

Energy Storage: Technologies, Opportunities, and Challenges

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NREL at a Glance

3,915 Workforce, including:

- 2,913 regular/limited term
- 531 contingent workers
- 223 postdoctoral researchers
- 155 graduate student interns
- 93 undergraduate student interns

—as of 5/15/2024

World-class research expertise in:

- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

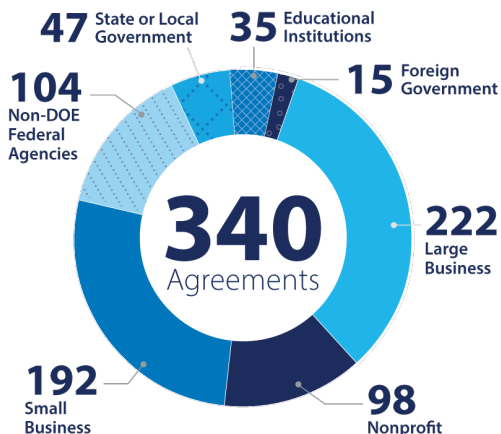
Partnerships with:

- Industry
- Academia
- Government

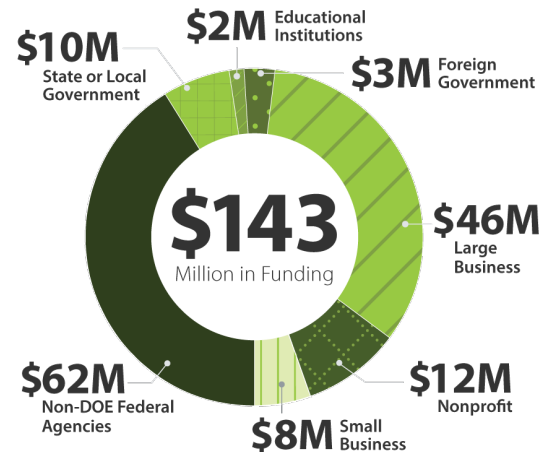
4 Campuses operate as living laboratories



More Than 1,100 Active Partnerships in FY 2023



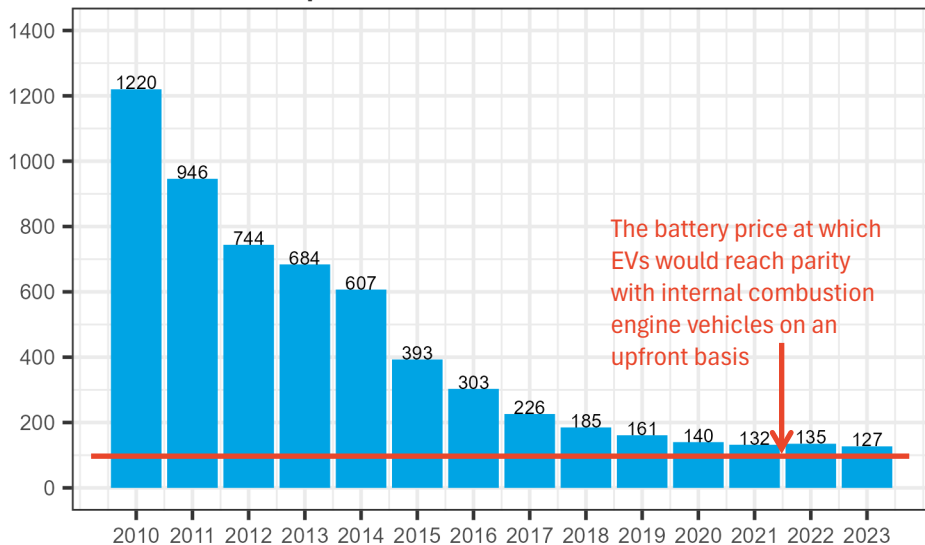
Agreements by Business Type



Funding by Business Type

Why all the hype about batteries, and why now?

Real 2021 \$ per kilowatt-hr

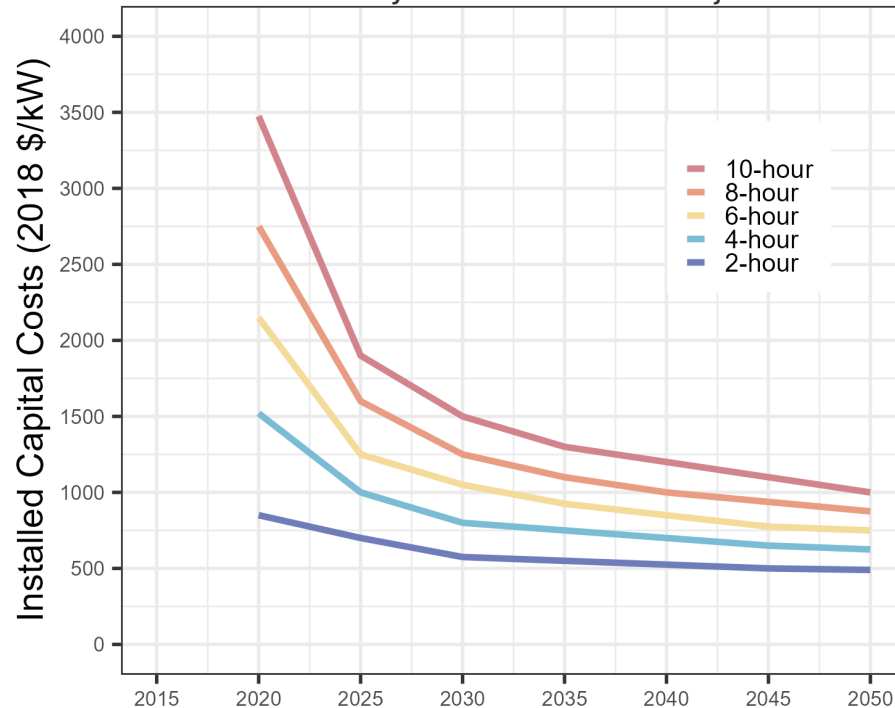


The battery price at which EVs would reach parity with internal combustion engine vehicles on an upfront basis

Source: BloombergNEF. Note: forecast prices are in nominal terms, observed prices are in real \$ per kilowatt-hr

73% cost reduction since 2010 due to technology improvements, economies of scale, manufacturing competition

60-MW Utility Scale BESS Cost Projections



Cost Projections (using \$/kW)

Source: Storage Futures Study – Storage Input Data
<https://www.nrel.gov/docs/fy21osti/78694.pdf>

Some Storage Terminology

- Applications for energy storage are defined by the following parameters:
 - **Power capacity (kW):** maximum rate of charge or discharge (in kilowatts or megawatts)
 - **Energy capacity (kWh):** amount of stored energy (in kilowatt-hours or megawatt-hours)
 - **Storage duration:** amount of time storage can discharge at its power capacity before depleting its energy capacity (in hours, usually)
 - **Round-trip efficiency (%):** The percentage of electricity put into storage that is later retrieved. *Storage is an electricity consumer, not a producer.*

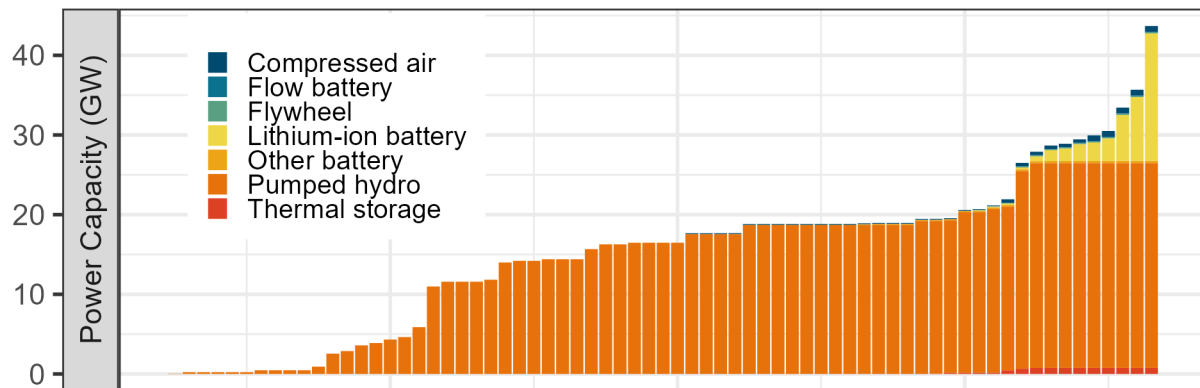
Category	Storage Duration
Short Duration	< 10 hours
Long Duration	10 – 100 hours
Seasonal Storage	100+ hours

Warning: not universal!

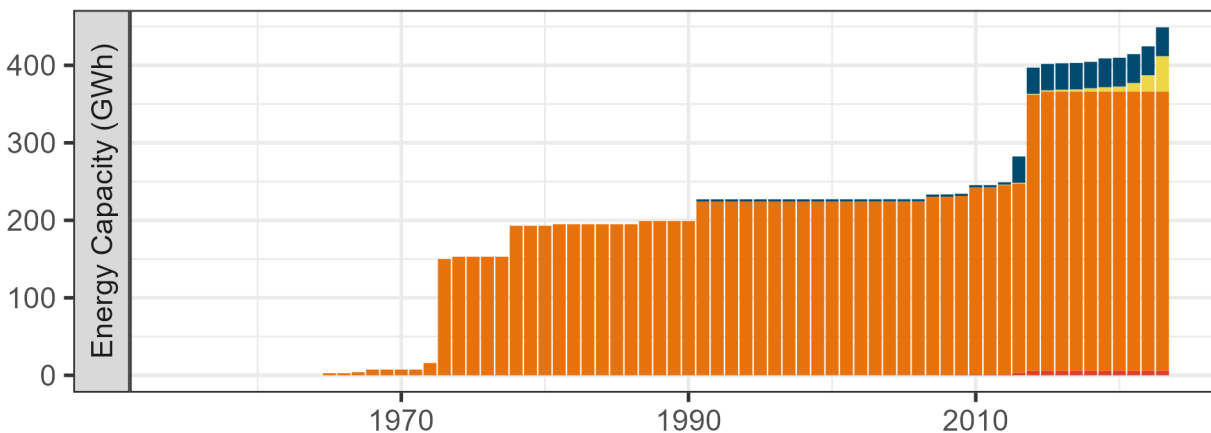
Source: The Challenge of Defining Long-Duration Energy Storage
<https://www.nrel.gov/docs/fy22osti/80583.pdf>

For example, a battery with 1 MW of power capacity and 4 MWh of usable energy capacity will have a storage duration of 4 hours.

Energy Storage in the United States



- Most of our utility-scale storage in the U.S. (and worldwide) is pumped hydro storage
- Batteries are starting to change the game



- U.S. battery capacity is expected to double between 2023 and 2024 (99% Lithium-ion)
- Most battery capacity is in California (>7 GW) but 50% of planned battery capacity is for Texas

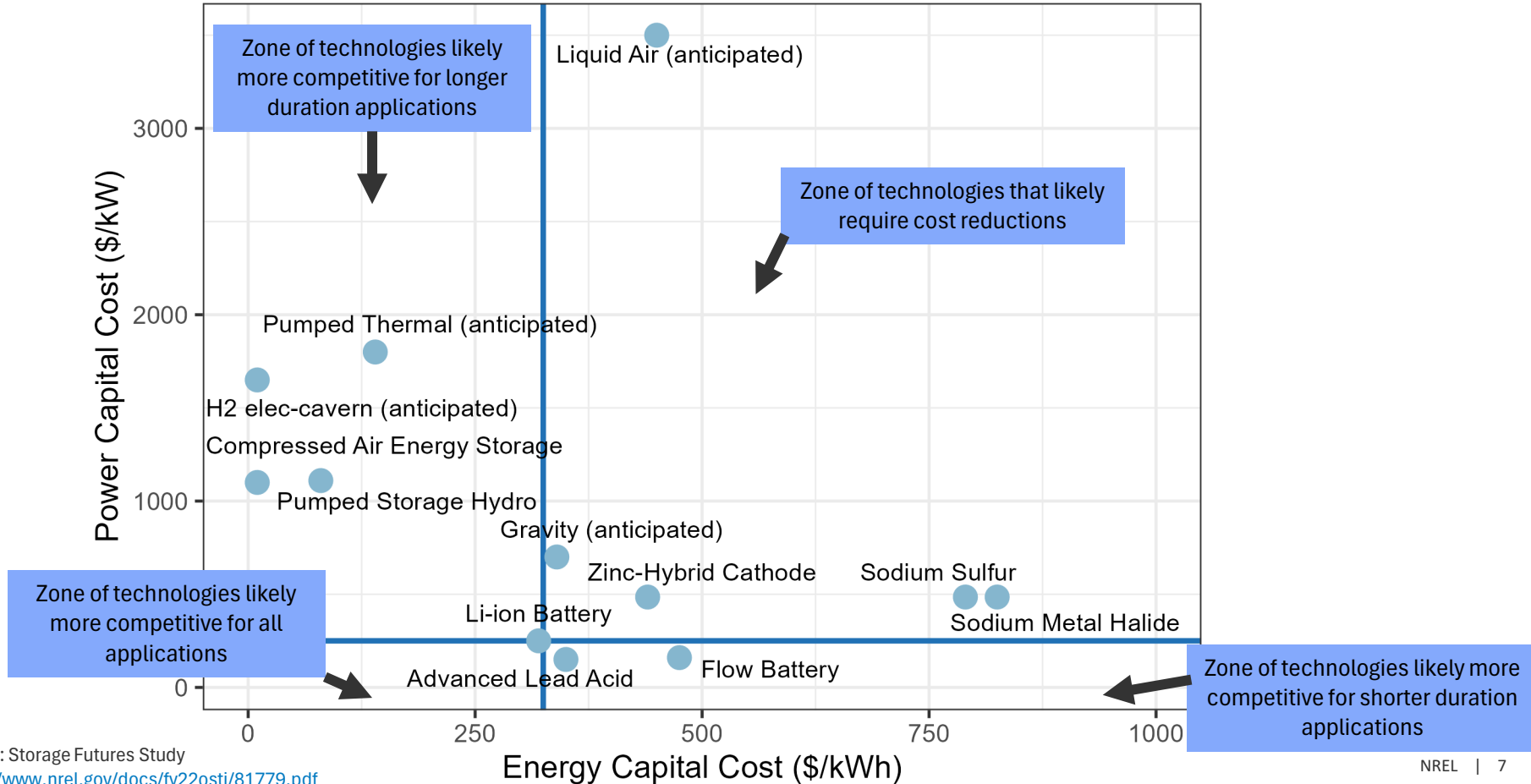
Source: Energy Information Administration (EIA)
<https://www.eia.gov/todayinenergy/detail.php?id=61202>

DOE Global Energy Storage Database
<https://gesdb.sandia.gov/statistics.html>

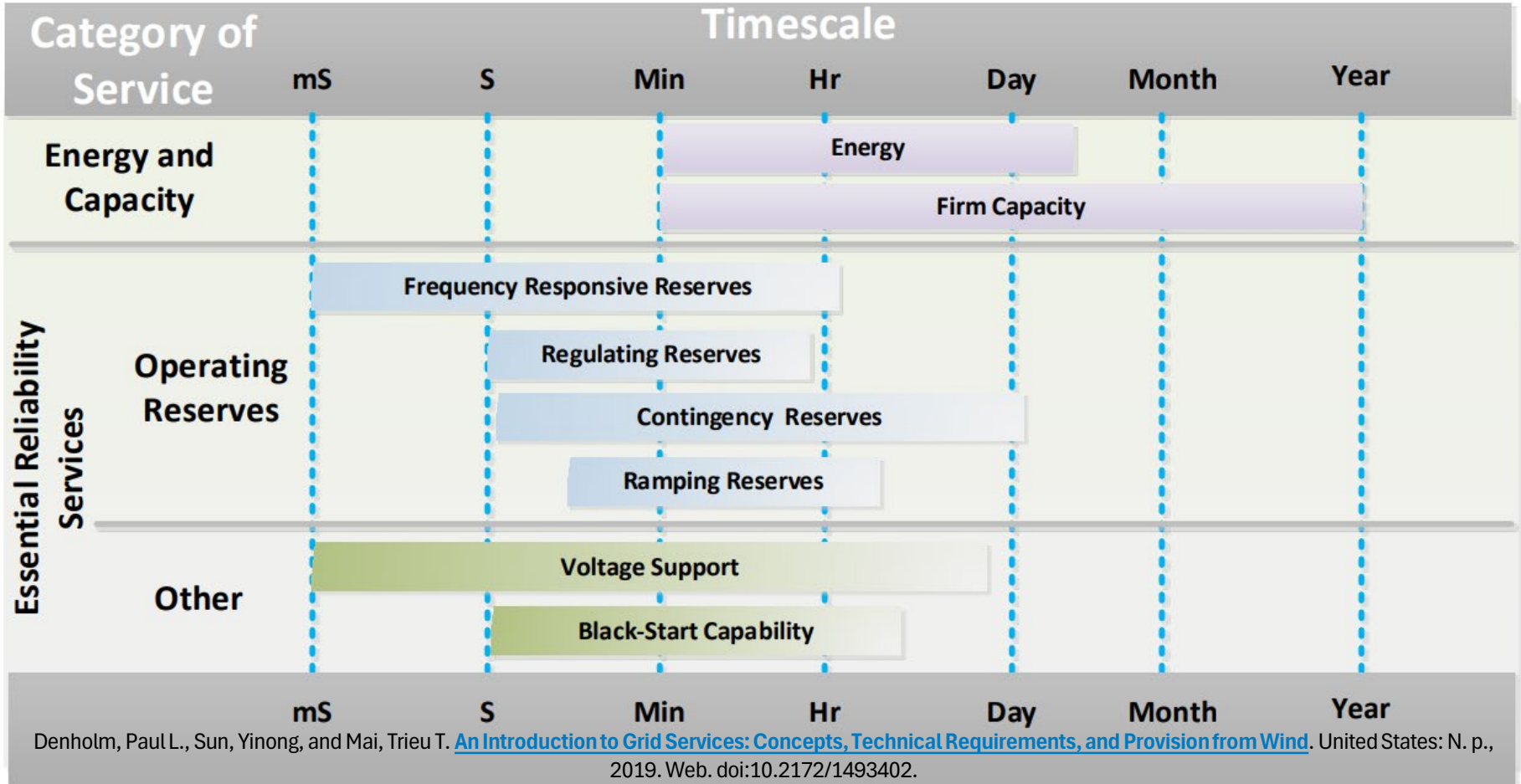
Non-exhaustive list of storage technologies

Technology	Round-trip efficiency	Description	Pros/cons
Lithium-ion Battery	85%	Moves lithium ions between positive and negative electrodes. Movement of ions creates an electrical current. Duration 2-10 hours (or more)	<p>Advantages:</p> <ul style="list-style-type: none"> • Current market leader • Dramatic reductions in cost • Used in transport techs (EVs) <p>Disadvantages:</p> <ul style="list-style-type: none"> • Most current chemistries use cobalt (finite, risky supply chain, unstable) • Degradation, overheating
Compressed air energy storage (CAES)	60-70%	Air is compressed into a chamber (typically underground); later the compressed air is allowed to expand and drive a turbine generator. Duration is 10-100+ hours	<p>Advantages:</p> <ul style="list-style-type: none"> • Mature Technology • Potential for large volumes of low-cost energy storage <p>Disadvantages:</p> <ul style="list-style-type: none"> • High capital cost • Location constrained by geologic suitability
Flow battery	60-70%	Two electrolytes undergo a redox reaction; later the reverse reaction is allowed to proceed, releasing electrical energy. Duration 2-10 hours	<p>Advantages:</p> <ul style="list-style-type: none"> • No geologic siting constraints <p>Disadvantages:</p> <ul style="list-style-type: none"> • High capital cost • Limited demonstrations
Pumped Hydro storage (PHS)	70%	Water is pumped from a lower to a higher elevation; then it is allowed to flow downhill through a turbine generator. Energy is stored as gravitational potential energy. Duration 10+ hours	<p>Advantages:</p> <ul style="list-style-type: none"> • Mature technology • Widespread deployment <p>Disadvantages:</p> <ul style="list-style-type: none"> • Constraints on plant locations, difficult to site
Hydrogen power-to-gas-to-power	40%	Electricity drives the production of hydrogen gas via electrolyzer; later the hydrogen is used to generate electricity in a turbine or fuel cell. Duration 100+ hours	<p>Advantages:</p> <ul style="list-style-type: none"> • Potential for large volumes of low-cost energy storage (seasonal) • Can Use geologic or man-made storage <p>Disadvantages:</p> <ul style="list-style-type: none"> • High Capital cost • Low efficiency • Low technology readiness level, limited demonstrations

Energy Storage Technologies

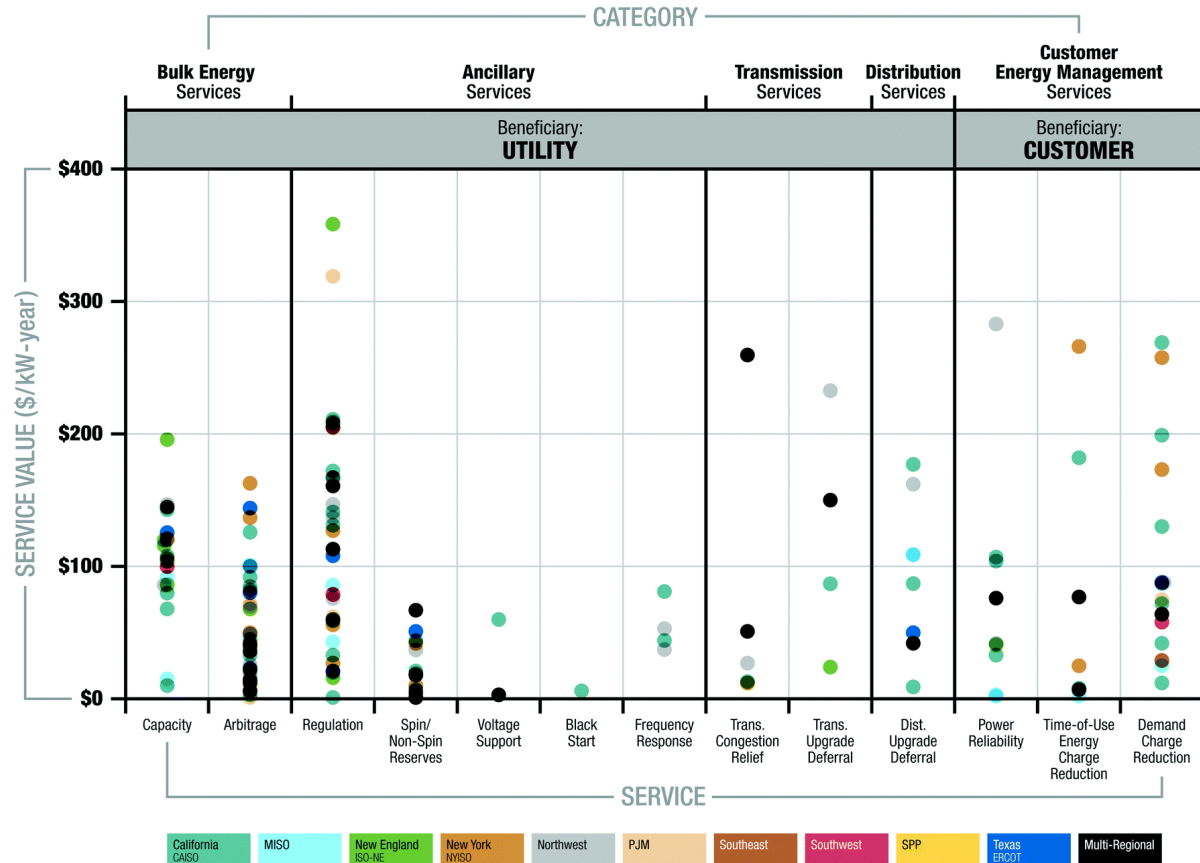


What can we get from storage?



The Value of Energy Storage

Energy Storage Values

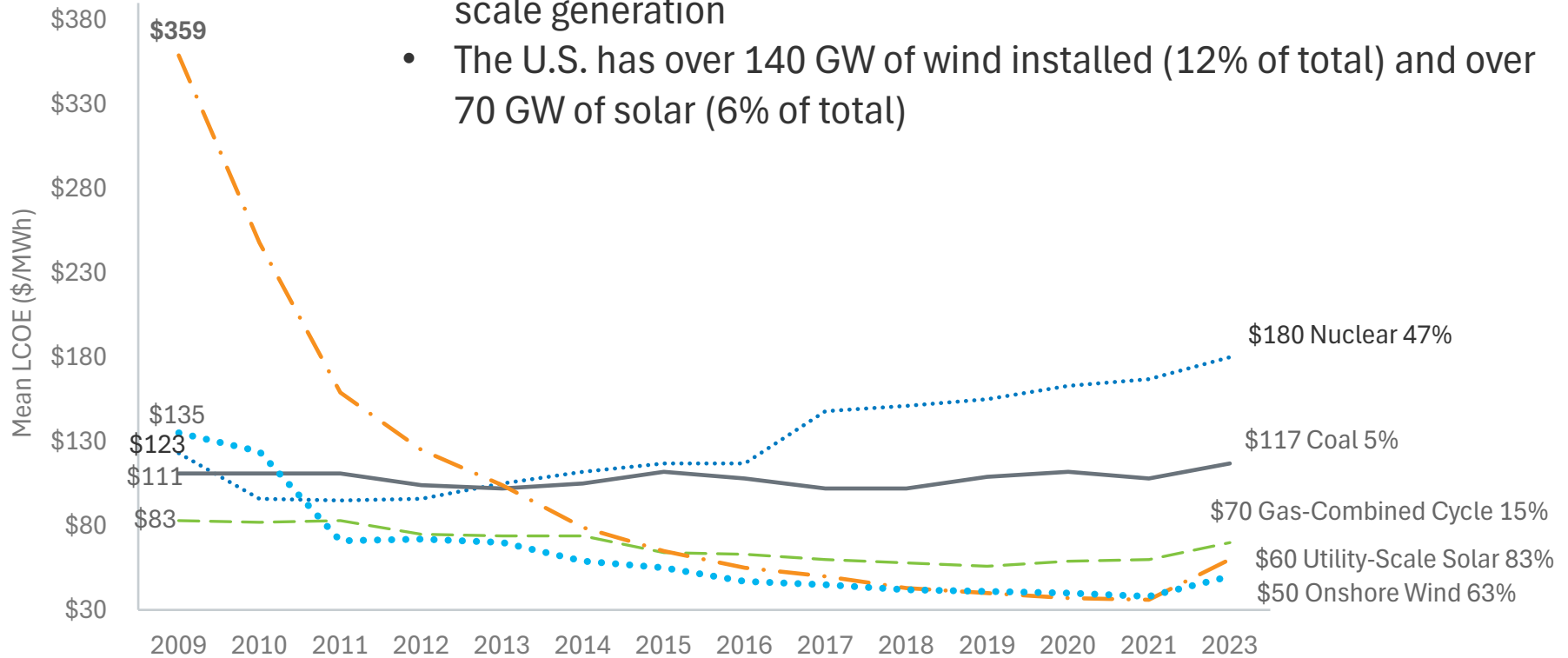


Summary:

- The value of energy storage varies significantly by region and energy storage characteristics, including energy capacities, but the value for regulation (\$1–\$359/kW-year) tends to exceed those for other ancillary services and arbitrage.
- Capacity or resource adequacy: \$10–\$196/kW-year.
- Transmission and distribution (T&D) deferral: \$9–\$233/kW-year.

The cost of renewables are falling too

- In 2023, wind, solar and batteries accounted for 82% of new utility-scale generation
- The U.S. has over 140 GW of wind installed (12% of total) and over 70 GW of solar (6% of total)



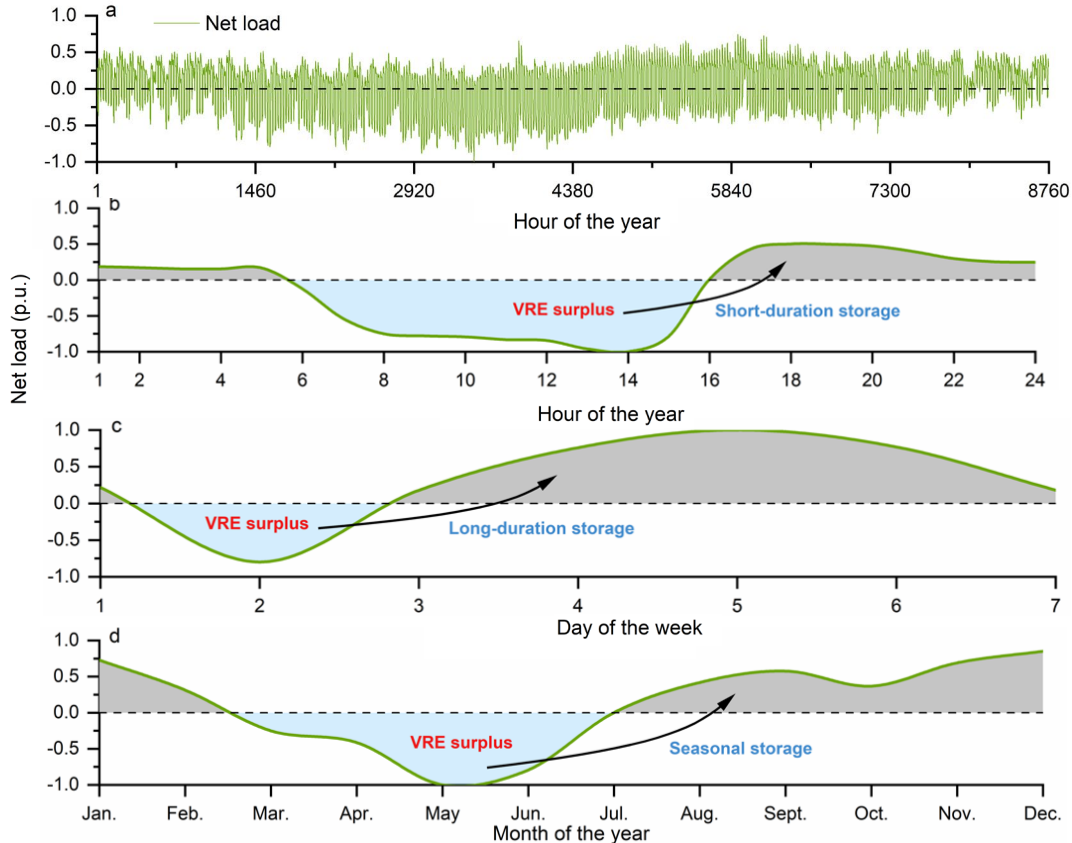
Sources: Lazard's Levelized Cost of Energy Analysis, 2023
EIA: <https://www.eia.gov/todayinenergy/detail.php?id=55719>

Storage plus renewables: addressing the balancing problem?

Multi-scale energy storage needs for 95% carbon-free CAISO power system

(28.4% wind and 51.5% solar PV energy share)

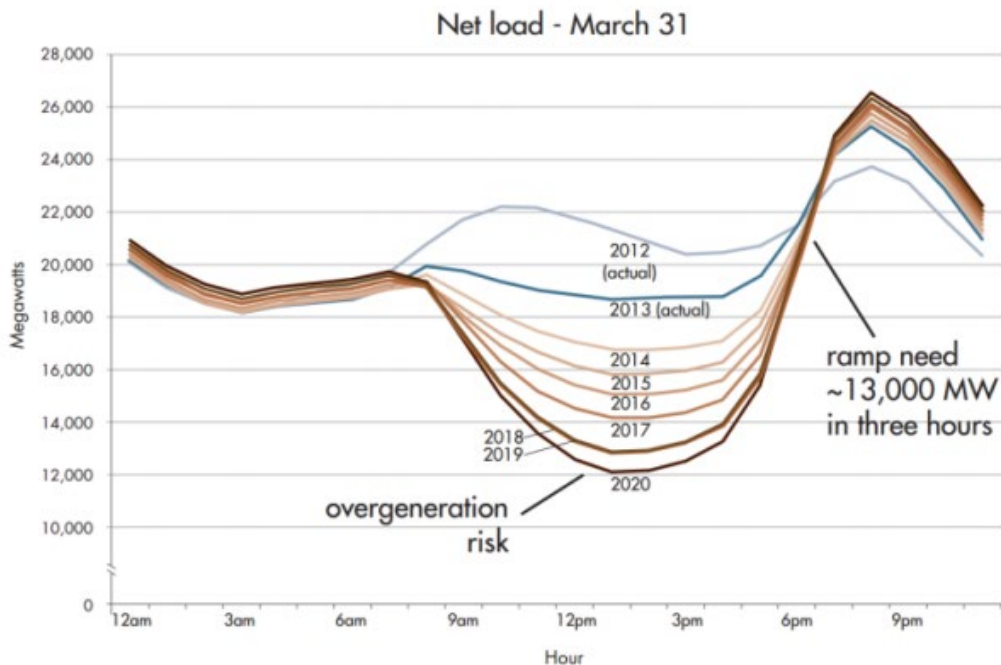
Ref : Guerra, O. J. [Beyond short-duration energy storage](#). Nature Energy 6, 460–461 (2021).



1. The shorter-term fluctuations of VRE resources and the late-afternoon net-load ramps that can occur in systems with significant solar generation (<10 hours of duration).
2. The diurnal mismatch that results from the demand peak typically occurring 4 to 6 h after the solar peak and the tendency of wind to generate more at night in many regions of the United States (10-100 hours of duration)
3. A significant seasonal mismatch among wind, solar, and demand patterns (> 100 hours of duration)

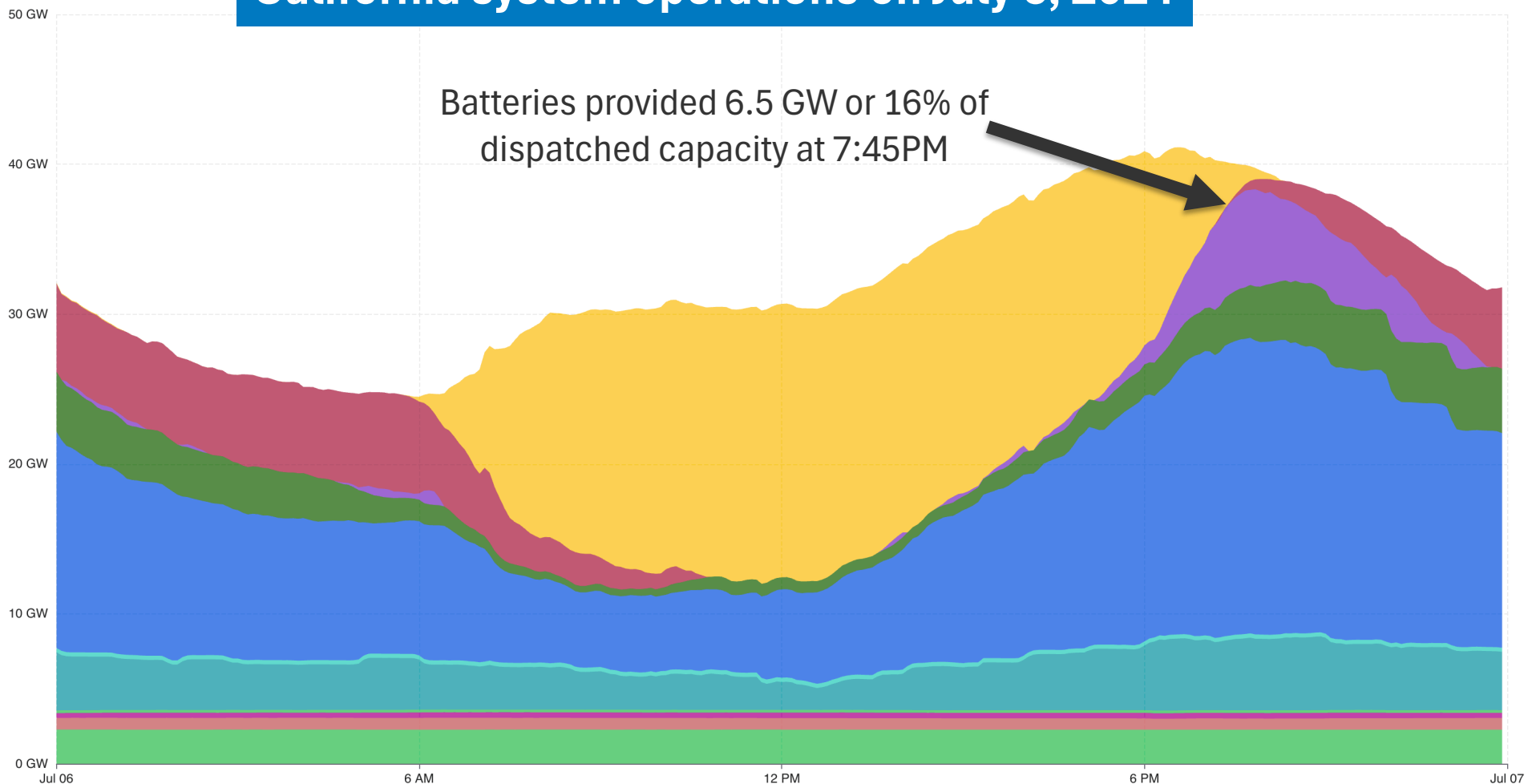
P. Denholm, D.J. Arant, S.F. Baldwin, D.E. Bilello, G.L. Brinkman, J.M. Cochran, et al. [The challenges of achieving a 100% renewable electricity system in the United States](#). Joule, 5 (2021), pp. 1331-1352

Technical challenge: maintaining diurnal balance



- Increased uncertainty in net load
 - More operating reserves to compensate for another ‘unknown’
- Greater variation in net load
- Increased ramp (speed and range)
- More requirements for **grid flexibility**
- “Shorter” system peak? (possibility for synergy with storage)

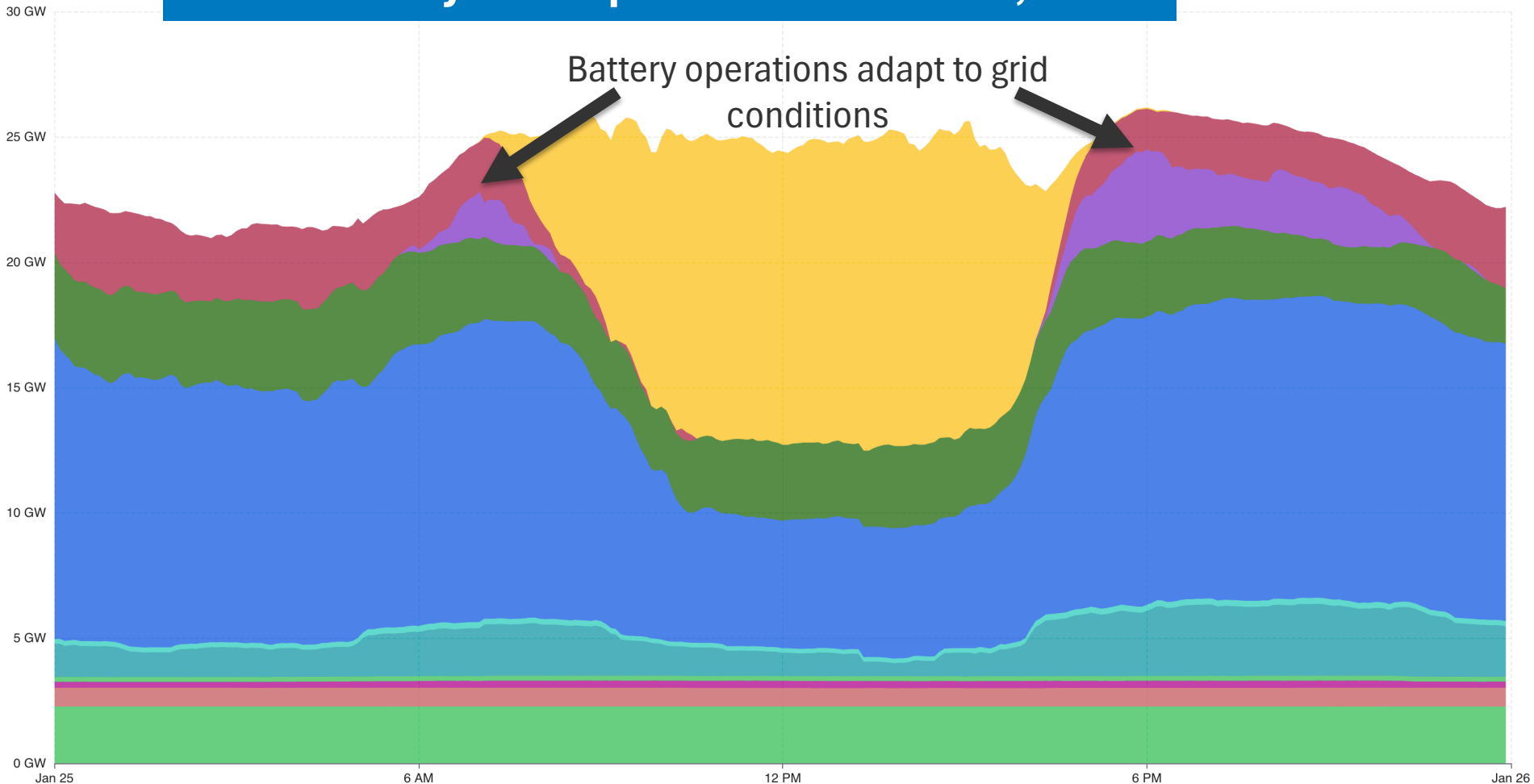
California system operations on July 6, 2024



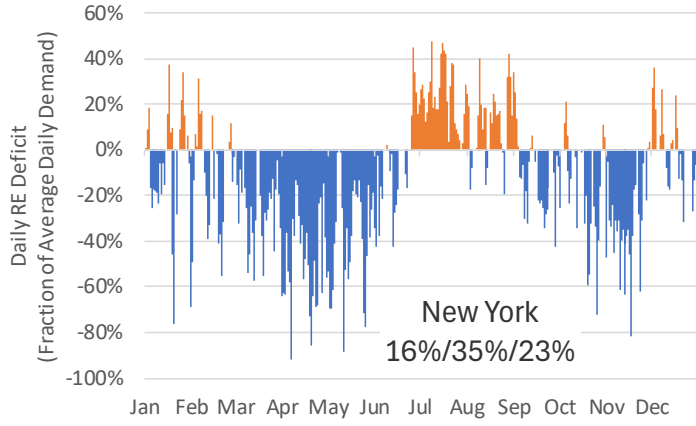
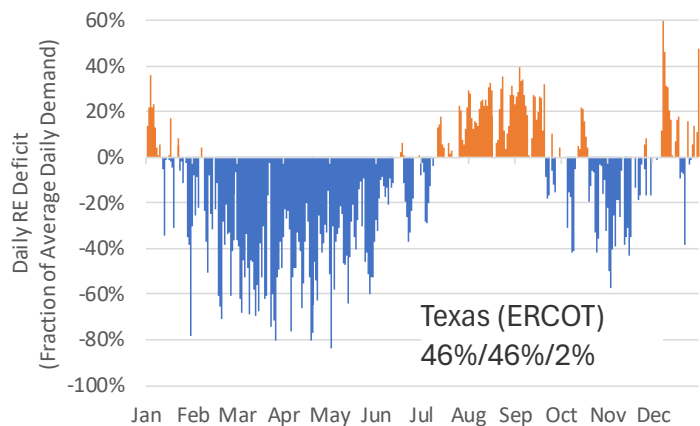
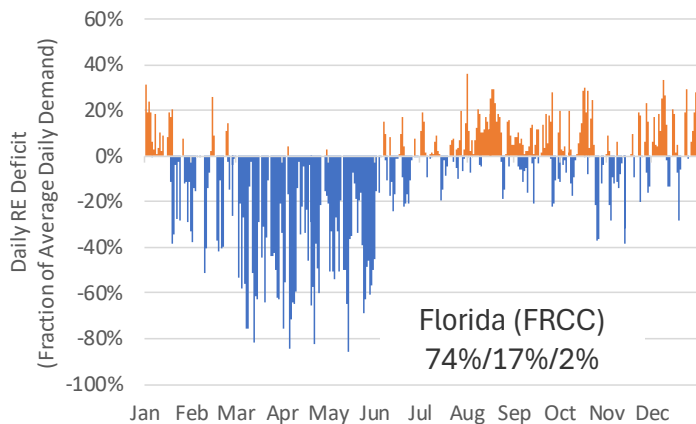
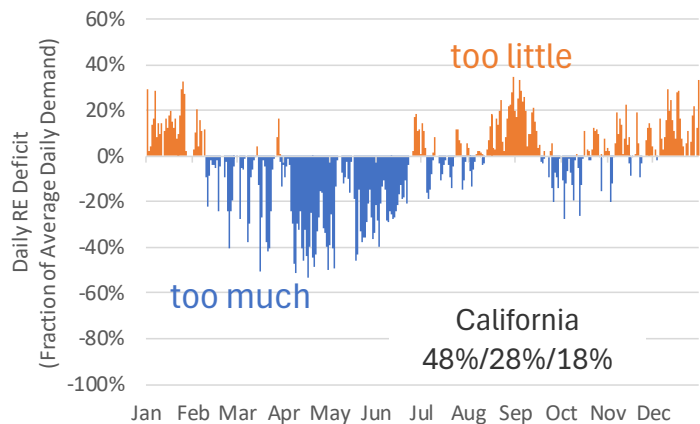
Batteries provided 6.5 GW or 16% of dispatched capacity at 7:45PM



California system operations on Jan 25, 2024



Technical challenge: the seasonal mismatch problem



Hypothetical scenario in which each region meets 95% of annual demand with RE (PV/wind/other RE).

How much can be curtailed to still be cost effective?

What can cost-effectively fill the gaps? This is not a problem that can be addressed short-/long-duration batteries (probably)

Source: [Denholm et al, Joule 2021](#)

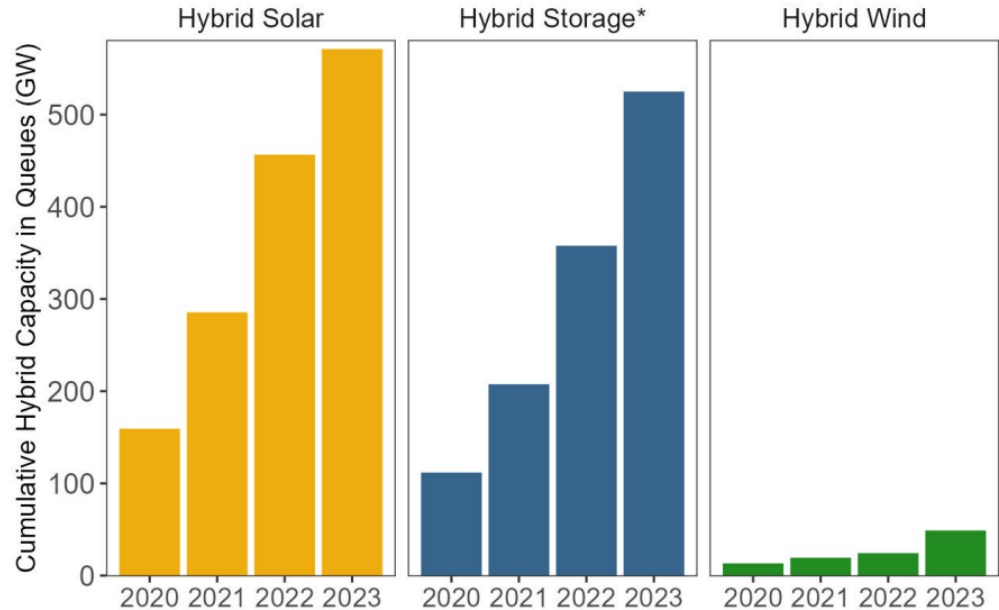
The Four Phases of Storage Deployment (U.S. electricity system)

Table ES-1. Summary of the Four Phases of Storage Deployment

Phase	Primary Services	National Deployment Potential (Capacity) in Each Phase	Duration	Response Speed
Deployment prior to 2010	Peaking capacity, energy time-shifting and operating reserves	23 GW of PSH	Mostly 8–12 hr	Varies
1	Operating reserves	<30 GW	<1 hr	Milliseconds to seconds
2	Peaking capacity	30–100 GW, strongly linked to PV deployment	2–6 hr	Minutes
3	Diurnal capacity and energy time shifting	100+ GW. Depends on both on Phase 2 and deployment of VRE resources	4–12 hr	Minutes
4	Multiday to seasonal capacity and energy time-shifting	Zero to more than 250 GW	>12 hr	Minutes

Hybrid Projects: Battery Storage with other Technologies

- Co-location can provide 7-8% cost savings by reducing costs related to site preparation, land acquisition, permitting, interconnection, etc.
- There may be trade-offs for the system performance and flexibility depending on the technical configuration
- Hybrids comprise over half of active solar capacity (and storage capacity) in interconnection queues according to recent LBNL analysis



- **Solar Hybrids** include: Solar+Storage (548 GW), Solar+Wind (0.2 GW), Solar+Wind+Storage (12 GW)
- **Wind Hybrids** include: Wind+Storage (35 GW), Wind+Solar (0.2 GW), Wind+Solar+Storage (13 GW)
- **Storage Hybrids** may be paired with any generator type; most are paired with solar
- **Gas Hybrids** include: Gas+Solar+Storage (10 GW) [not shown above]

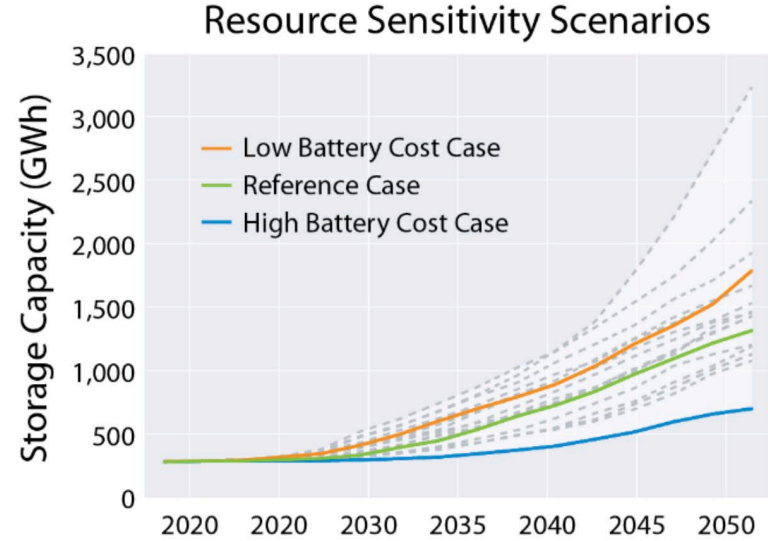
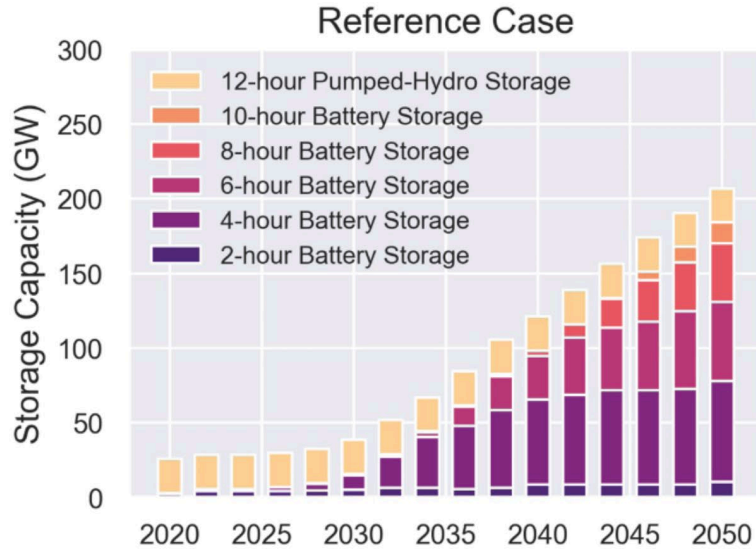
Sources: <https://www.nrel.gov/docs/fy19osti/71714.pdf>

Queued up: 2024 Edition, Lawrence Berkeley National Laboratory

https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_R2.pdf

Large Storage Growth Projected – NREL’s Storage Futures Study

- 100 – 650 GW in 2050, or 5X today’s capacity
- Driven by storage costs, natural gas prices, renewable energy cost



Conclusions

1. Storage is cost-competitive for provision of several essential reliability services, but with limited market size.
2. Battery storage is starting to change the landscape of bulk-scale storage on the U.S. electricity grid
3. When properly scheduled, long-duration (several hours of capacity) batteries provide an alternative to combustion turbines for meeting peak capacity requirements.
4. We are approaching a “tipping point” where storage provides a cost-effective alternative to conventional peaking capacity.
5. Renewable plus storage plants are also increasingly cost competitive. Renewables can help accelerate the storage tipping point and increase the overall market size.



Thank You

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