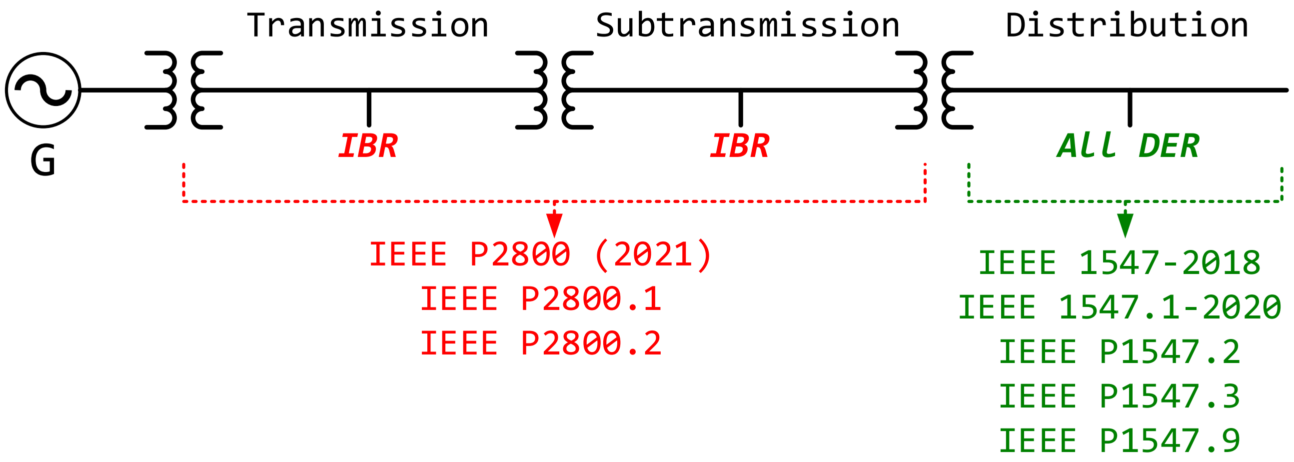


Categories for Energy Storage Codes and Standards

DOE Energy Storage Safety Codes and Standards Update
Publication released quarterly
[Available: https://www.sandia.gov/energystoragesafety-ssl/](https://www.sandia.gov/energystoragesafety-ssl/)

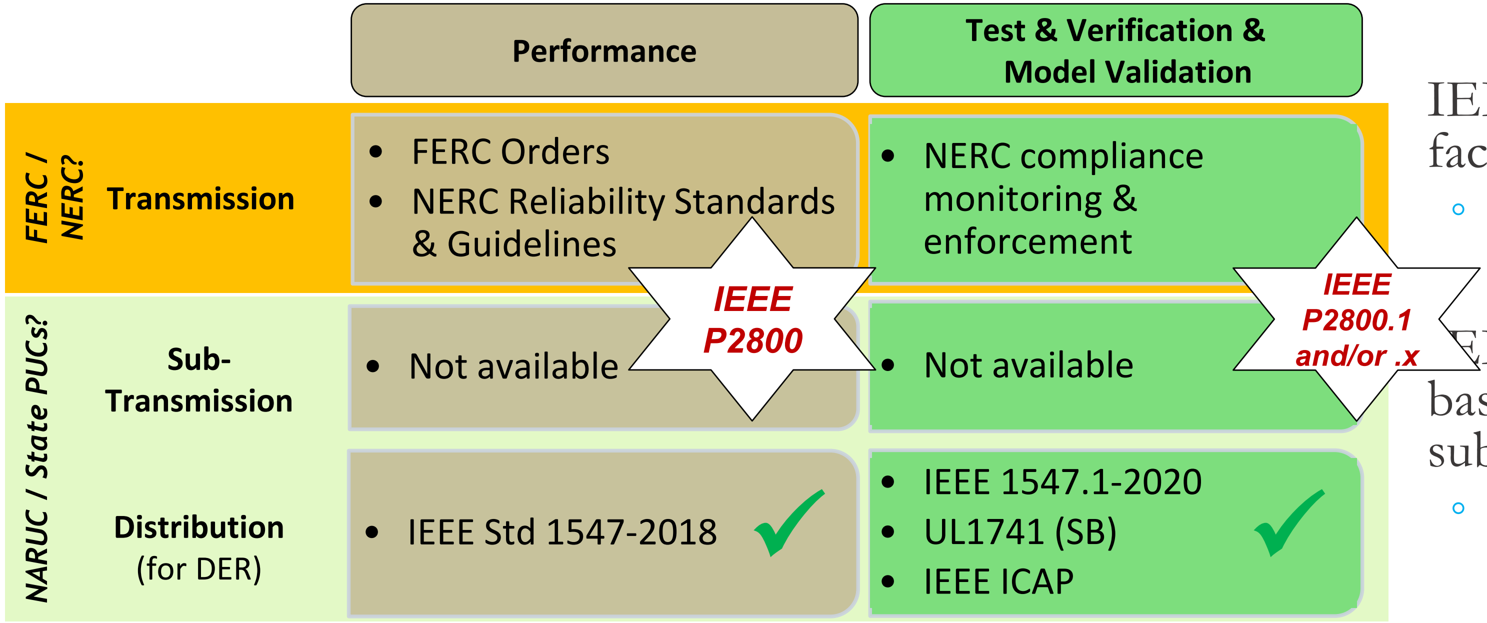
B. R. Chalamala, D. Rosewater, Y. Preger, R. Wittman, J. Lamb and A. Kashiwakura, "Grid-Scale Energy Storage Systems: Ensuring safety," in IEEE Electrification Magazine, vol. 9, no. 4, pp. 19-28, Dec. 2021.

Need for Interconnection Standards



IEEE P2800 (2021)
IEEE P2800.1
IEEE P2800.2

IEEE 1547-2018
IEEE 1547.1-2020
IEEE P1547.2
IEEE P1547.3
IEEE P1547.9



		Performance	Test & Verification & Model Validation
FERC / NERC?	**Transmission**	- FERC Orders - NERC Reliability Standards & Guidelines	- NERC compliance monitoring & enforcement
NARUC / State PUCs?	**Sub-Transmission**	- Not available	- Not available
	Distribution (for DER)	- IEEE Std 1547-2018 ✓	- IEEE 1547.1-2020 - UL1741 (SB) - IEEE ICAP ✓

IEEE P2800

IEEE P2800.1 and/or .x

Standards drive uniformity of requirements across jurisdictions

Diverse & different requirements across various jurisdictions

Inverter-based resources (IBR) are different from synchronous generators

Requirements may not be balanced

IEEE 1547 becoming widely adapted as the de facto DER interconnect standard
- IEEE 1547.9 new standard for energy storage interconnection

EEE P2800 applies to interconnection of inverter based resources at the transmission and subtransmission levels
- Currently under development

R&D Gaps and Engineering Challenges

Further improvements in energy density, cost and performance (all battery technologies)

Materials and technologies for longer duration energy storage, esp. efficiency improvements

Safety of electrochemical storage – addressing foundational materials issues

Reducing system level complexity including making systems modular

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

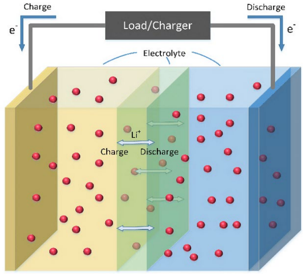
Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

Emerging battery technologies are burdened by lower efficiencies (compared to Li-ion), large footprints, and no ready monetizable market segment to deploy projects

Making Energy Storage Mainstream to Grid Operators

Technology

- **Lower cost, longer cycle life systems; longer duration 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

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

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