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Energy Storage and the Electric Grid

Stabilizing the Renewable Energy Dominated Utility Grid Through Storage

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Sandia National Laboratories

Intersolar India, December 10, 2020

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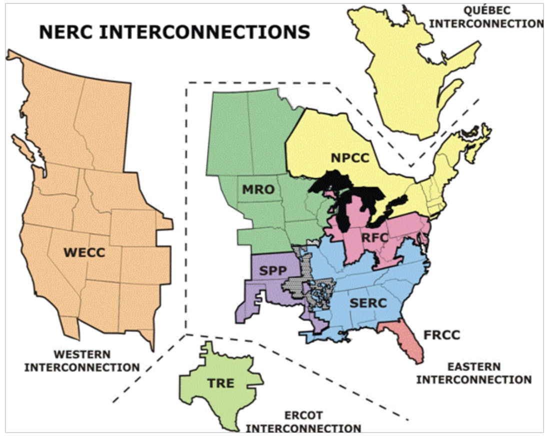
Electric Power Grids Today

- 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

Today's Challenges

Economic

- Aging electric power system in developed countries increase operating costs substantially due to outages and inefficient energy technologies.
- Rapid load growth in developing countries requires tremendous investment in grid infrastructure.

Environmental

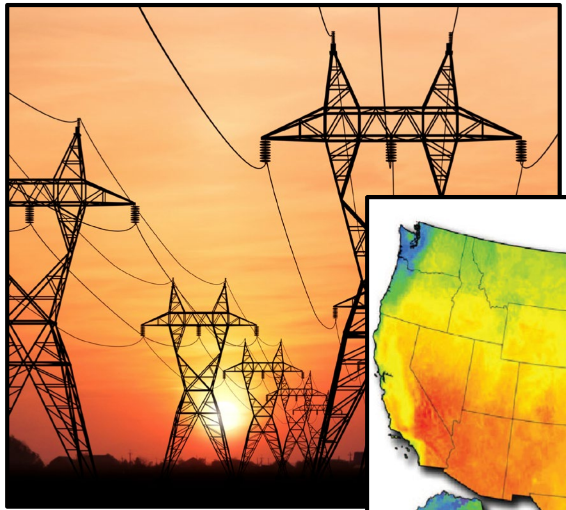
- Increasing frequency and severity of extreme weather (drought, storms, etc.) affect the ability to generate power and stress resiliency of the grid.
- Need to mitigate climate change

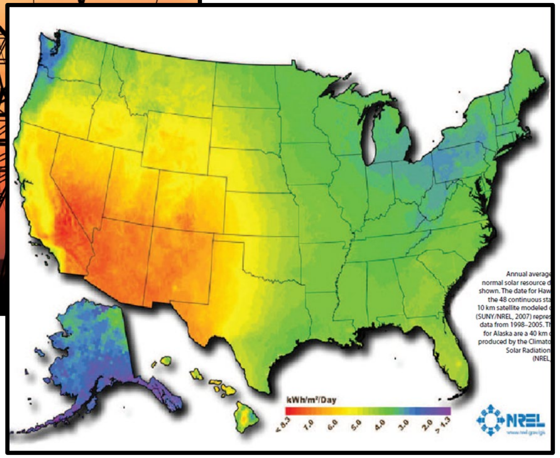
Security

- Physical: Damage to infrastructure by malicious actors or natural hazards increases risk to critical assets
- Cyber: Disruption of energy production/energy flow and damage to equipment caused by cyber threats/attacks.

Competitiveness

- Increasing competition worldwide in energy sector as countries are moving toward clean energy technologies
- Improving competitiveness globally requires steep cost reduction by technology/manufacturing advances, and competitive energy markets



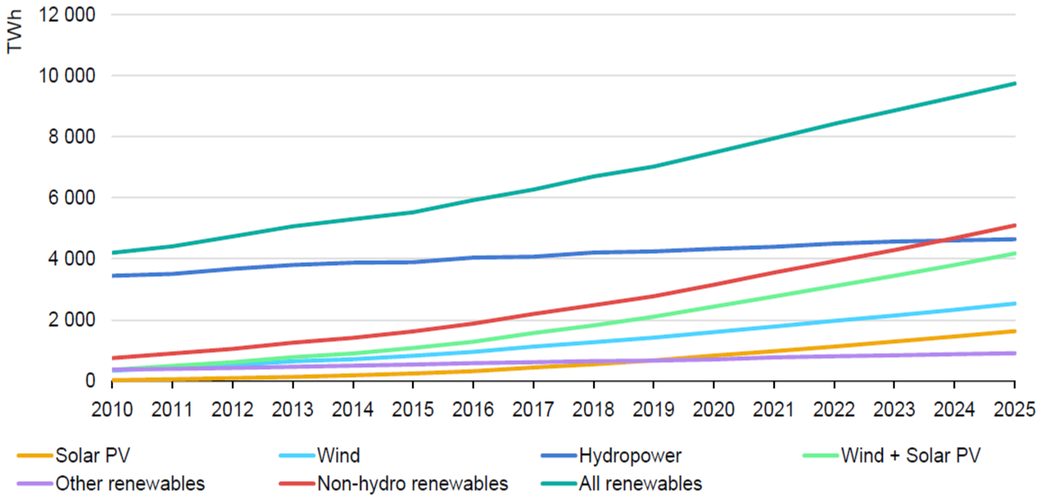


Source: NREL

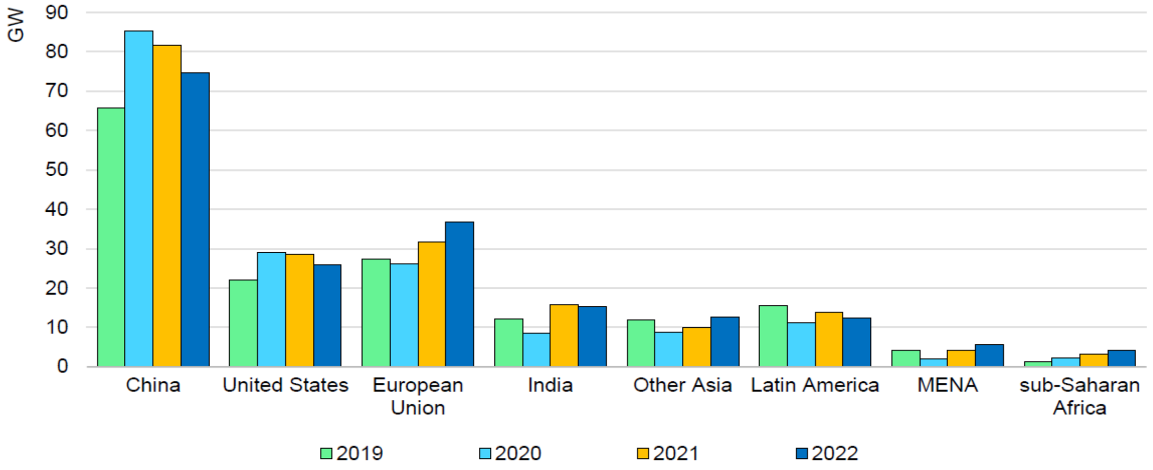
Today's Trends – Increasing Renewables

- 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

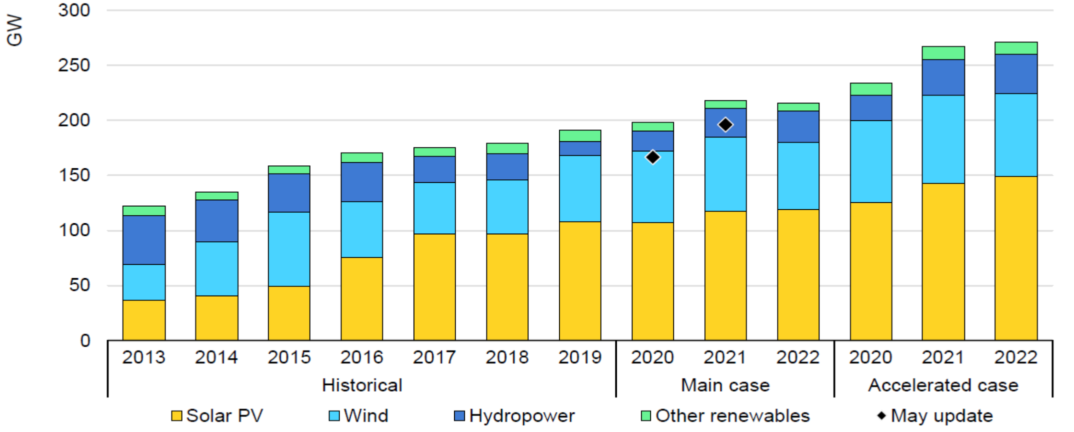
Renewable generation 2010-2025



Renewable capacity addition by country 2019-2022



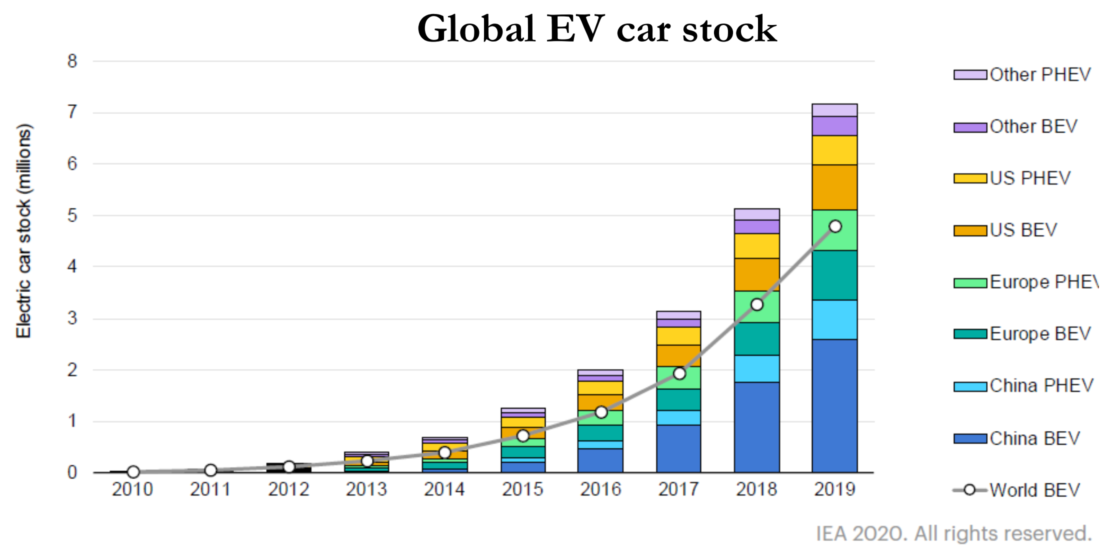
Renewable capacity addition by technologies

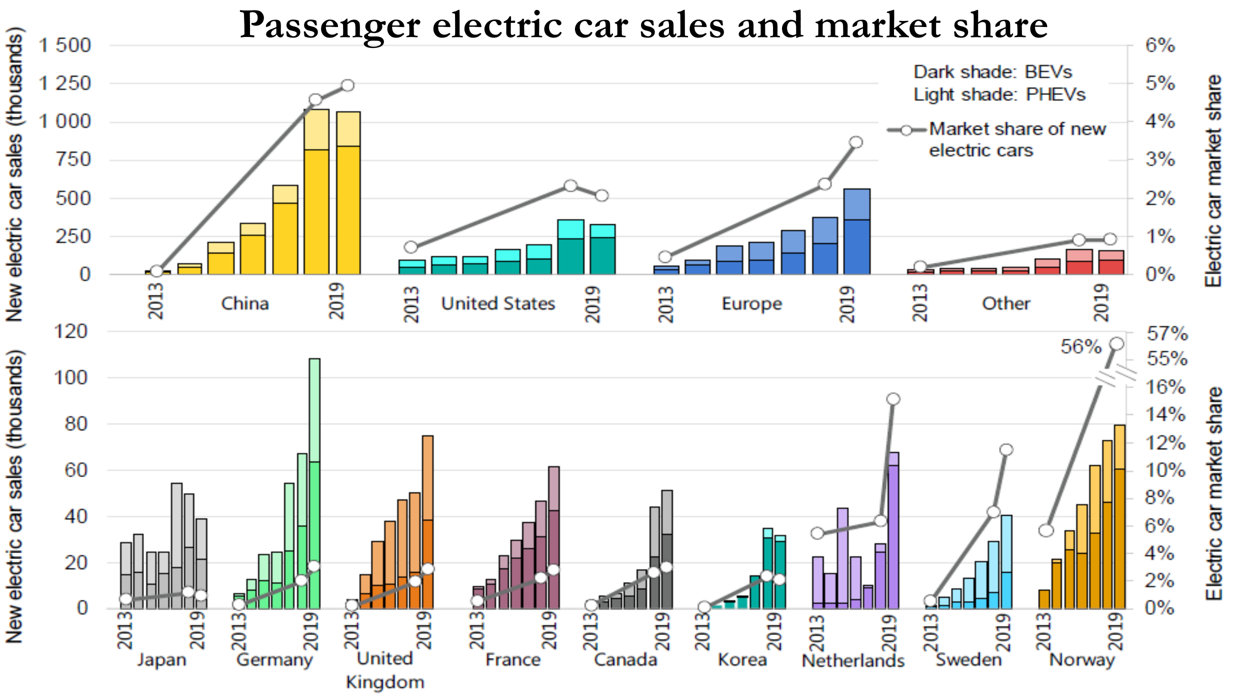


Source: IEA Renewables 2020

Today's Trends – 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

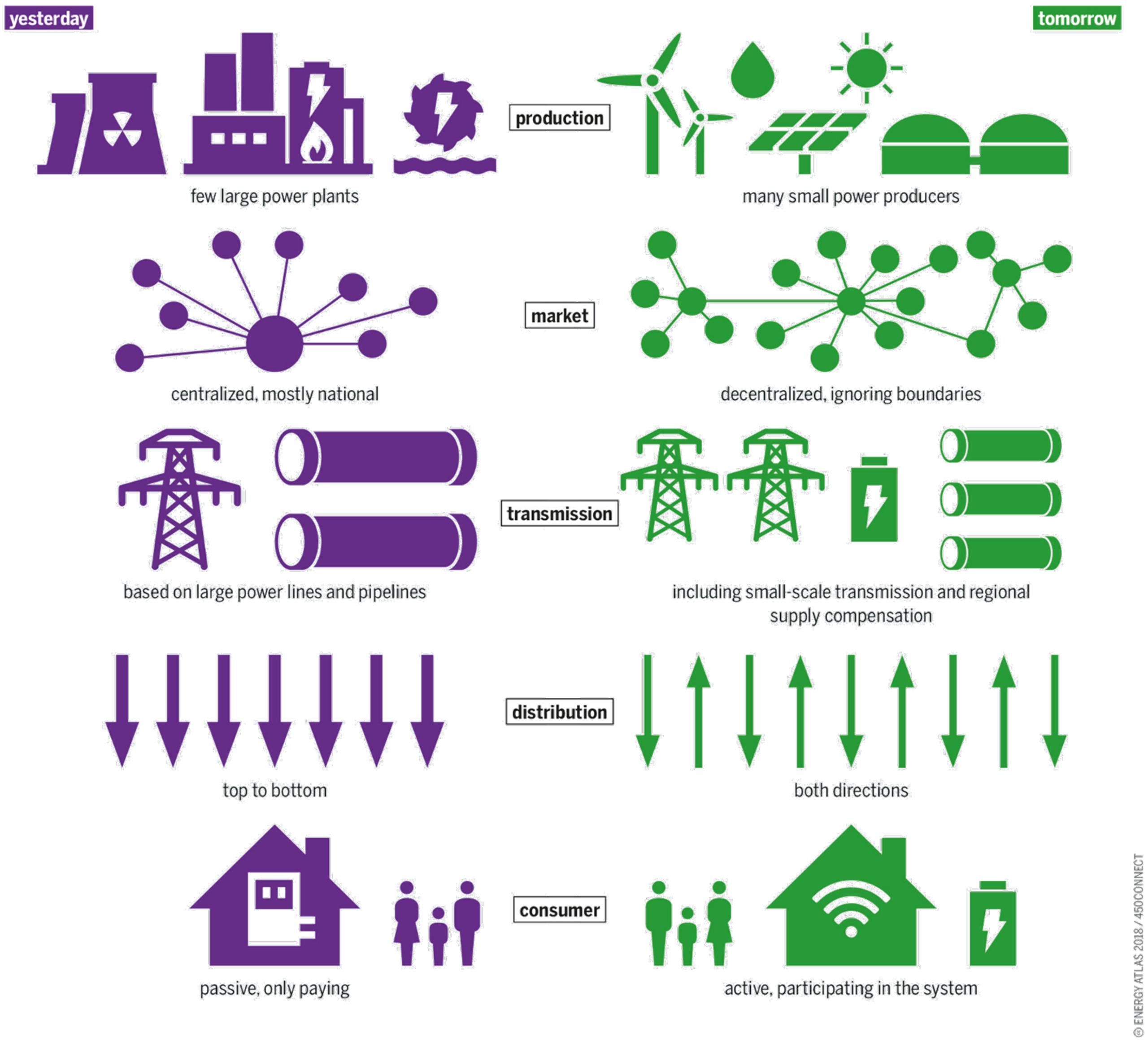




Sources: IEA Global EV Outlook

Today's Trends – Grid Modernization

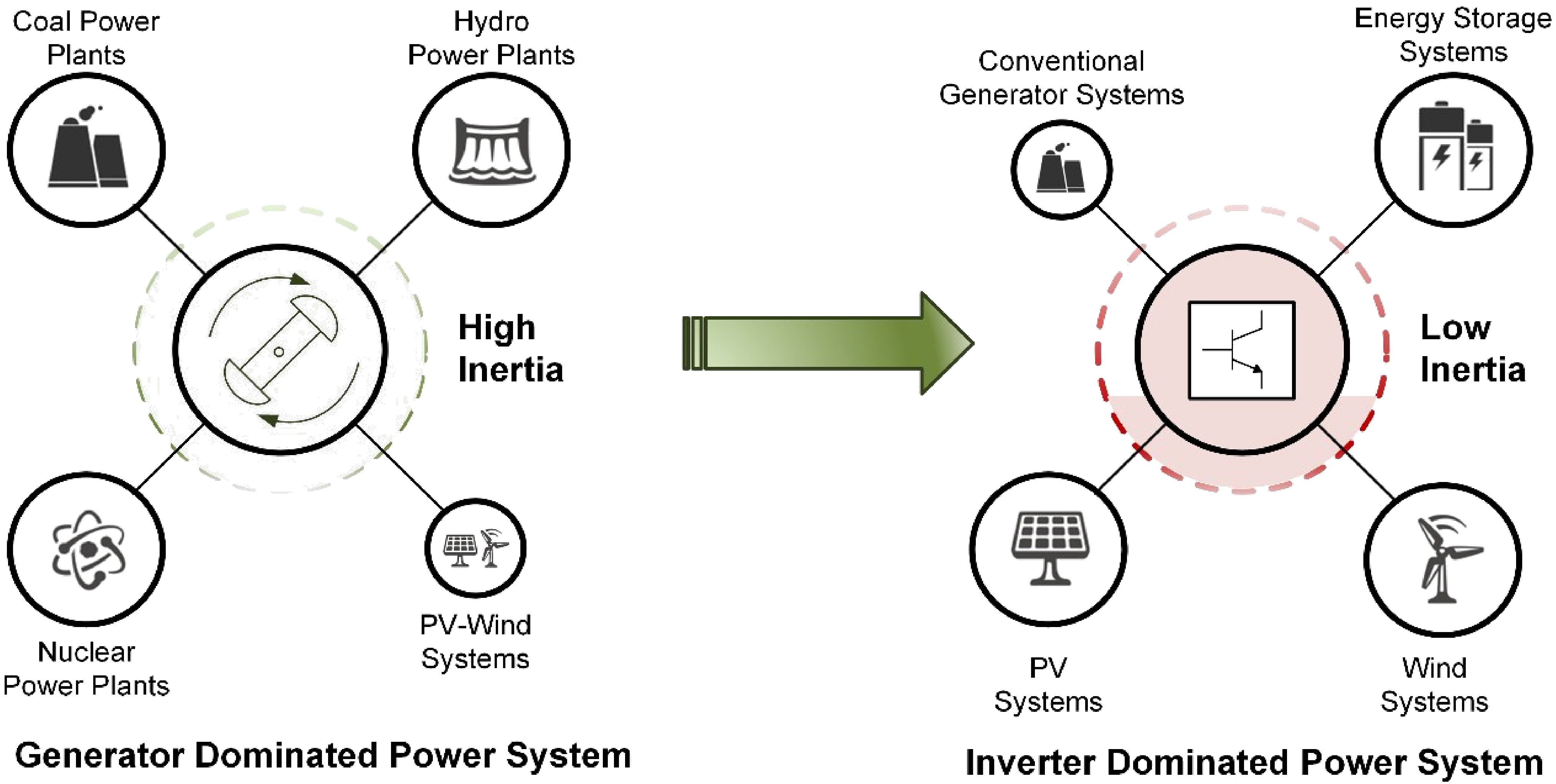
- Grid modernization will replace aging infrastructure, and meet emerging trends including low-inertia generations resources, renewables, and distributed energy resources for greater resilience and flexibility.
  - Large central plants with hierarchical controls to decentralized, and smaller generations and distributed controls
  - One-directional passive loads to two-way flows of electricity and information – Consumers can be energy producers!
  - Automation and digitalization through communication and control layers
  - Penetration of energy storage systems, transport electrification, and behind-the-meter devices
  - Power-electronics-interfaced units, and smart metering (e.g., PMU)



Sources: DOE Quadrennial technical review

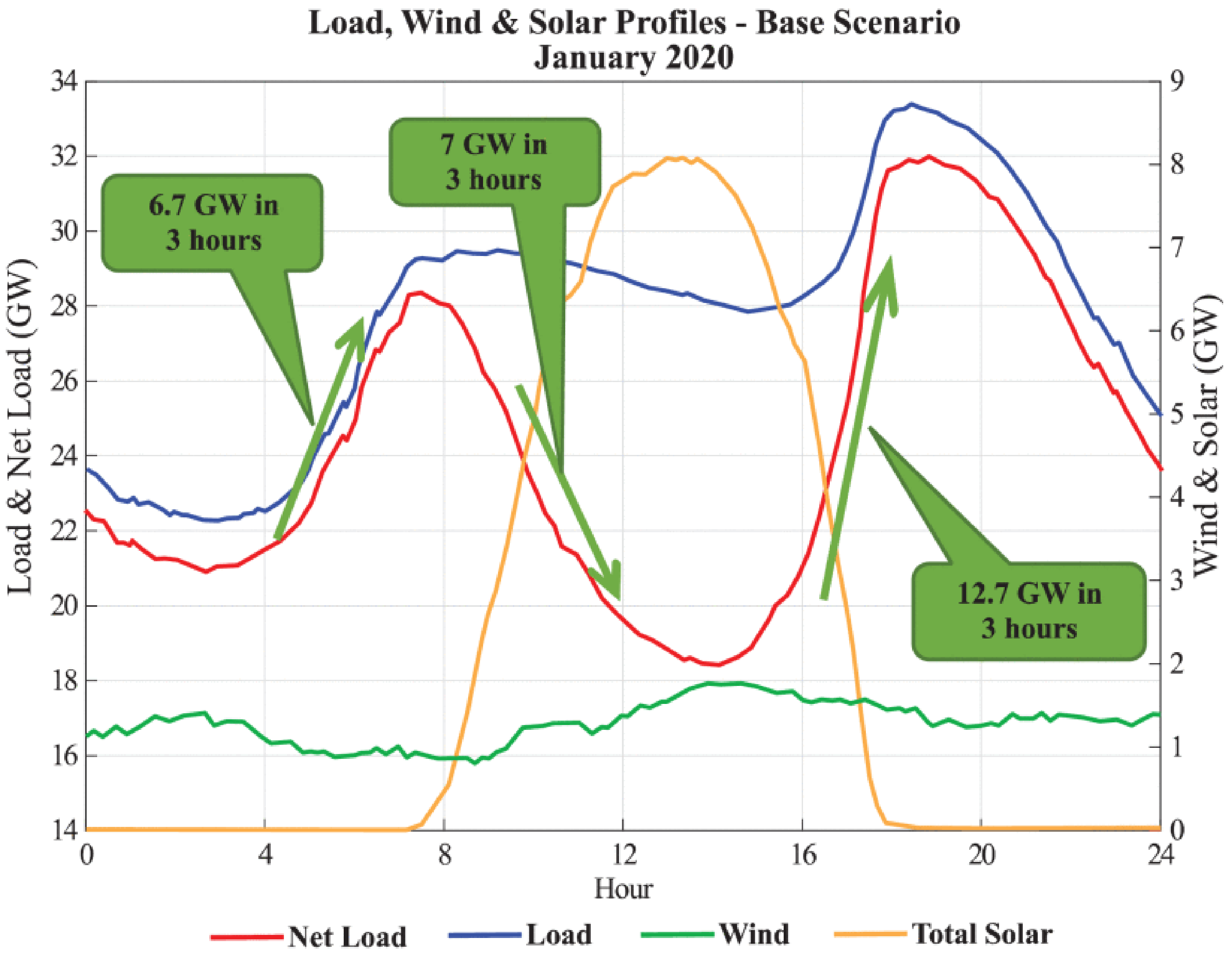
Operating Challenges of Grid of the Future – Low Inertia

- The power conversion system is at the center of DER, Energy Storage, and EV infrastructure
- System will operate with much lower inertia



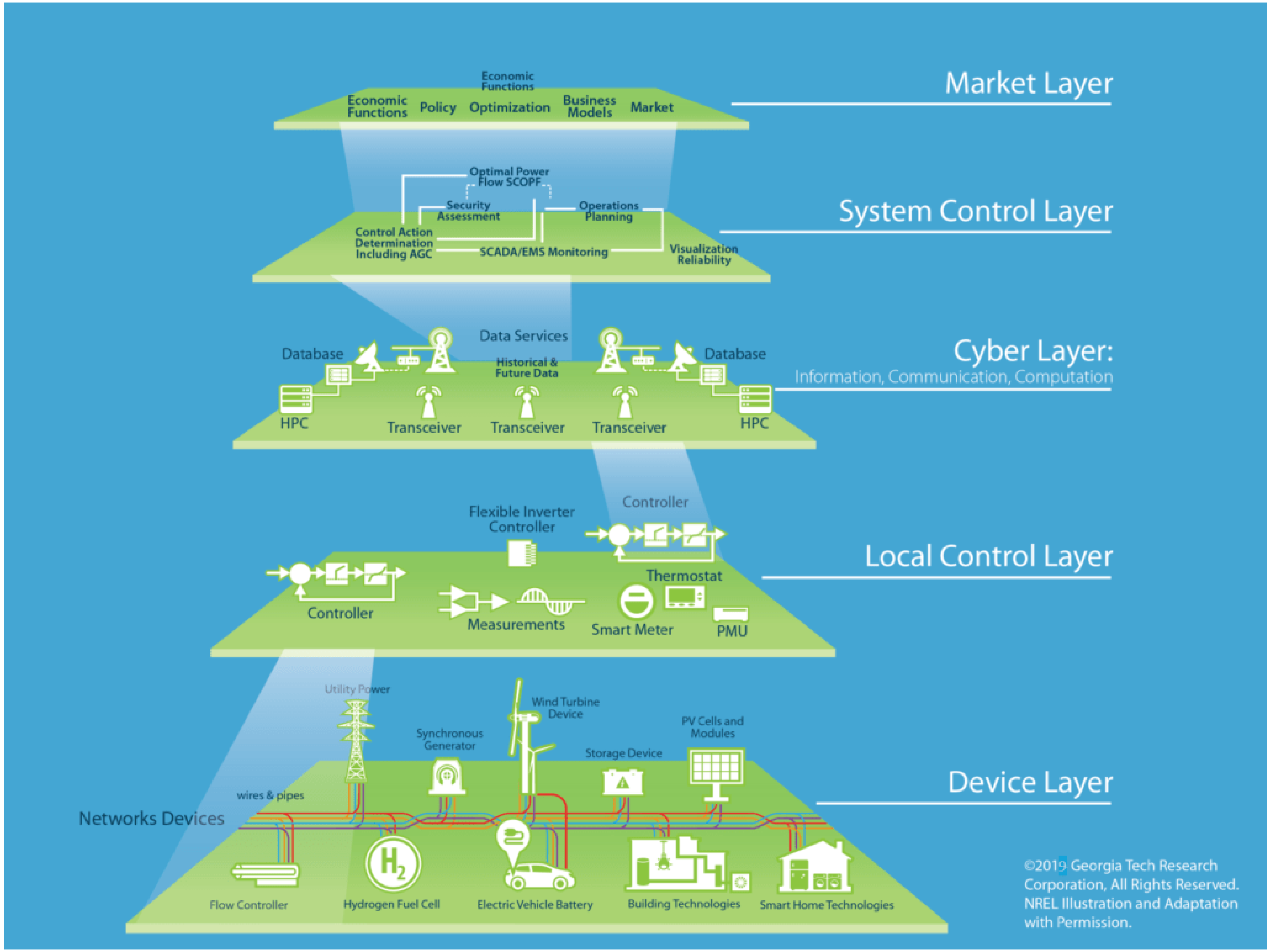
Source: U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," Applied Sciences, vol. 7, no. 7, p. 654, Jun. 2017.

Operating Challenges of Grid of the Future – High Variability And Uncertainty



- 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.

Operating Challenges of Grid of the Future – Communication and Control



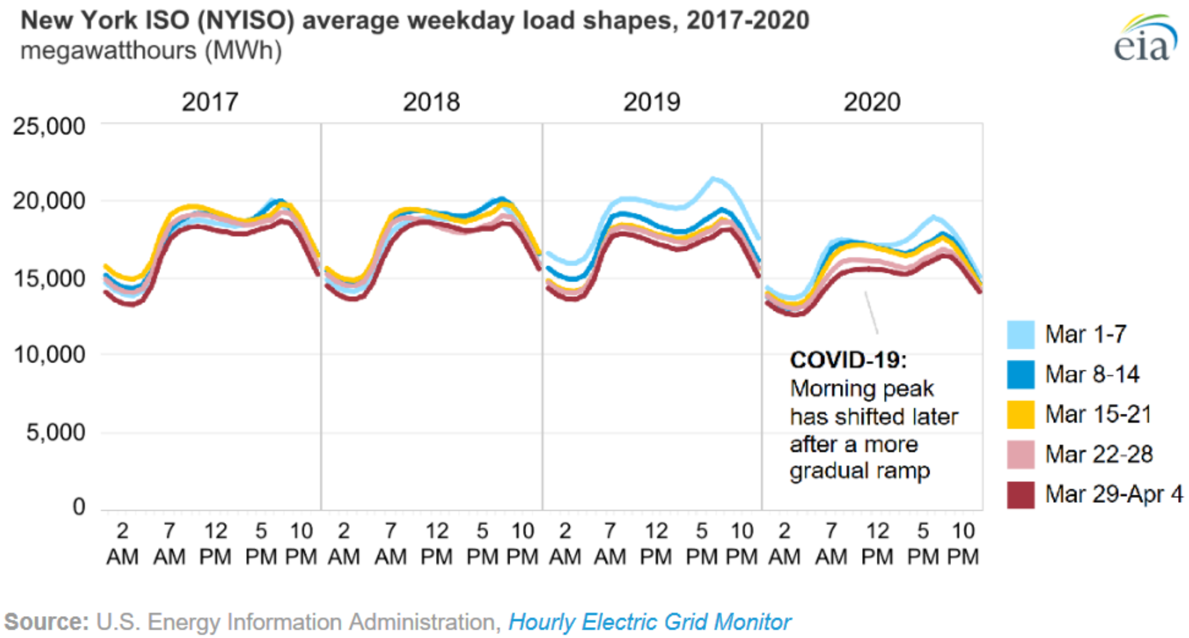
Sources: E&E News, Georgia Tech ACES

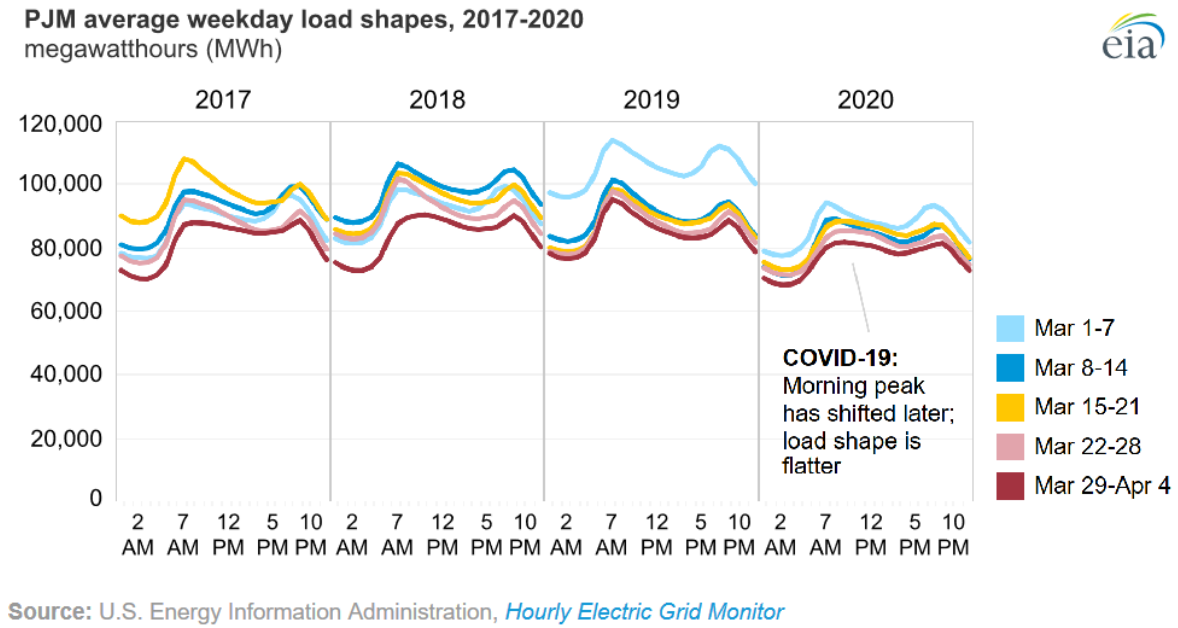
- Smart grid control and monitoring require fast, reliable and secure communication between all components.
- Large amount of networked device increases connectivity of grid assets, but creates a great challenge for cyber security as target domain for attack increases.

Operating Challenges of Grid of the Future – Maintaining Reliability

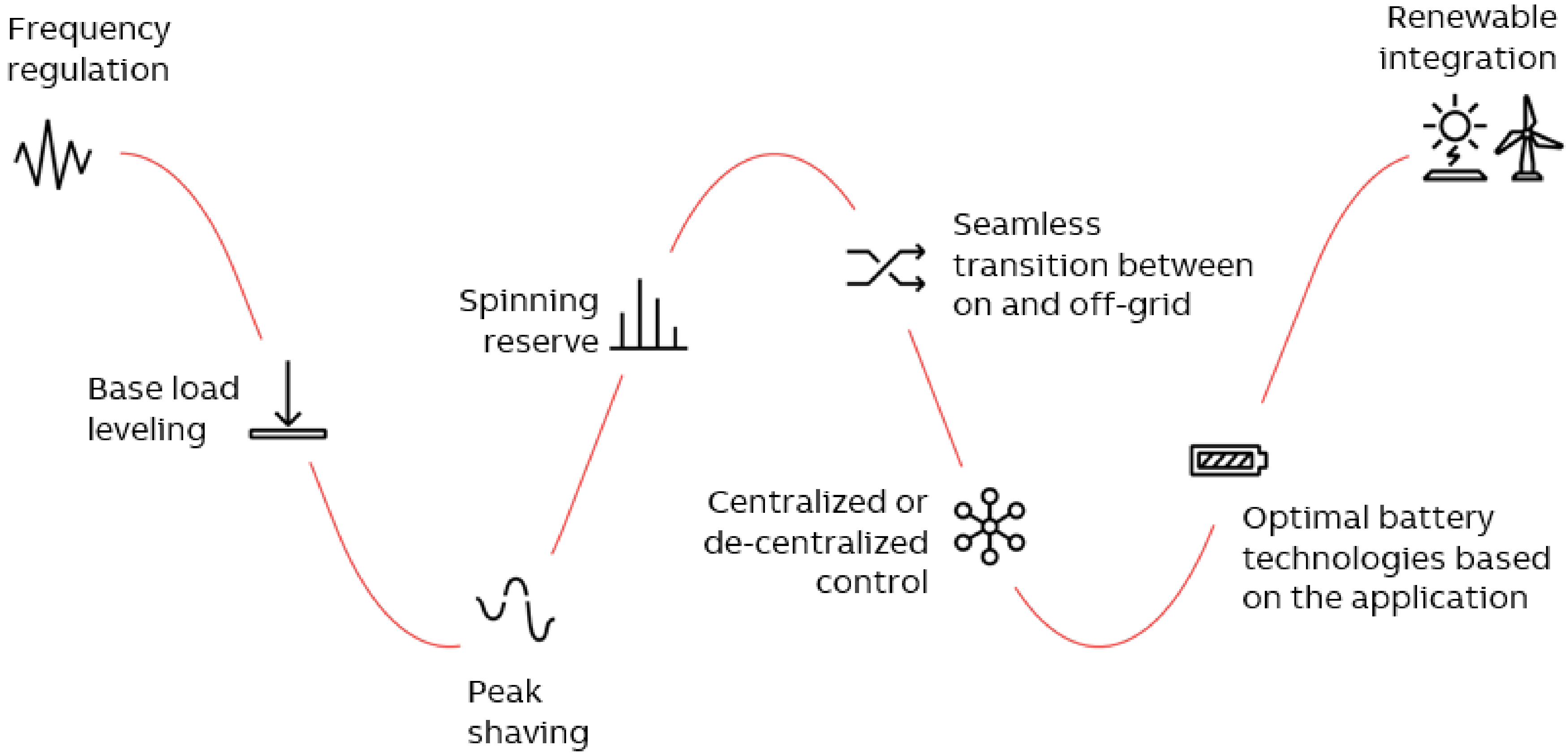
Grid should have adequate generation capacity to meet peak demand, considering:

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





Operating Challenges of Grid of the Future – Maintaining Frequency

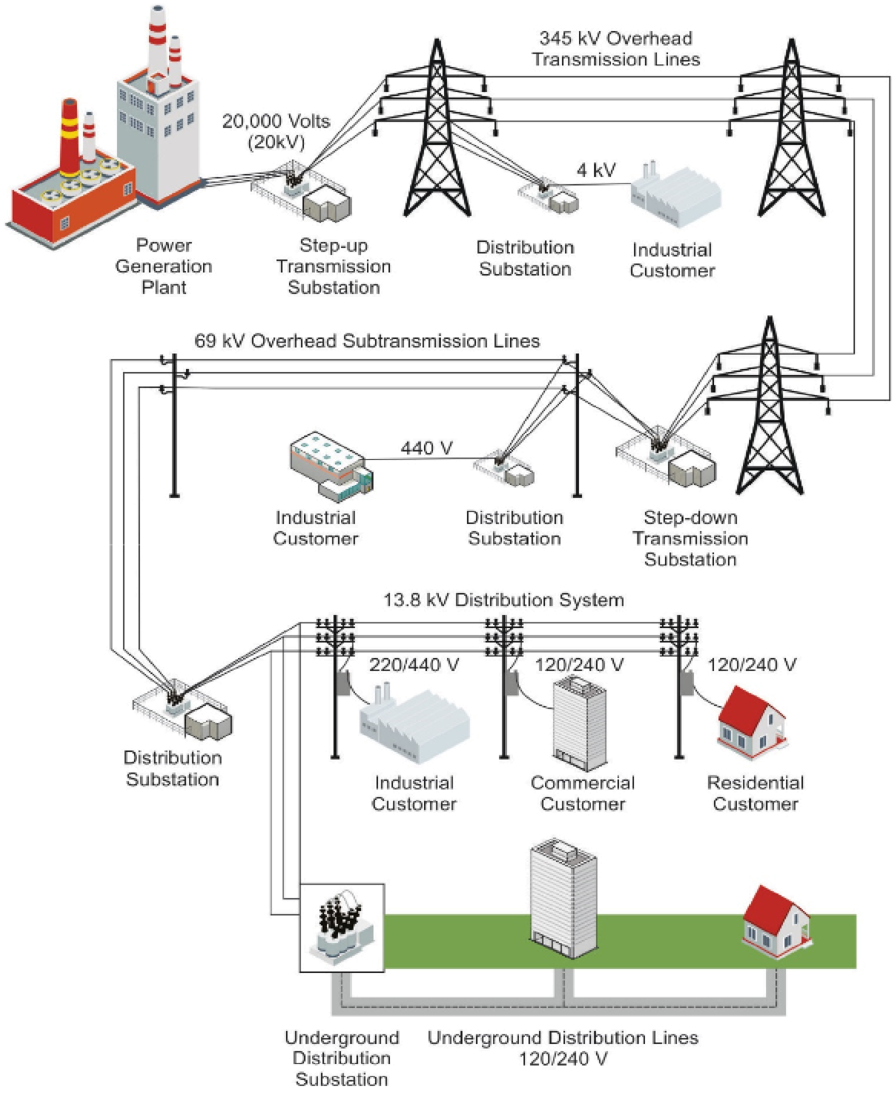


Sources: Hitachi ABB Power Grid

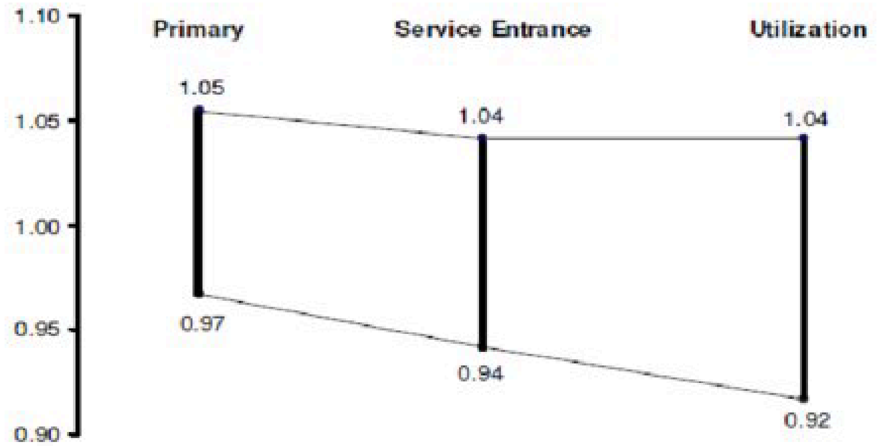
- Employ operating reserves able to respond to unplanned events
- Automatic control and protection (e.g., under-frequency load shedding)
- New options: demand response, DER, energy storage

Operating Challenges of Grid of the Future – Maintaining Voltage

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

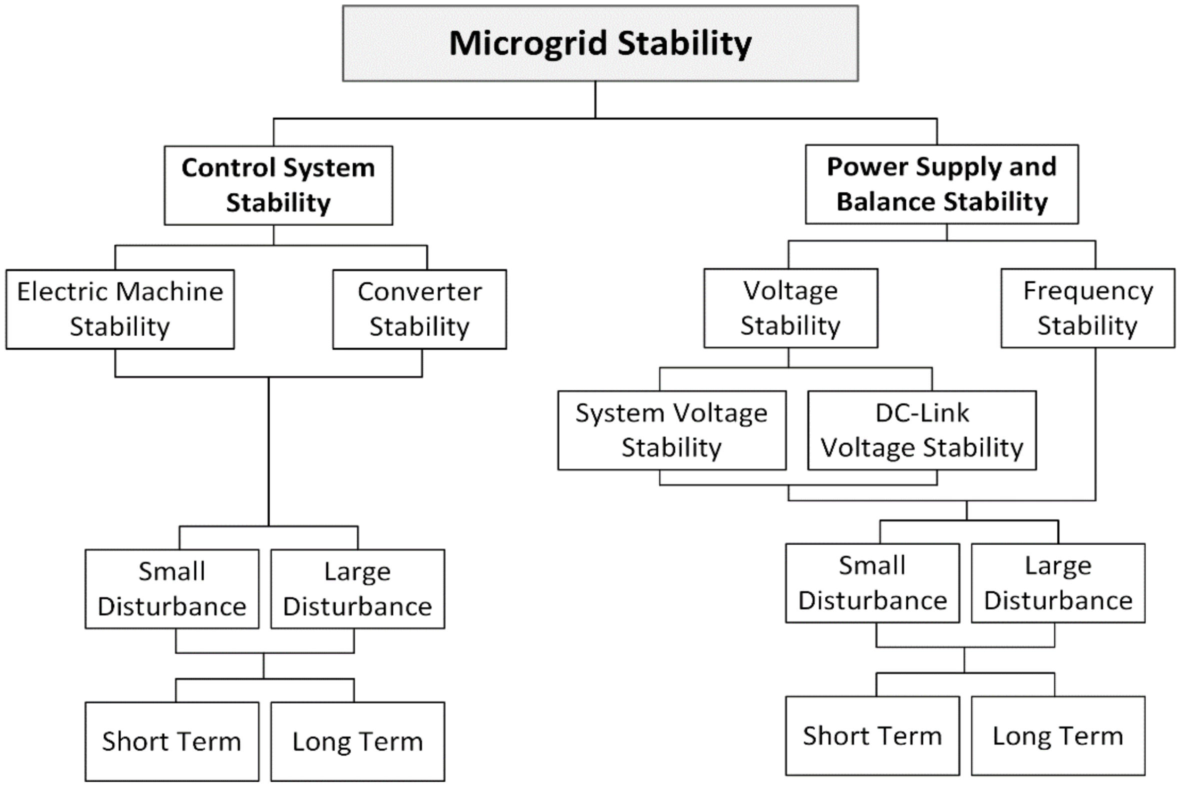


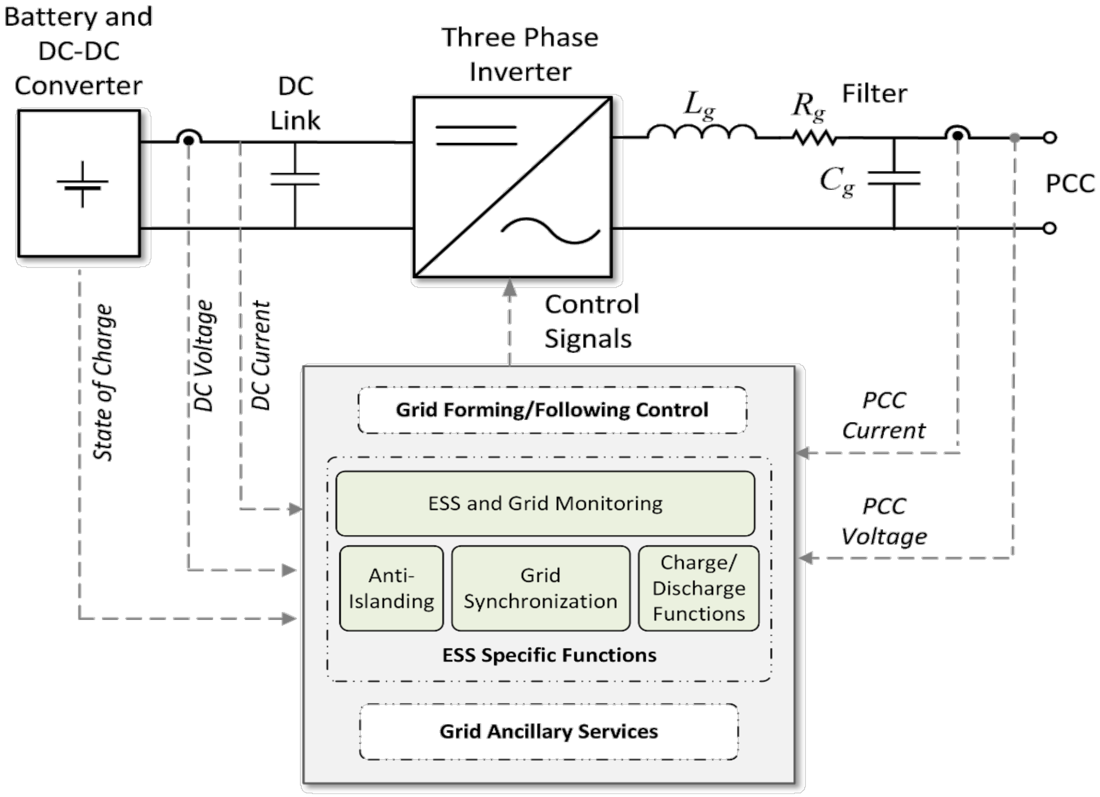
	Service		Utilization	
	Min	Max	Min	Max
Range A (normal)	-5%	+5%	-8.3%	+4.2%
Range B (emergency)	-8.3%	+5.8%	-11.7%	+5.8%



Operating Challenges of Grid of the Future – Other Considerations

- As a new operation paradigm is emerging (e.g., Microgrid with power-electronics-based DERs), reliability is extended to incorporate control system stability.
- Short-term voltage and frequency stability, as well as transient rotor angle stability issues, become more prominent due to low inertia of power-electronics-interfaced DERs.

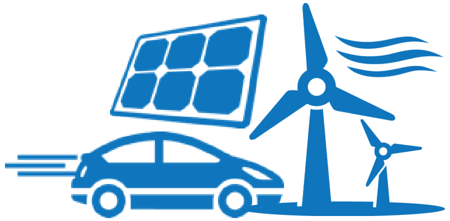




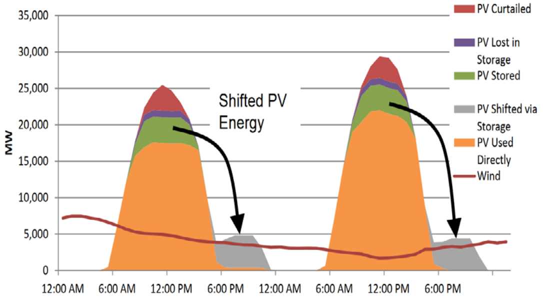
Sources: IEEE PES Task Force on Microgrid Stability Definitions, Analysis, and Modeling

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.

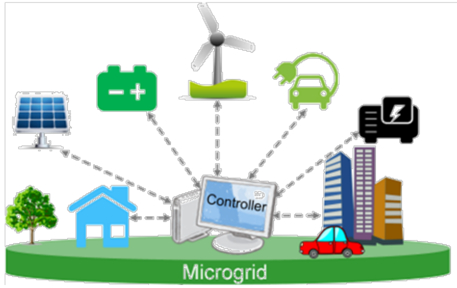


Balancing renewable variability



Peak shaving and energy shifting

Regulation/contingency reserves

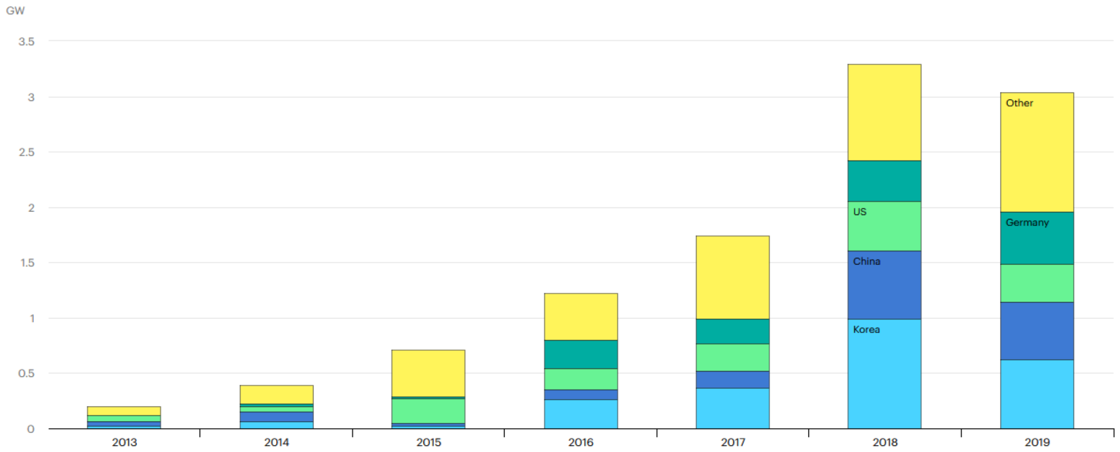


Microgrid

Sources: Berkeley Lab, NREL, Energy Sage.

Energy Storage in the Grid Today

- Energy storage installations increasing globally.
  - Total 2.9 GW Battey 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

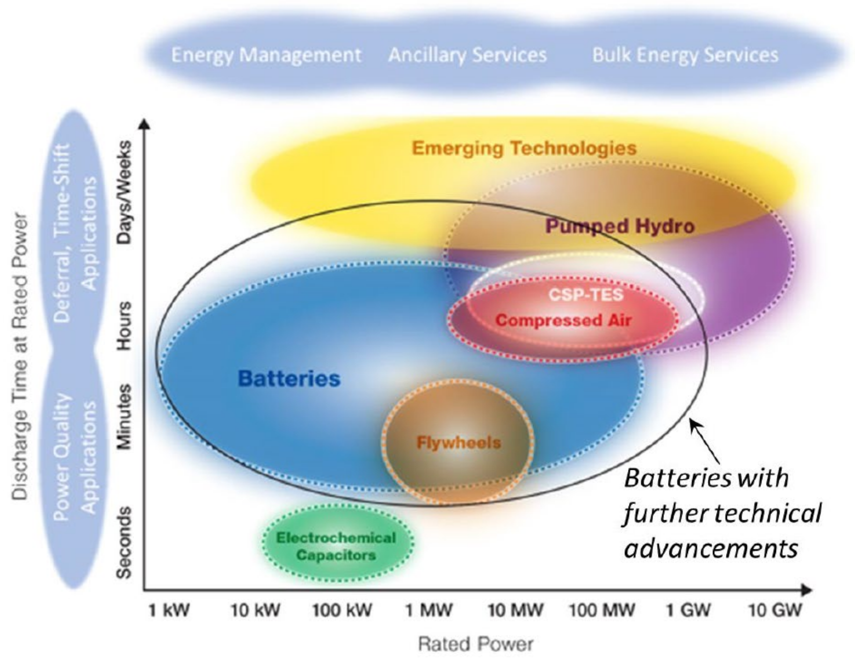
Key driver of energy storage growth is co-location with renewables

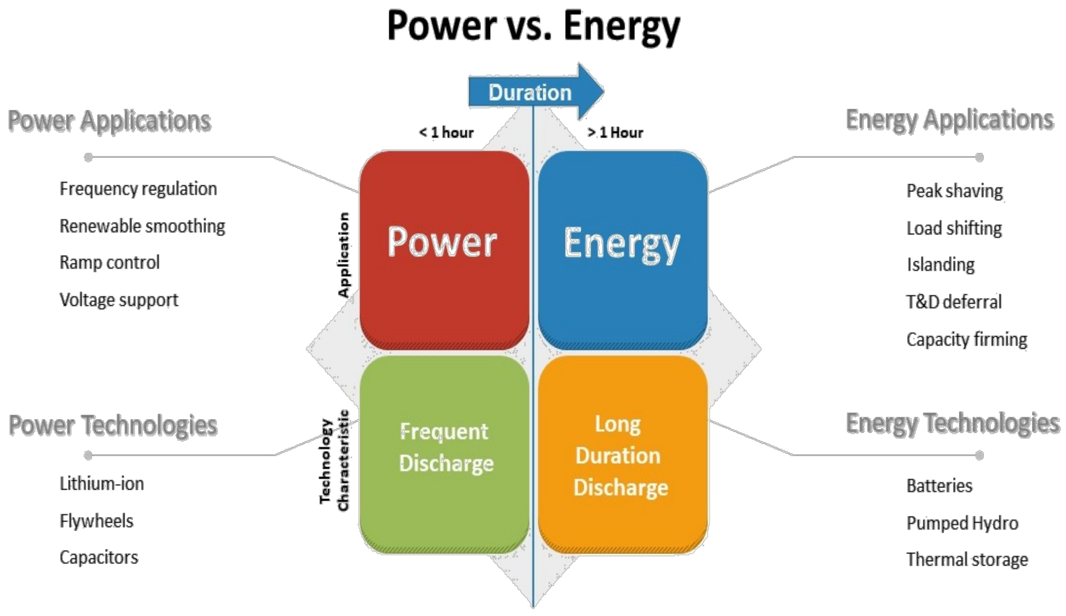
Sources: IEA (https://www.iea.org/reports/energy-storage)

Range of Technologies and Applications

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

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

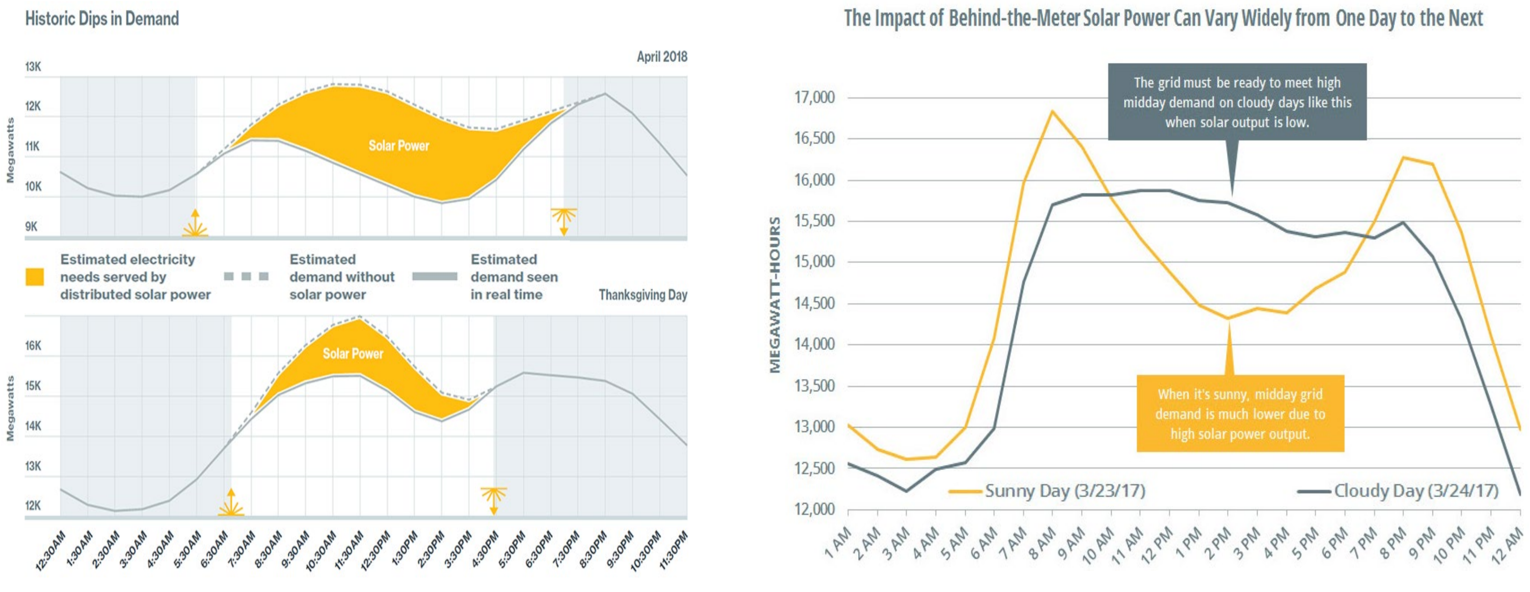




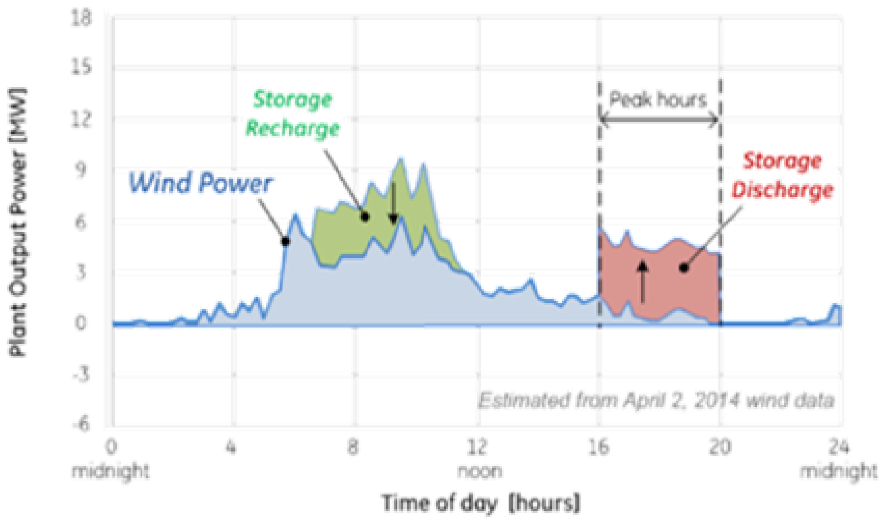
Sources: Potential Benefits of High-Power High-Capacity Batteries, DOE Report, Jan 2020,
Energy Storage Primer, IEEE Power and Energy Society, 2020

Energy Storage for Peaking Demand

- Renewable generation is quickly growing, impacting traditional net-demand profile:
  - Variability of regional renewable resources (e.g., residential rooftop solar) make the net-demand “peakier”
  - Variable renewable generation (e.g., behind-the-meter solar power) introduce uncertainty in demand prediction
- Battery energy storage is an ideal peaking resource (cost competitive compared to other peaking resources) for short peak created by PV or wind (≤ 6 hrs)



Net demand change and uncertainty due to renewables

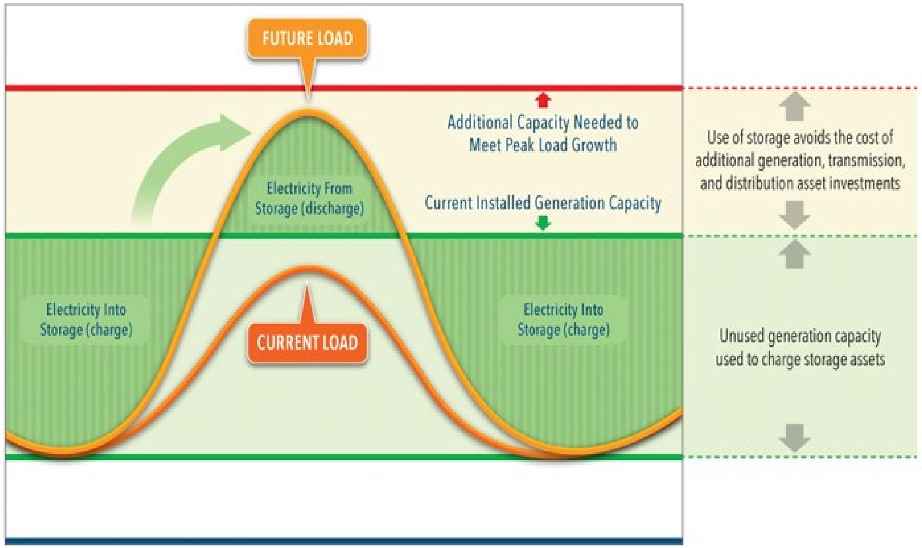


Energy storage as a peaking resource

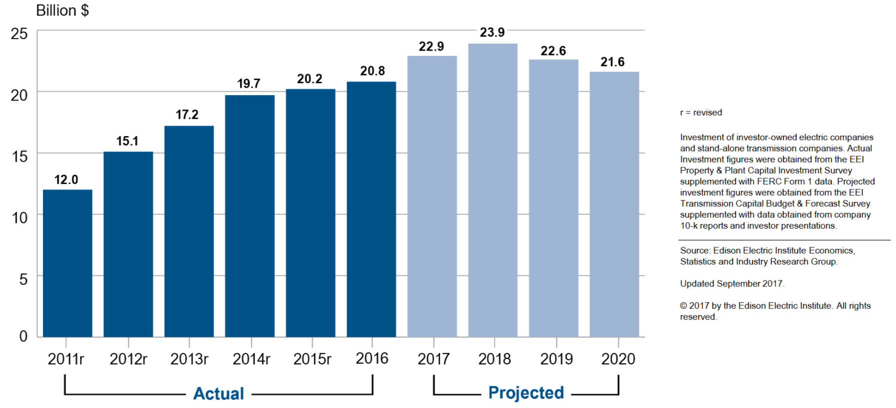
Sources: New England ISO, Sandia SAND report SAND2017-7835J

Energy Storage for Growing Demand in T&D

- Capacity expansion of Transmission and Distribution (T&D) is unavoidable due to growing peak demand.
- Energy storage, when located electrically "downstream" and acting as a distributed energy resources (DER), is compelling for costly and uncertain T&D upgrade deferral and prolonged T&D equipment lifetime.
- Defer or avoid the need to upgrade electrical T&D equipment:
  - Requires relatively small amount of storage to serve a peak demand
  - Storage with 4% rated power output of the T&D equipment's power rating will defer an upgrade of T&D equipment for two years
- Extend the life of existing T&D equipment:
  - Energy storage reduces wear on existing T&D equipment, i.e., utilities aging fleet of underground cables which are expensive to replace.
- Energy storage reduces T&D investment risk due to uncertainty in predicted load demand growth.



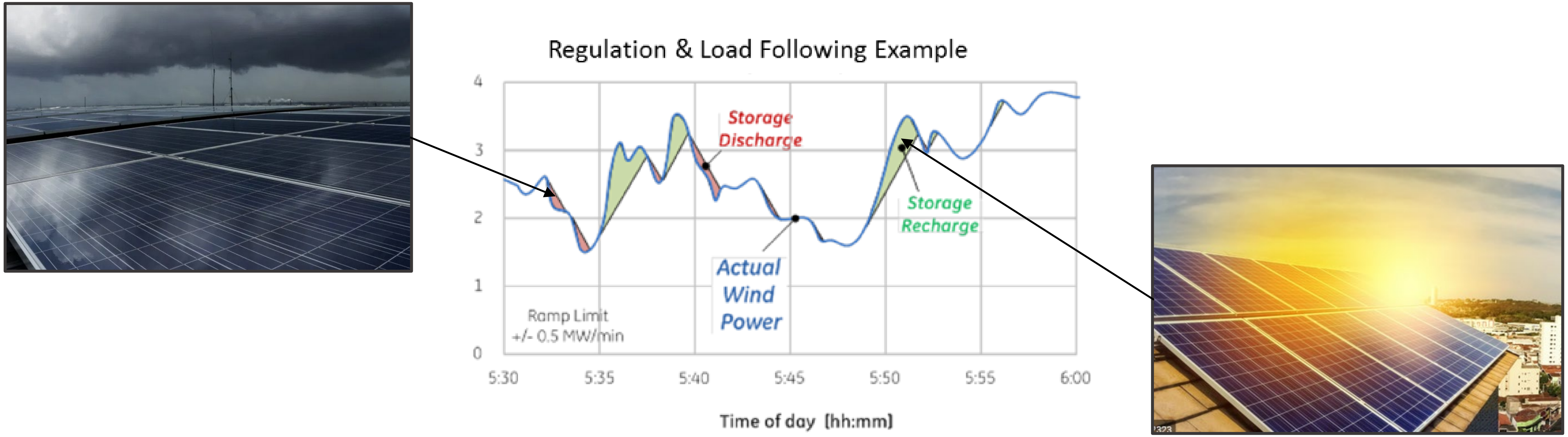
Historical and Projected Transmission Investment
(Nominal Dollars)



Sources: Energy Storage Association, NRStor Inc, Edision Electric Institute

Energy Storage for Frequency Regulation

- As wind and solar penetration continues to increase, battery energy storage becomes the most cost-effective options for grid services.
- For large wind/solar penetration, short-term fast charging/discharging of energy storage provides regulation and load following services as generation from wind and solar fluctuate along with system load.
- Grid-scale energy storage provides a fast response to severe disruptions and emergency events to maintain grid stability.



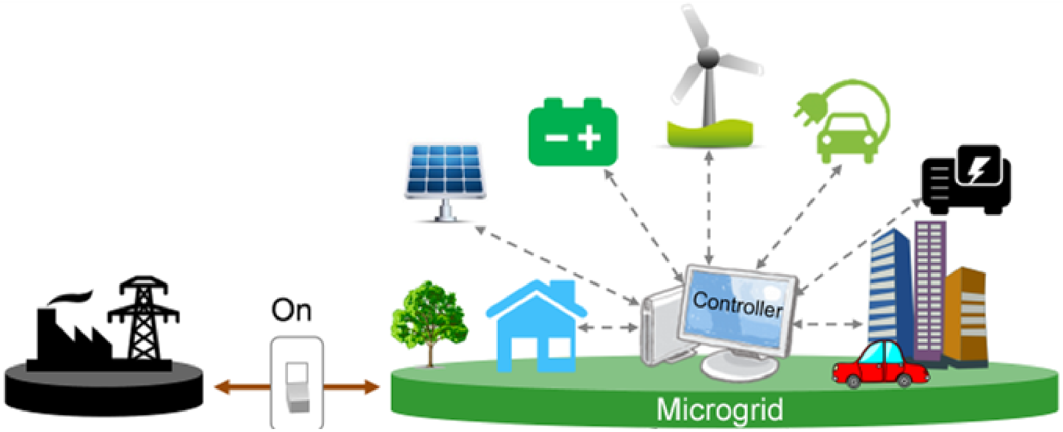
Example of regulation & load following due to variable renewable generations

Sources: Sandia SAND report SAND2017-7835J

Energy Storage for Microgrids

- Microgrids are low/medium-voltage electric grids that can operate locally as a single controllable entity
  - Consists of distributed energy resources (DER), renewables, energy storage, and loads
  - Diversified rather than concentrated risk, increasing stability, reliability, and resilience
  - Reduces grid congestion and peak loads, and offers grid services including energy, capacity, and ancillary services
- Energy storage is a key component of Microgrids achieving reliable and resilient operations
  - Maintains power quality and maximizes duration of Microgrid operations in the case of unplanned islanded operation
  - Provides local management of variable renewable generation, particularly on-site solar

Microgrid in Cheetah Plains Lodge, South Africa's Kruger National Park, featured by 300 kW of PV with 1,027 kWh of Lithium-ion storage capacity and a 150 kVA diesel generator.

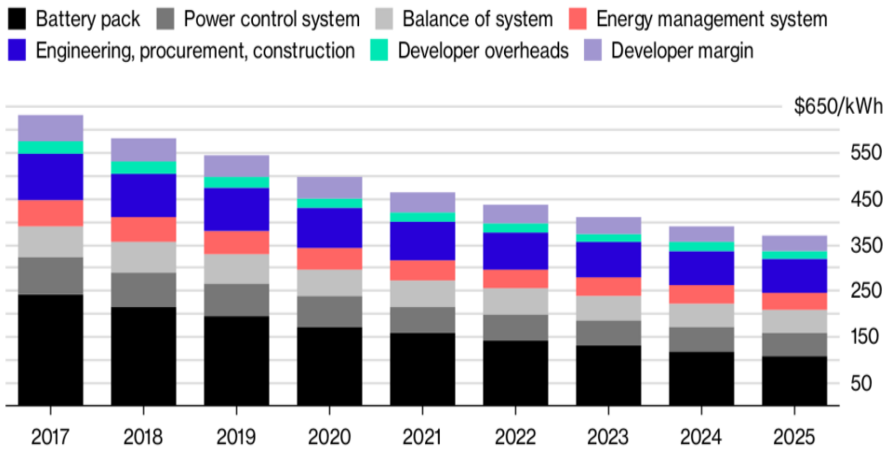


Microgrid can operate in two modes: 1) grid-connected, 2) isolated. Energy storage provides reliable service for transition between modes.

Sources: Berkeley Lab, PV Magazine.

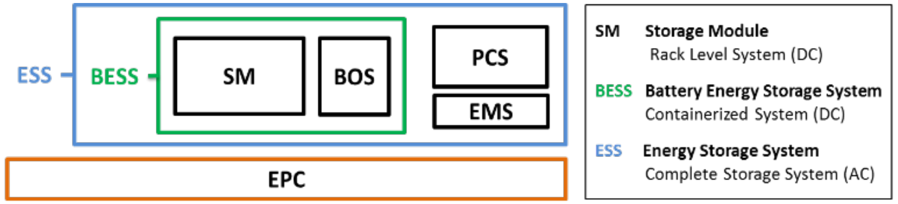
Grid Integration of Energy Storage

- 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



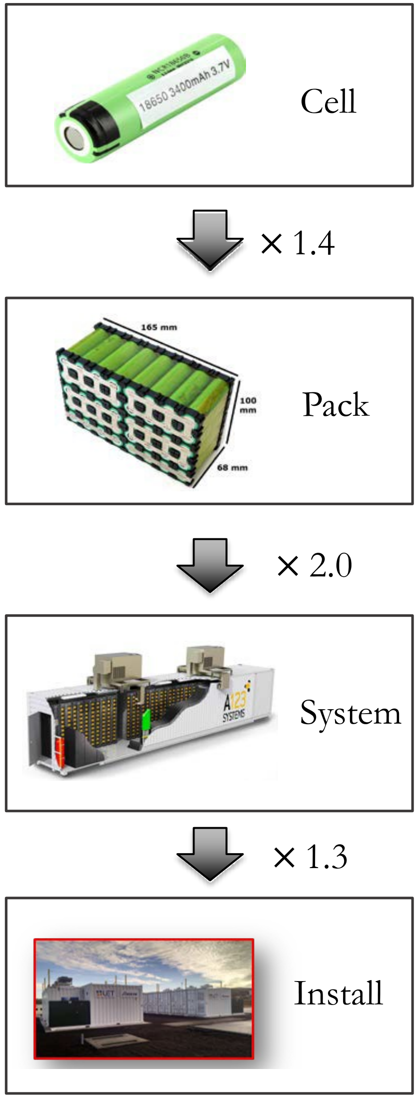
Note: Benchmark numbers for a 1MW/1MWh project
Source: Bloomberg New Energy Finance (BNEF)
Bloomberg

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.



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

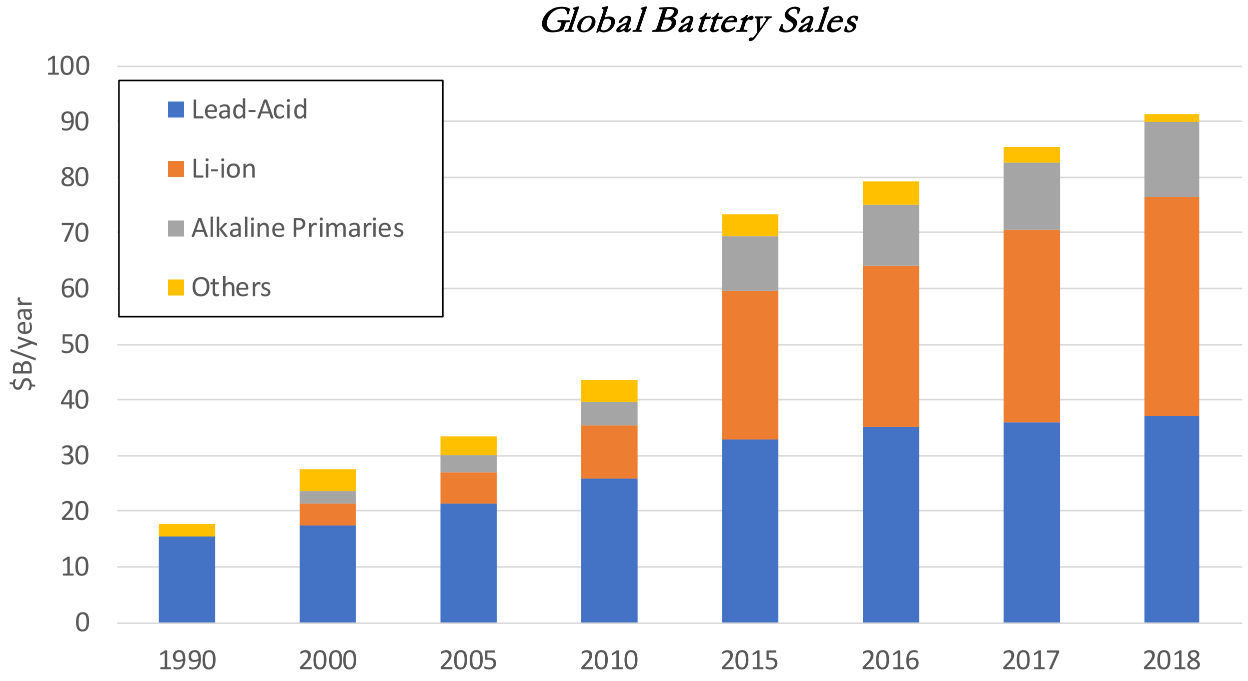
- **Market Drivers**
  - Consumer electronics, mobile devices and EVs – primarily Li-ion batteries.
  - Grid energy storage – growing market, currently modest size. Range of technologies.

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



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

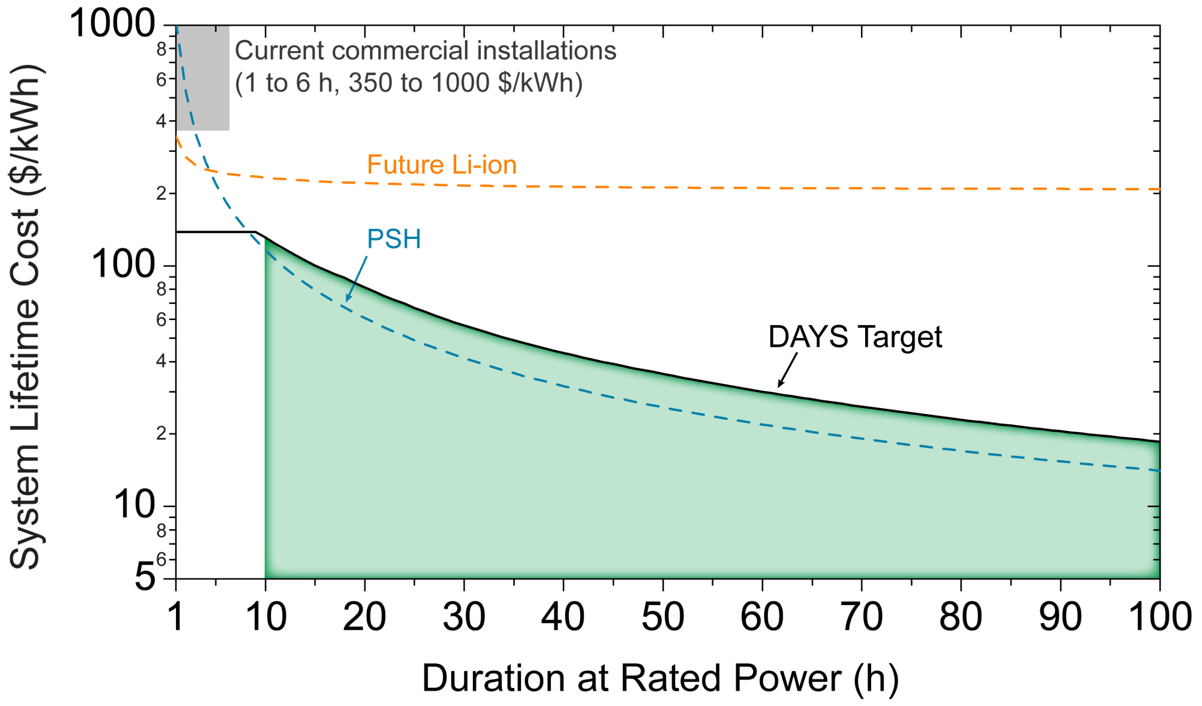
Sources: S. Banerjee, DOE ESGC South/Southwest Workshop, June 2020

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

Long Duration Energy Storage

- 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.

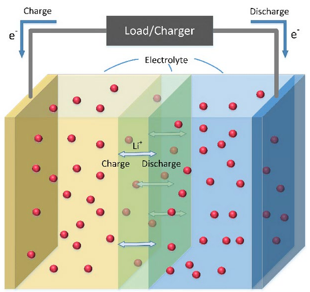


Sources: Albertus et al., Joule 4, 21-32, January 15, 2020.

Making Energy Storage Mainstream

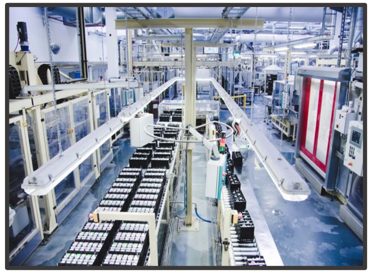
Technology

- 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

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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