NREL Transforming ENERGY

Storage Futures Study: Four Phases Framework and Modeling

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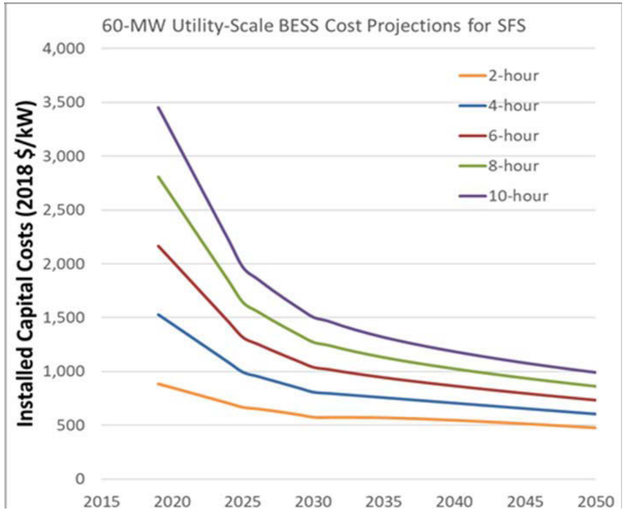
Storage Futures Study

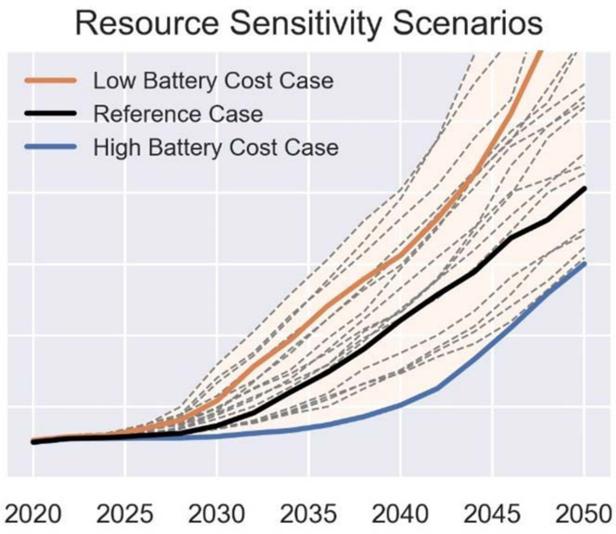
NREL is analyzing the rapidly increasing role of energy storage in the electrical grid through 2050.

- “Four Phases” - theoretical framework driving storage deployment
- Techno-Economic Analysis of Storage Technologies
- Deep dive on future costs of distributed and grid batteries
- Various cost-driven grid scenarios to 2050
- Distributed PV + storage adoption analysis
- Grid operational modeling of high-levels of storage

One Key Conclusion: Under all scenarios, dramatic growth in grid energy storage is the least cost option.

https://www.nrel.gov/analysis/storage-futures.html





SFS: Planned reports and discussed reports today

✓ = discussed today

✓ **The Four Phases of Storage Deployment:** This report examines the framework developed around energy storage deployment and value in the electrical grid.

Storage Technology Modeling Input Data Report : A report on a broad set of storage technologies along with current and future costs for all modeled storage technologies including batteries, CSP, and pumped hydropower storage.

✓ **Grid-Scale Diurnal Storage Scenarios :** A report on the various future capacity expansion scenarios and results developed through this project. These scenarios are modeled in the ReEDS model.

Distributed Storage Adoption Scenarios (Technical Report): A report on the various future distributed storage capacity adoption scenarios and results and implications. These scenarios reflect significant model development and analysis in the dGen model.

Grid Operational Impacts of Storage (Technical Report): A report on the operational characteristics of energy storage, validation of ReEDS scenarioson capturing value streams for energy storage as well as impacts of seasonal storage on grid operations. Released late 2021

Key Learnings Summary: A final summary report that draws on the prior reports and related literature, generates key conclusions and summarizes the entire activity. Released late 2021

All reports are or will be linked to the SFS website: https://www.nrel.gov/analysis/storage-futures.html

Four Phases: A Visionary Framework

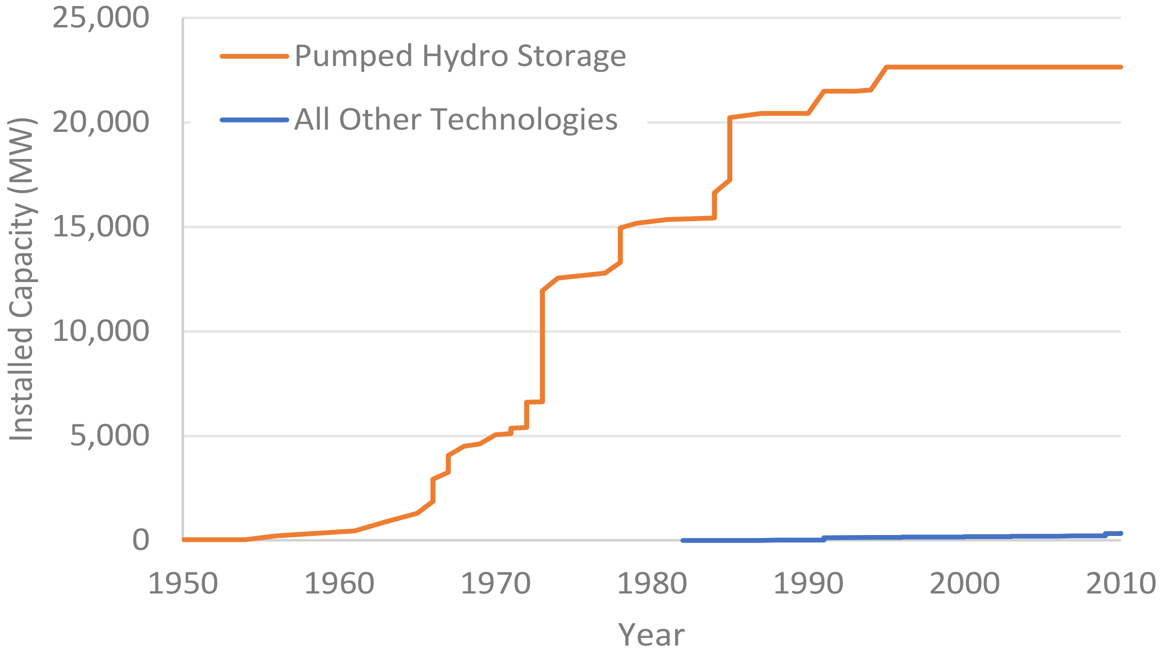
- The Four Phases report synthesizes a large body of work into a straightforward *narrative* framework we anticipate will be helpful to stakeholders.
- The important conclusions are the trends and the drivers of deployment rather than the specific quantities and timing.

The Four Phases of Storage Deployment

Phase	Primary Service	National Potential in Each Phase	Duration	Response Speed
Deployment prior to 2010	Peaking capacity, energy time shifting and operating reserves	23 GW of pumped hydro storage	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 variable generation resources	4–12 hr	Minutes
4	Multiday to seasonal capacity and energy time shifting	Zero to more than 250 GW	Days to months	Minutes

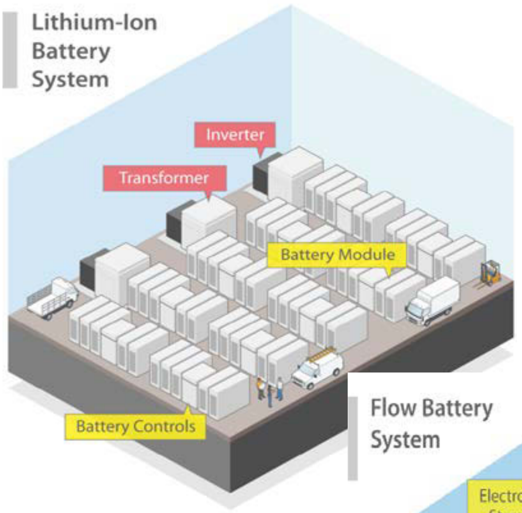
While the Phases are roughly sequential there is considerable overlap and uncertainty!

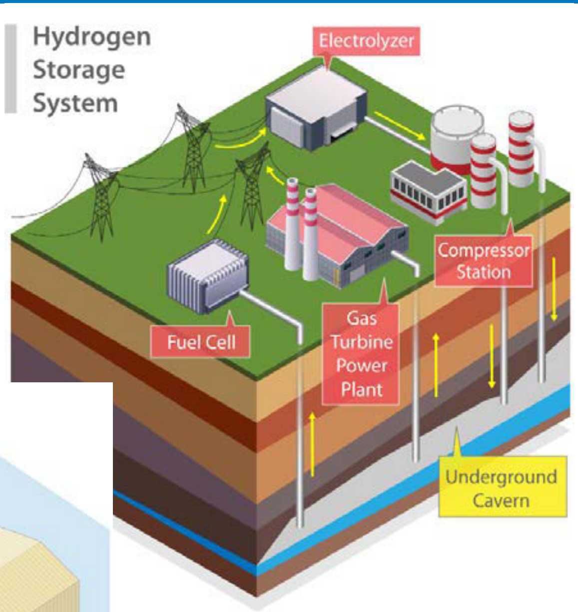
US Historical Deployment



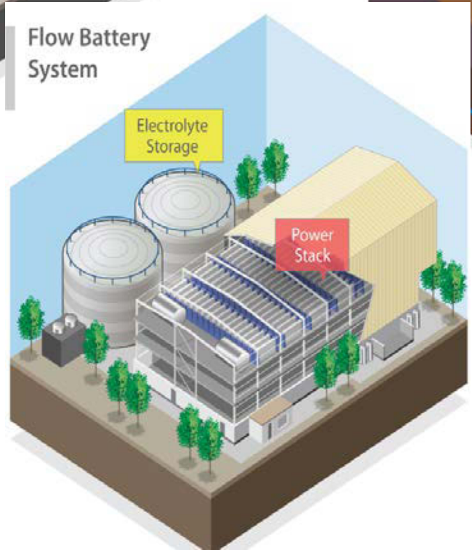
Pumped storage continues to play an important role, and there are likely new opportunities for additional deployments

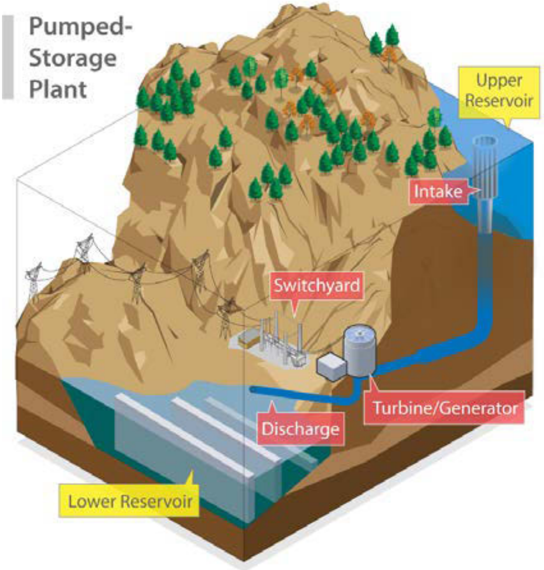
Framework: Power vs Energy



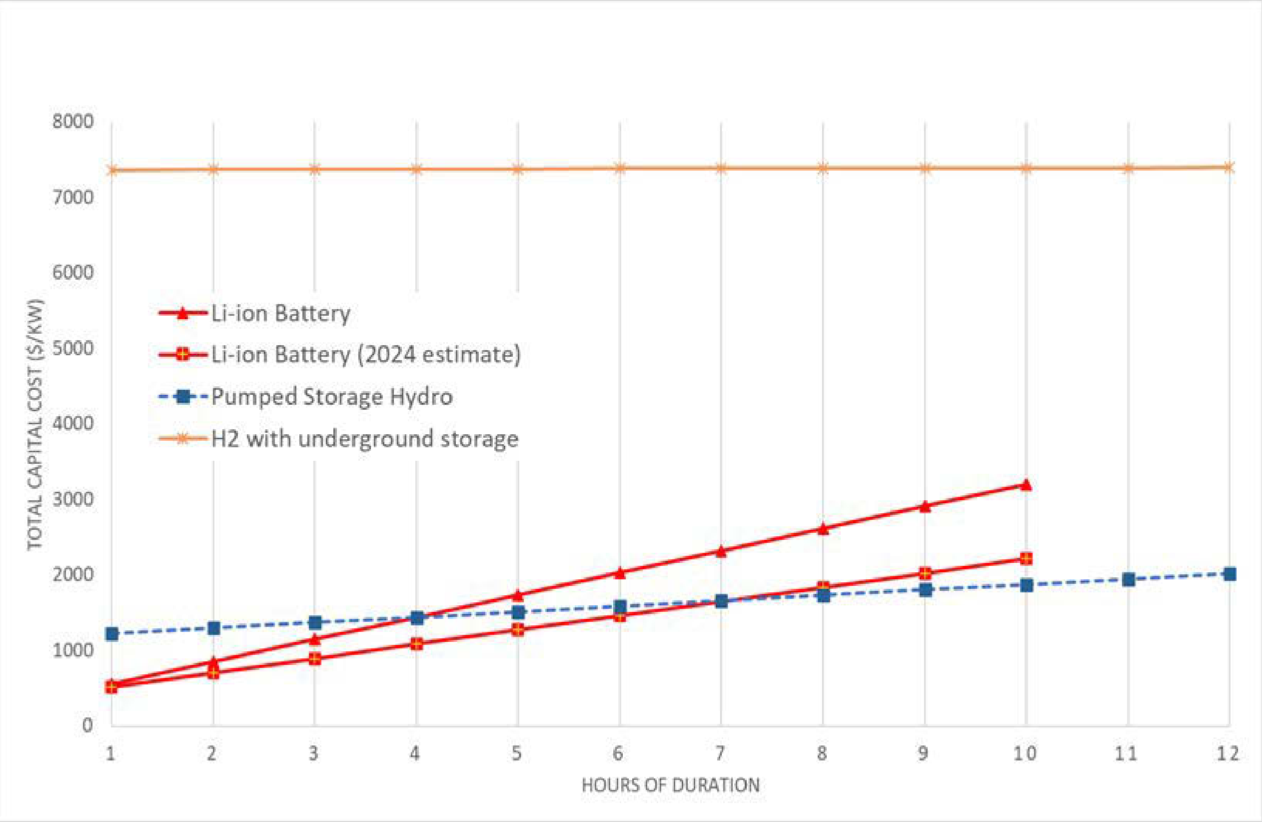


Power-related components are annotated in red and energy components in yellow. Images are not to scale



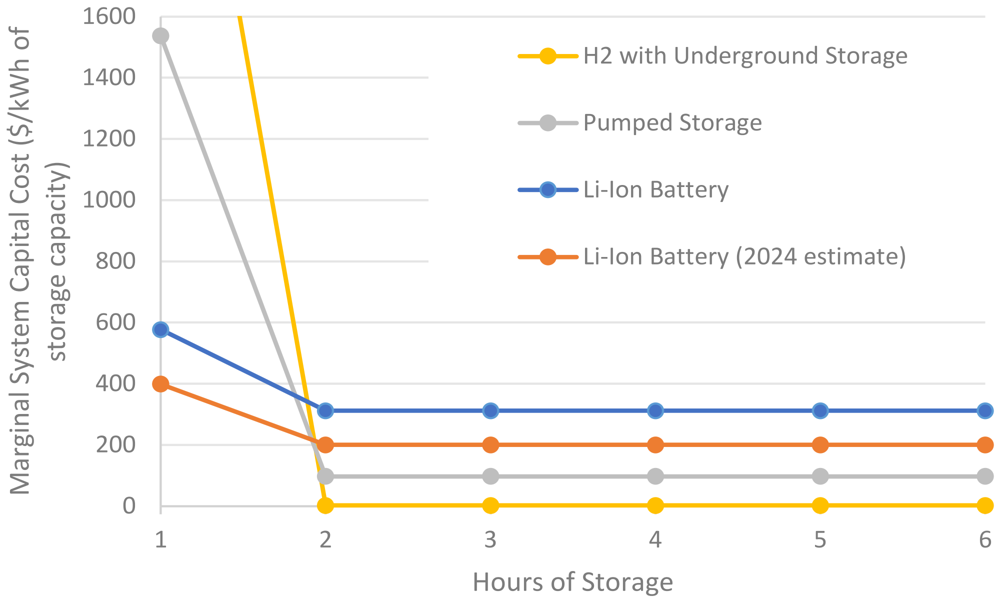


Valuation Framework: Costs



Simplified relationship between capital cost of energy storage and duration using 2020 cost estimates

Valuation Framework: Marginal Cost



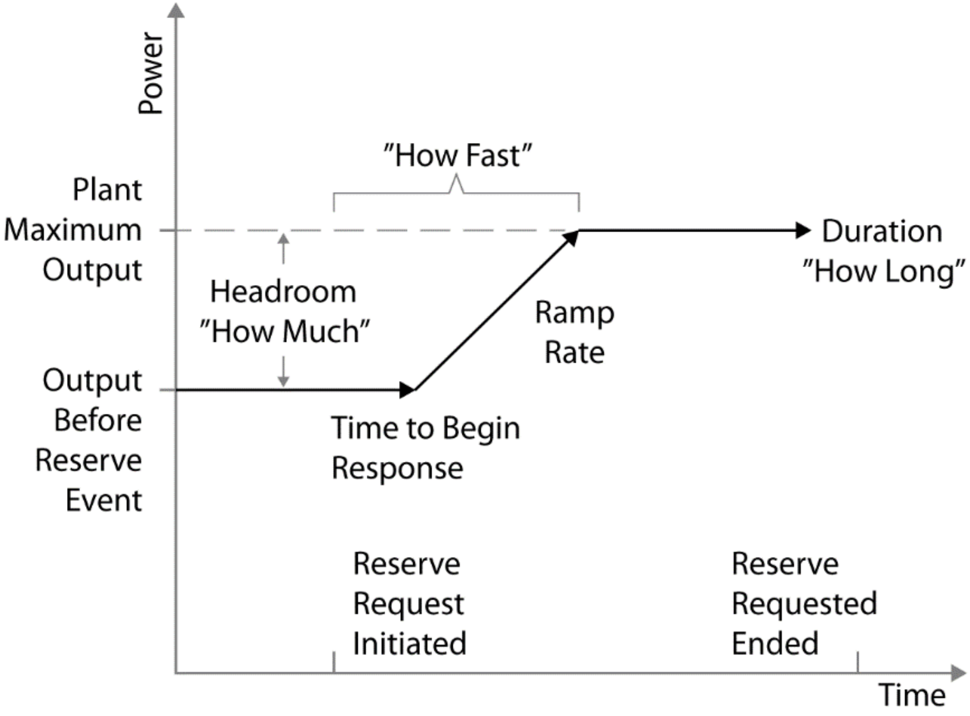
Simplified relationship between capital cost of energy storage and duration using 2020 cost estimates - incremental

Services

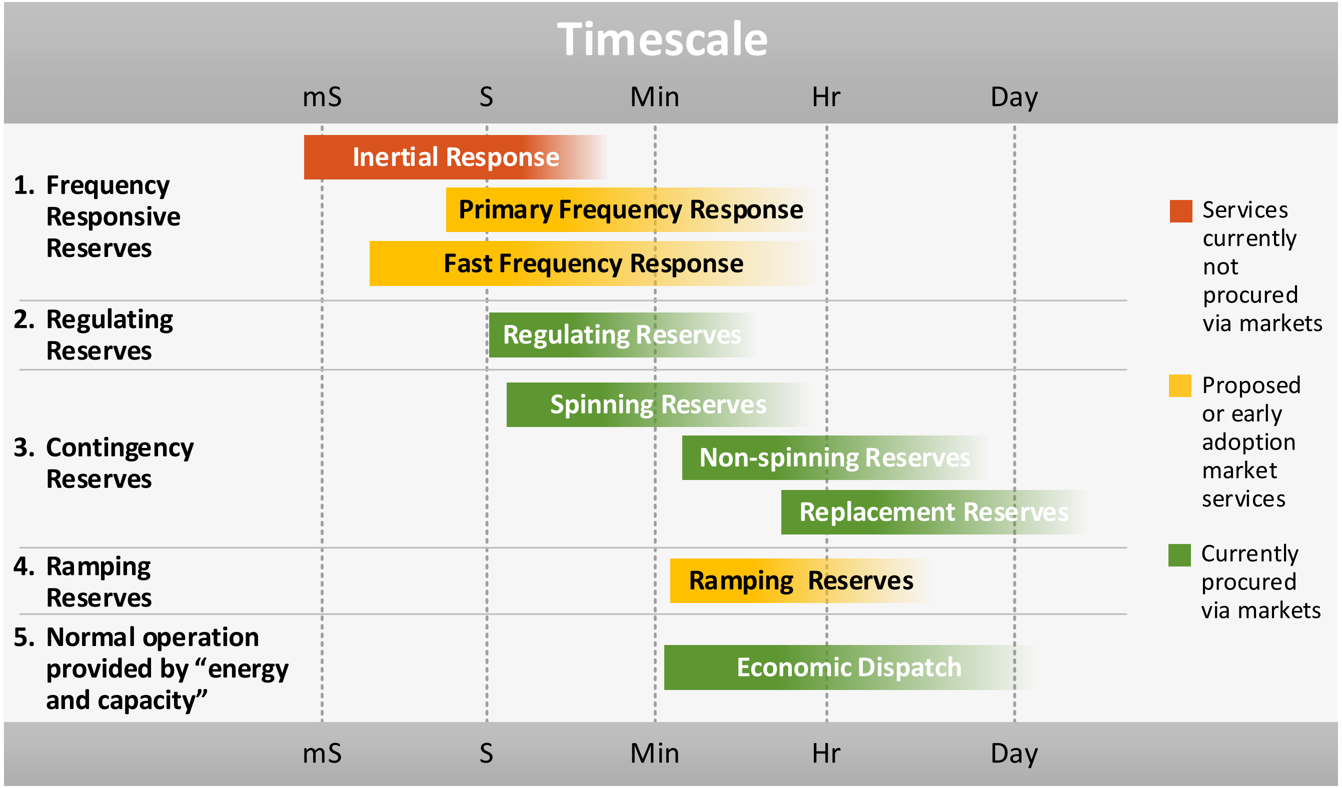
Four Major Categories of Bulk Power System Storage Services

Service	Description
Capacity	Firm capacity
Energy	Energy shifting/dispatch efficiency/avoided curtailment
Transmission	Avoided capacity, congestion relief
Ancillary services	Operating reserves, voltage support

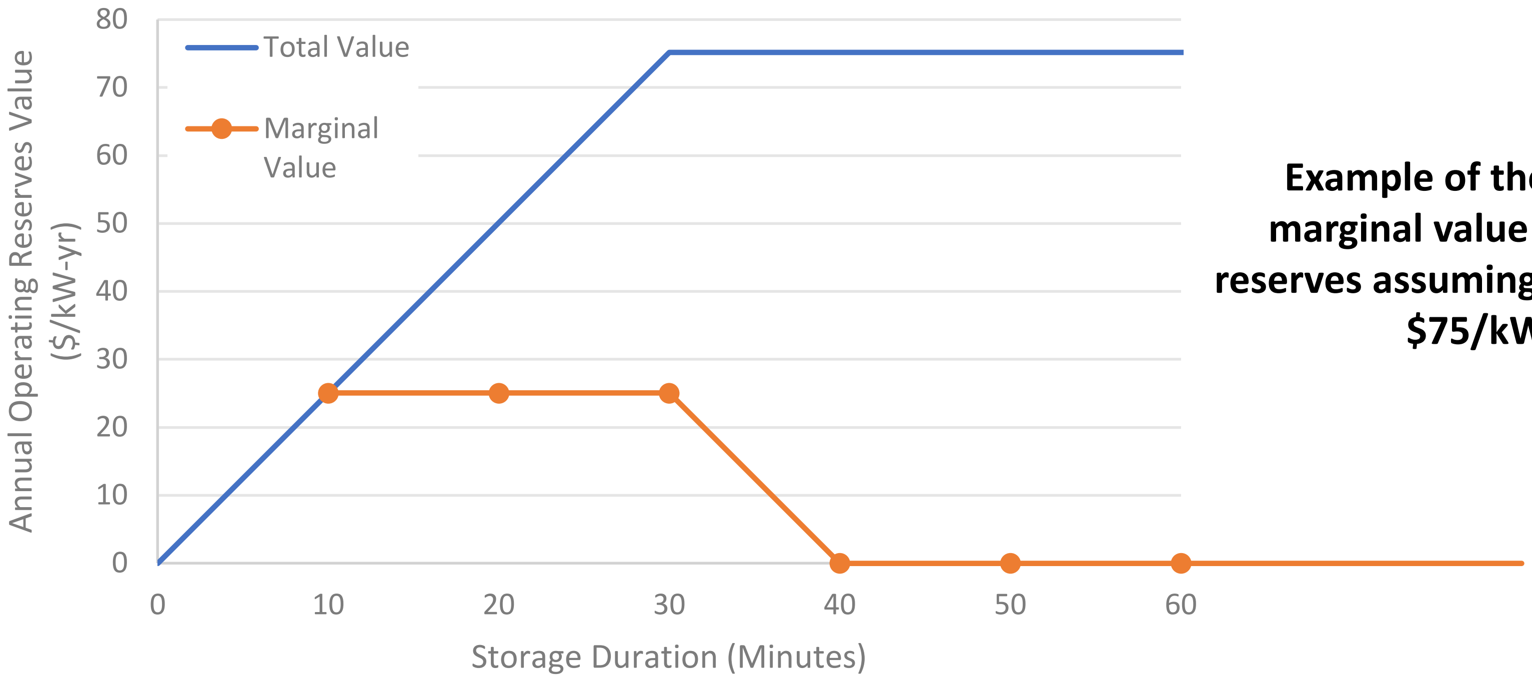
Phase 1: Short-Duration Storage for Operating Reserves



Reserve Types

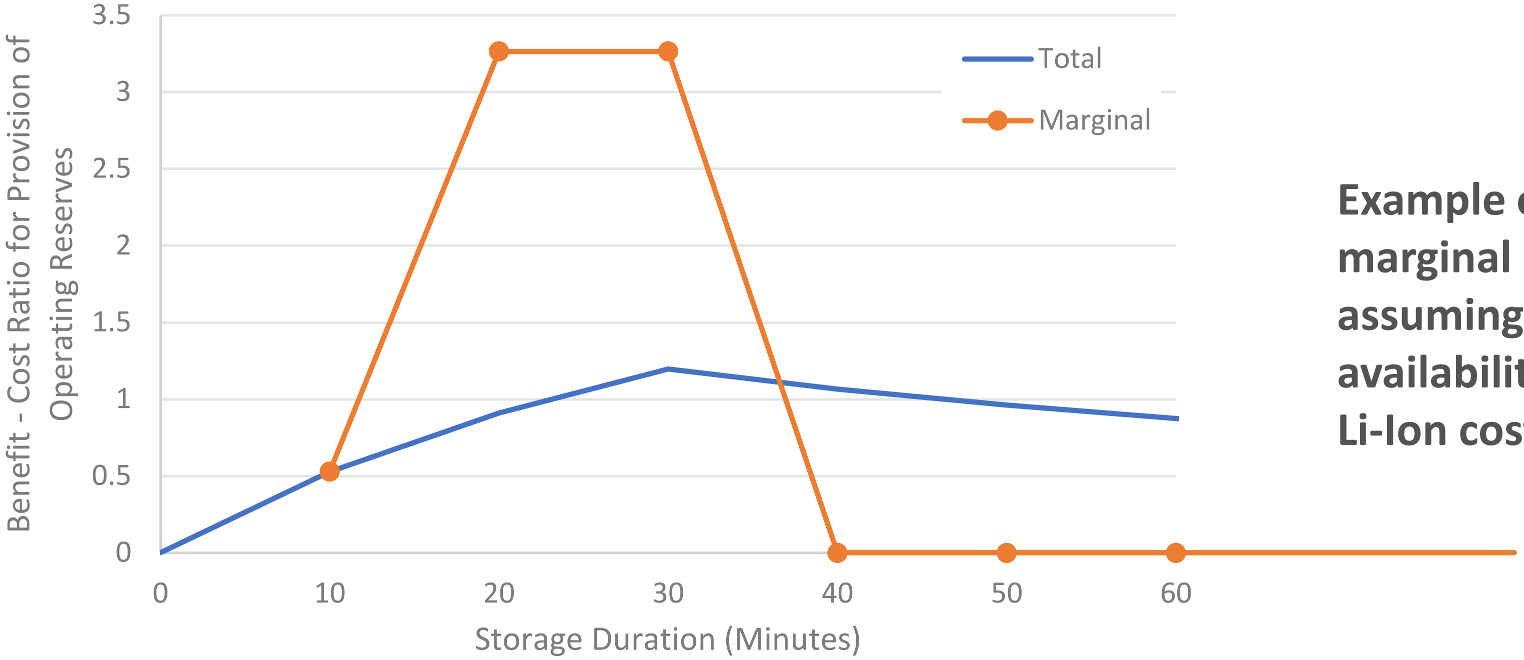


Example Value



Example of the total and marginal value of spinning reserves assuming tariff value of $75/kW-yr

Example Benefit/Cost Ratio



Example of total and marginal B/C ratio assuming 90% battery availability and 2020 Li-Ion cost estimates

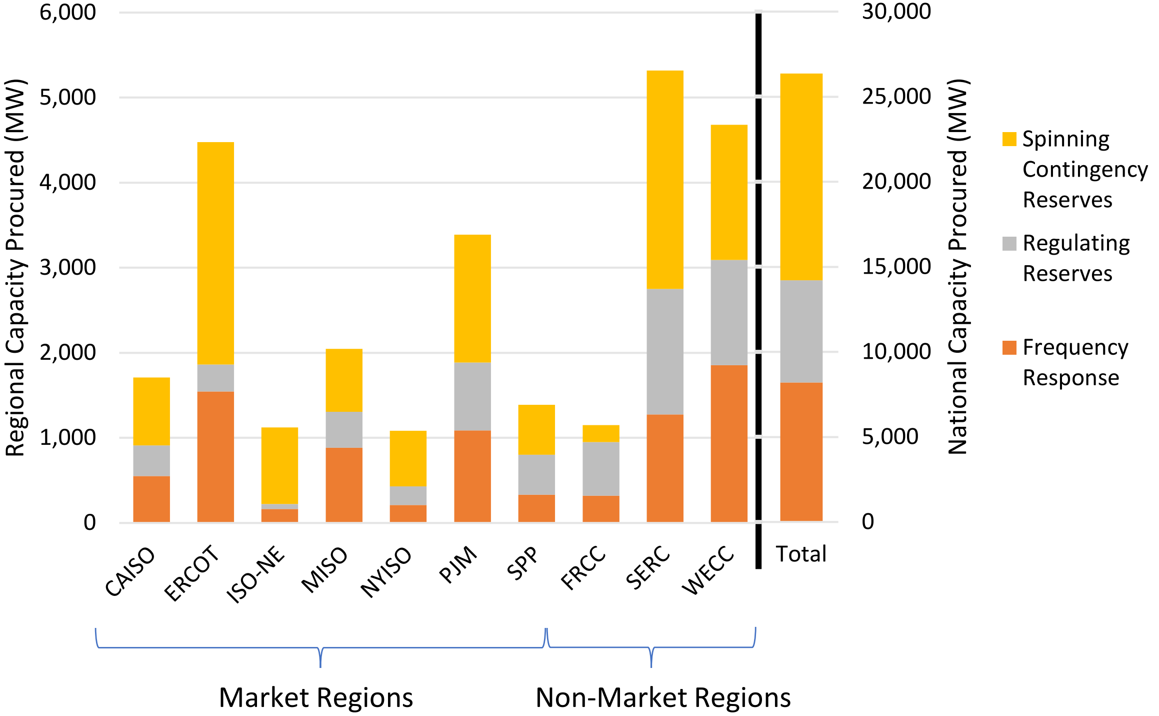
Phase 1: Short-Duration Storage for Operating Reserves

Phase 1 Utility-Scale (>0.5 MW) Storage Deployment with 1 hour or less capacity, 2011–2019

Region	Deployment (MW)
Alaska & Hawaii	27
California	139
Non-CAISO Western Interconnection	29
Texas	108
PJM	182
New York & New England	66
Other Regions in the Eastern Interconnection	171
Total	721

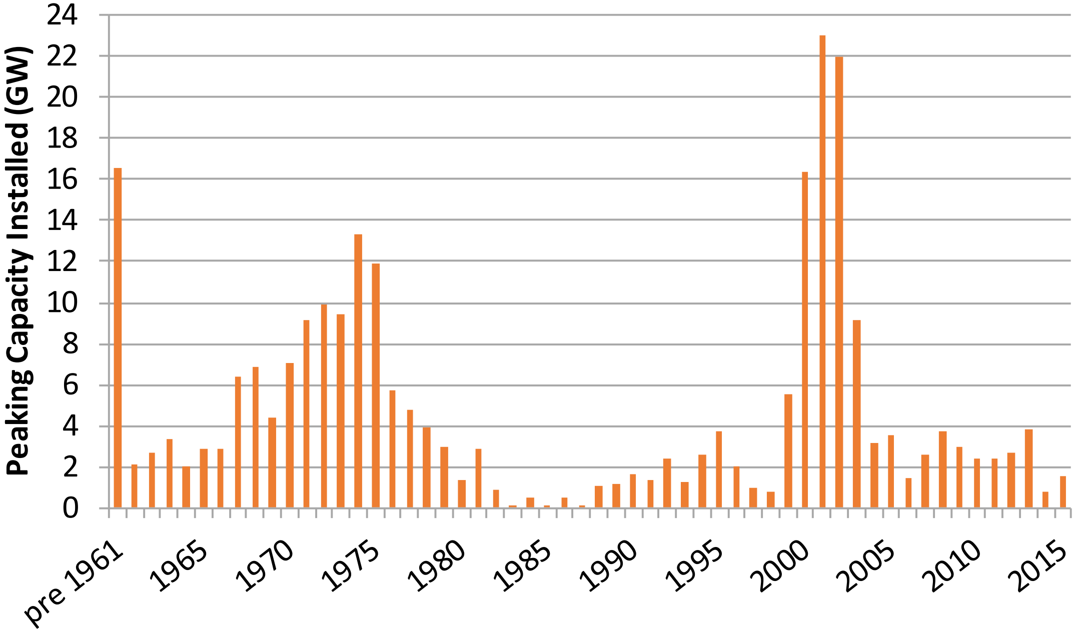
Capacity includes 656 MW of Li-ion batteries, 47 MW of flywheels, and 18 MW of other battery types.

Limits to Phase 1



Current U.S. grid requirements for high-value operating reserve products potentially served by energy storage in Phase 1

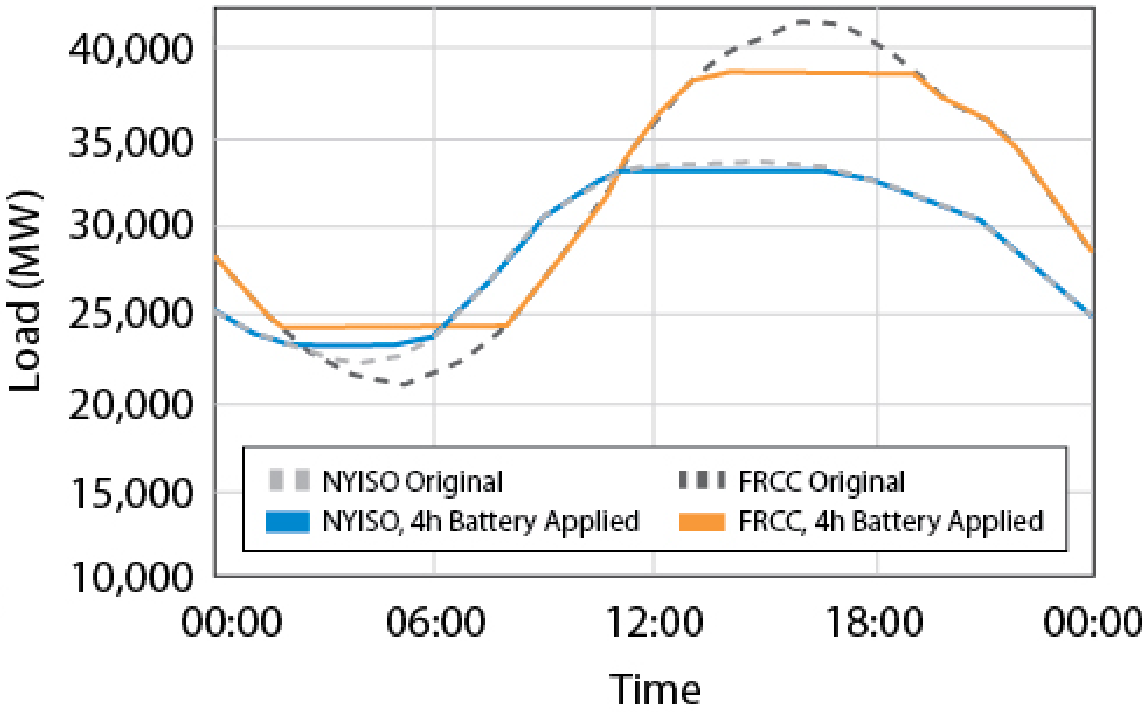
Phase 2: The Rise of Battery Peaking Plants



Over the next 20 years, we would expect about 150 GW of peaking capacity to retire

Installation dates of U.S. peaking capacity (non-combined Heat and Power, Combustion Turbines, Internal Combustion, oil/gas steam) (EIA 860)

Key Issue: Duration Required to Reliably Decrease Net Peak



NYISO = New York Independent System Operator FRCC= Florida Reliability Coordinating Council

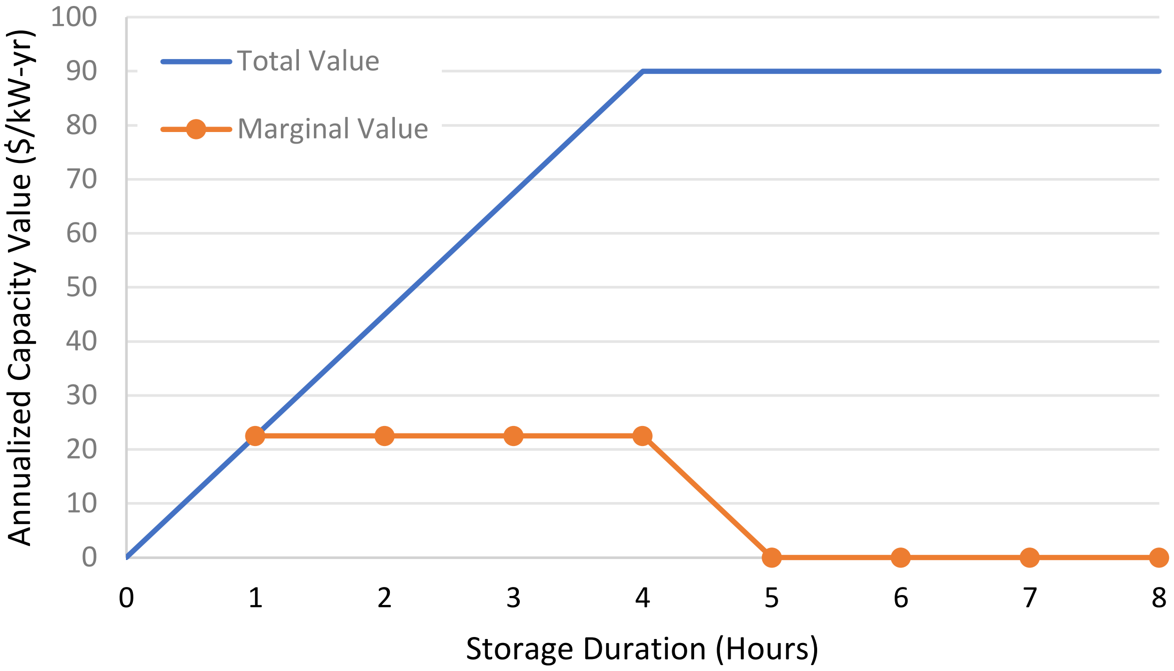
Duration Requirements

Regional Energy Storage Duration Requirements in response to FERC 841

Market Operator	Duration Minimum (hours)
ISO-NE	2
CAISO	4
NYISO	4
SPP	4
MISO	4
PJM	10

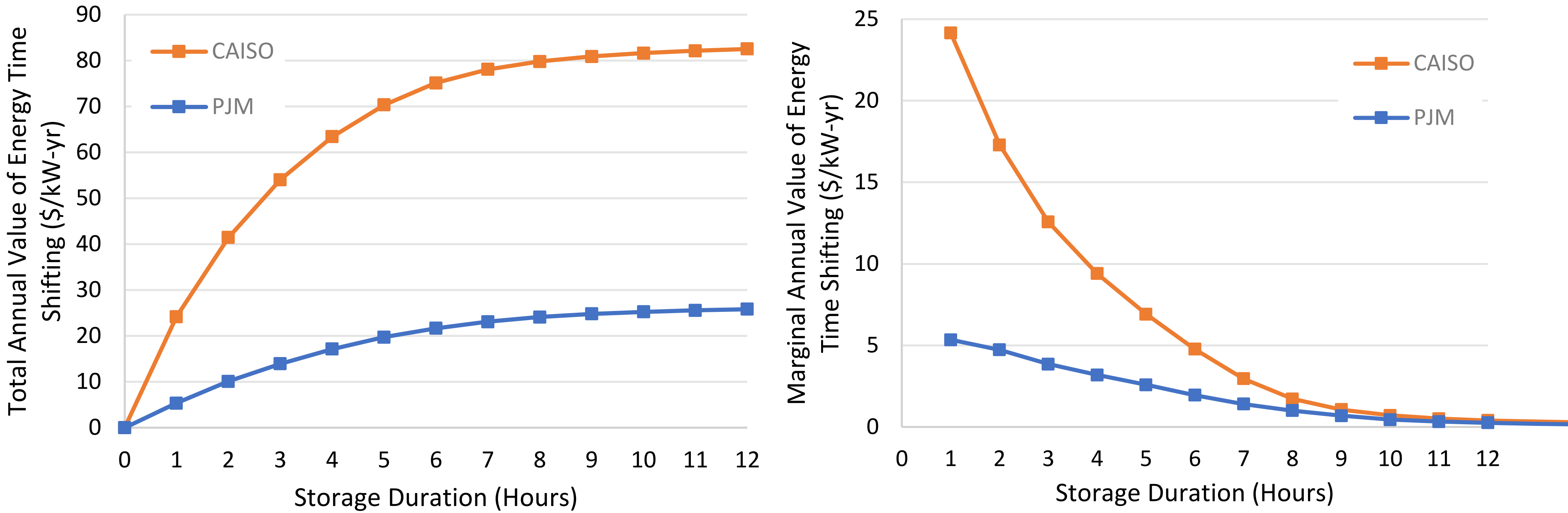
[1] PJM is in the process of updating this value based on an effective load carrying capability calculation. ("PJM Interconnection L.L.C., Docket No. ER21-278-000 Effective Load Carrying Capability Construct," PJM, October 30, 2020, https://www.pjm.com/directory/etariff/FercDockets/5832/20201030-er21-278-000.pdf.)
FERC 841 https://www.ferc.gov/media/order-no-841

Capacity Value as a Function of Duration



Value of storage providing capacity, assuming a 4-hour duration requirement and a $90/kW-yr capacity payment

Energy Shifting Value

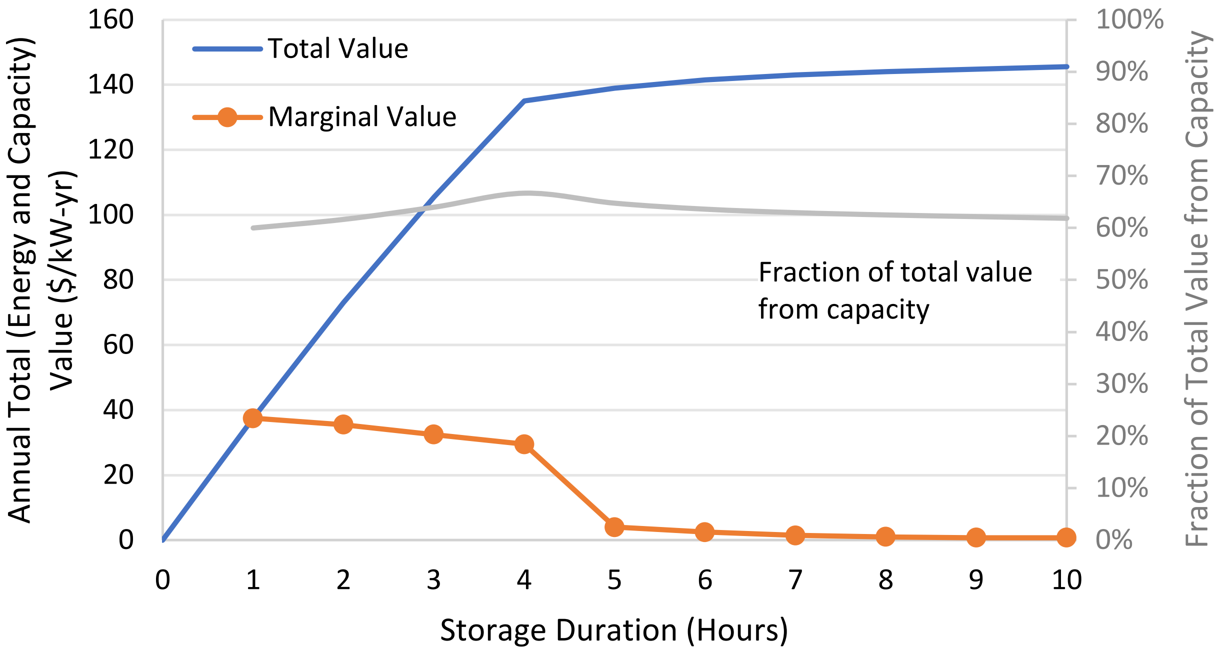


(a) Total value

(b) Marginal value

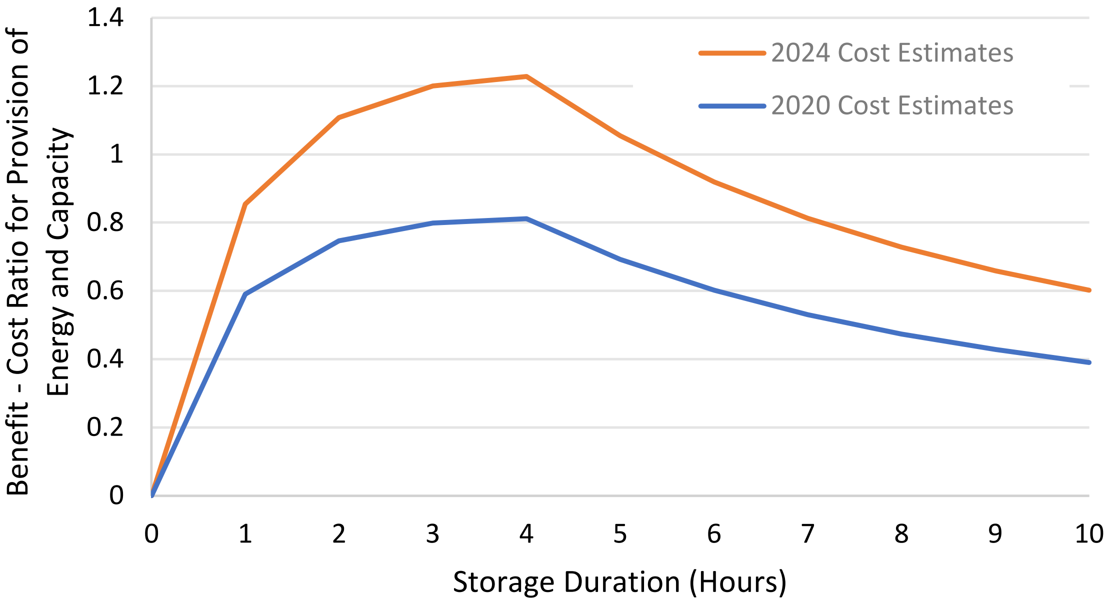
Example of the total and marginal value of energy time-shifting using 2019 energy market values

Total Value



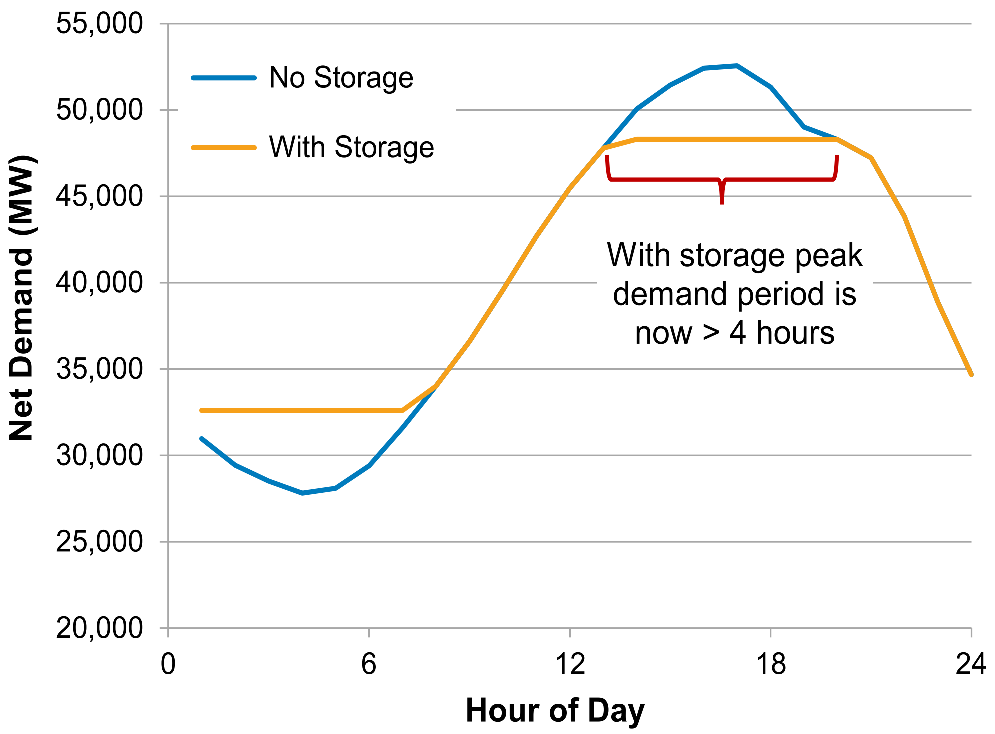
Example of the total and marginal value and of a battery storage system providing peaking capacity

Example Benefit/Cost Ratio



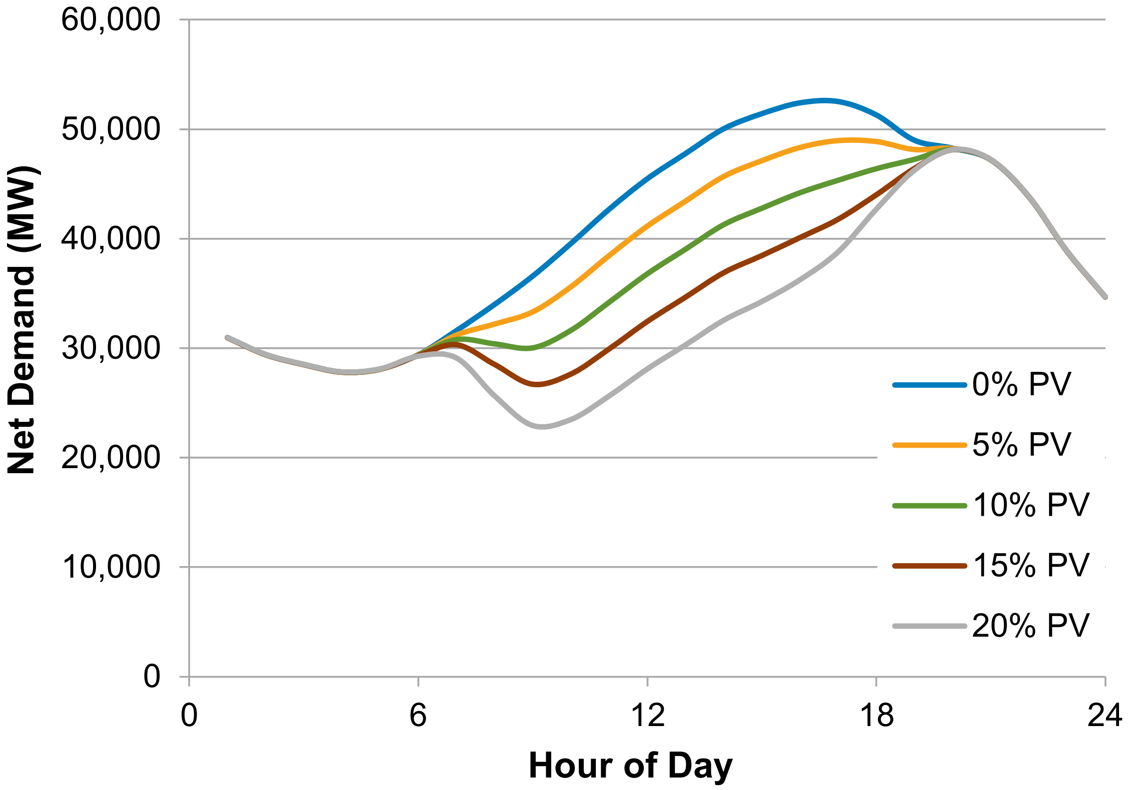
Example of the Benefit/Cost ratio of a battery storage system providing peaking capacity

Limits – Widening Peaks



Simulated impact of increased 4-hour storage deployment on net load shape

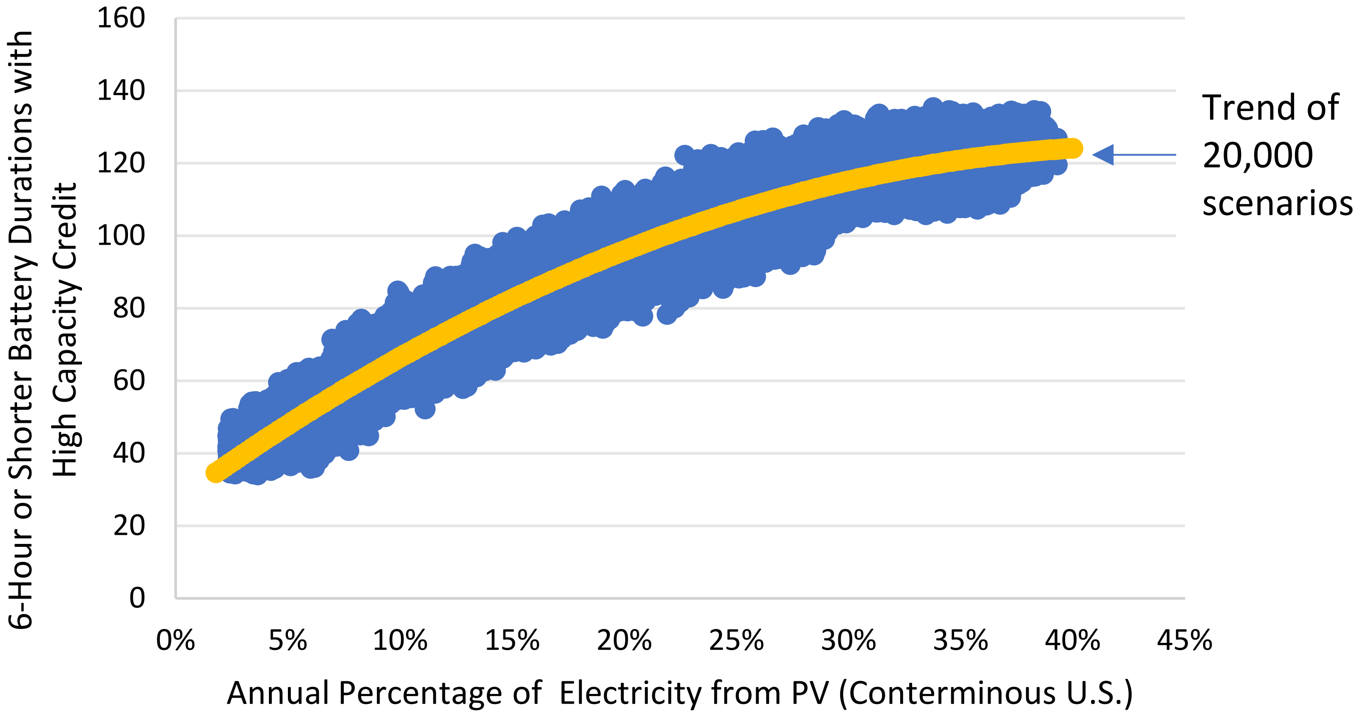
But Peak Narrows with PV Deployment



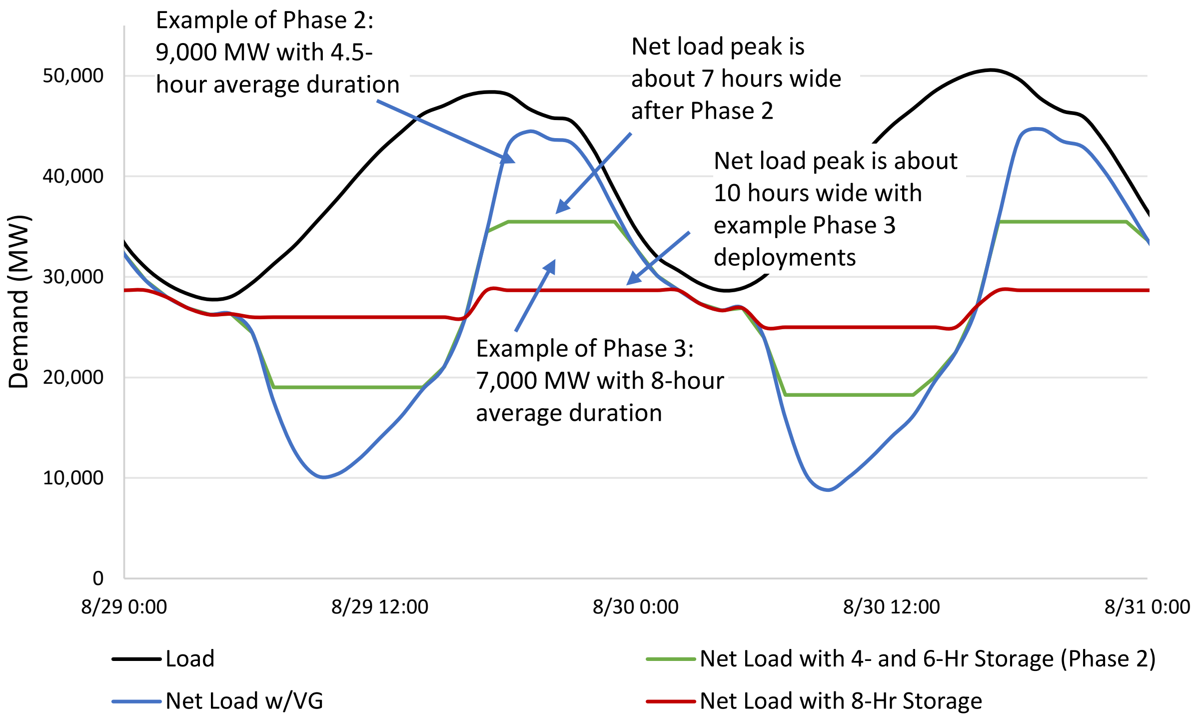
PV increases opportunities for storage as peaking capacity – California Example

Potential for Phase 2

The potential opportunity of Phase 2: National potential of 4–6 hour batteries with high capacity credit

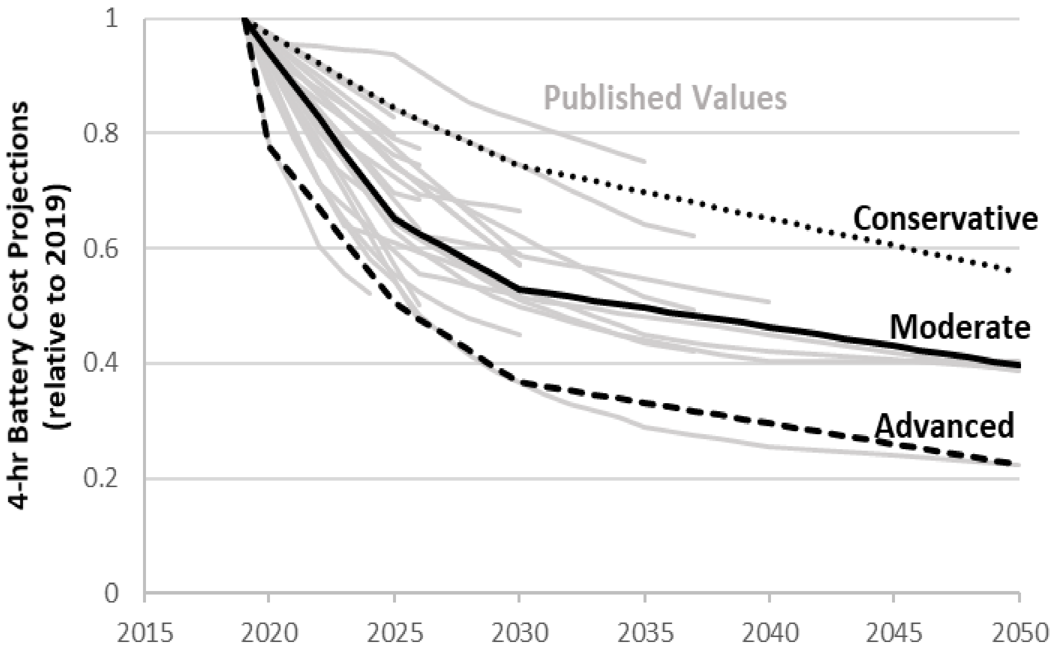


Phase 3: The Era of Ubiquitous Storage?



Longer peaks with greater storage deployment

Storage Costs Are Projected to Decline Beyond 2020

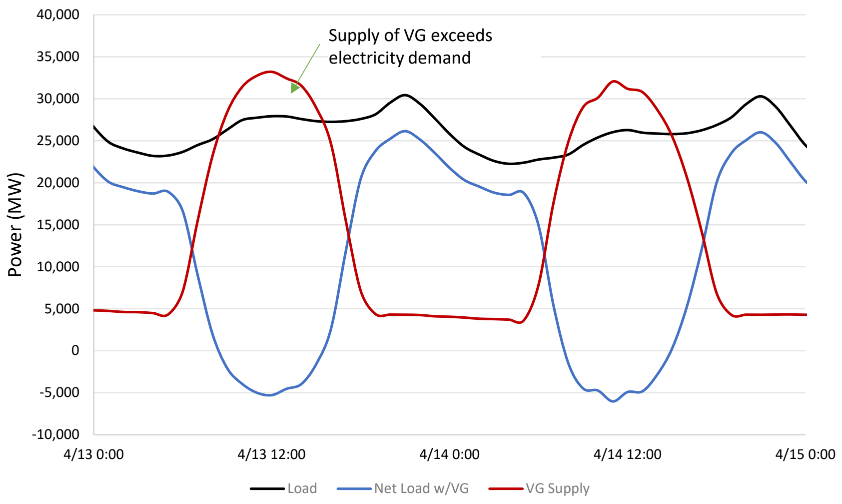


Cost declines (from 2018) range from 21% to 67% by 2030

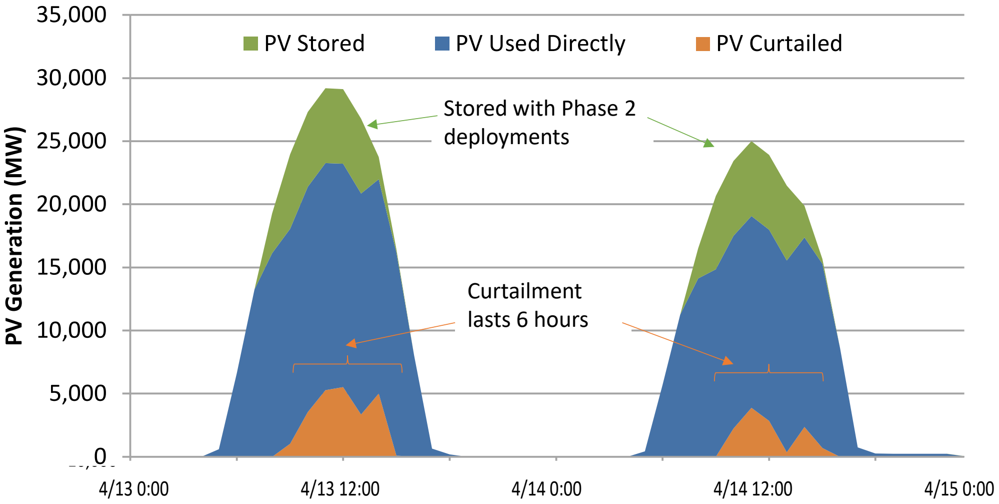
Source: Augustine, Chad, and Nate Blair. Energy Storage Futures Study: Storage Technology Modeling Input Data Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78694. https://www.nrel.gov/docs/fy21osti/78694.pdf.

Phase 3: Continued Deployment of <8 Hr storage?

VRE supply and net load during two spring days



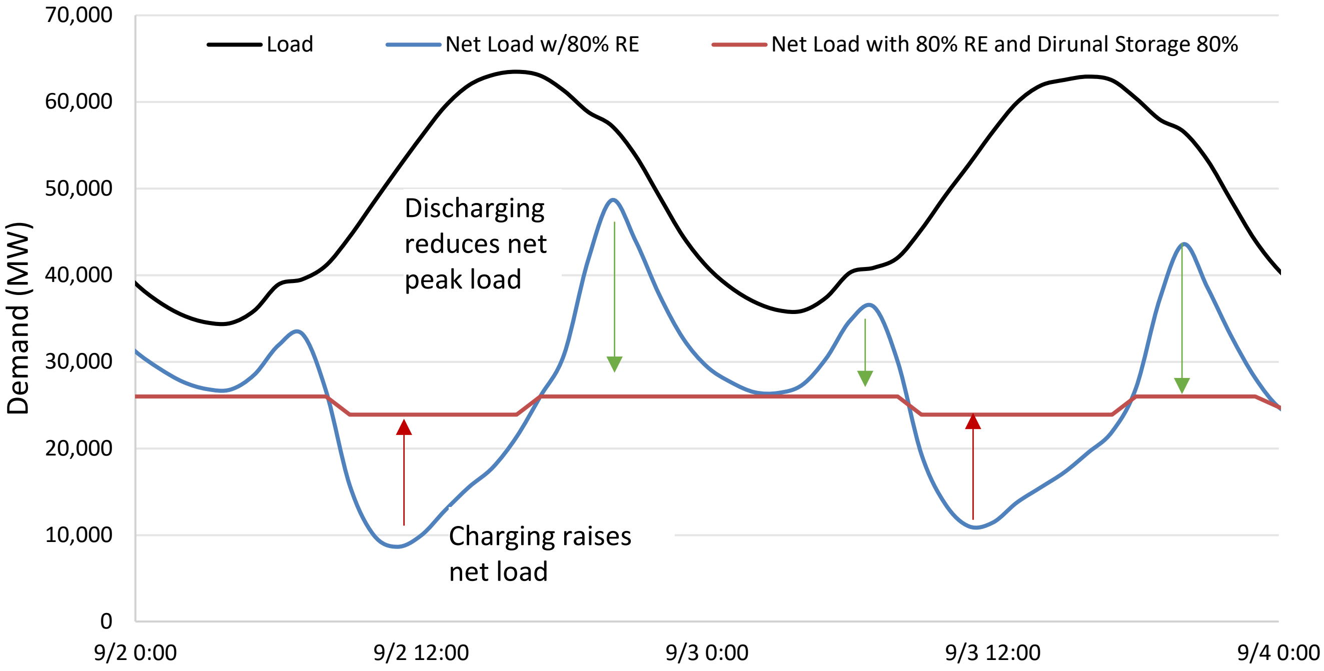
Residual curtailment after Phase 2 storage deployments



Availability of curtailed energy during a spring period showing length of curtailment events

Phase 3: Ultimate Limits Due to Seasonal Mismatch

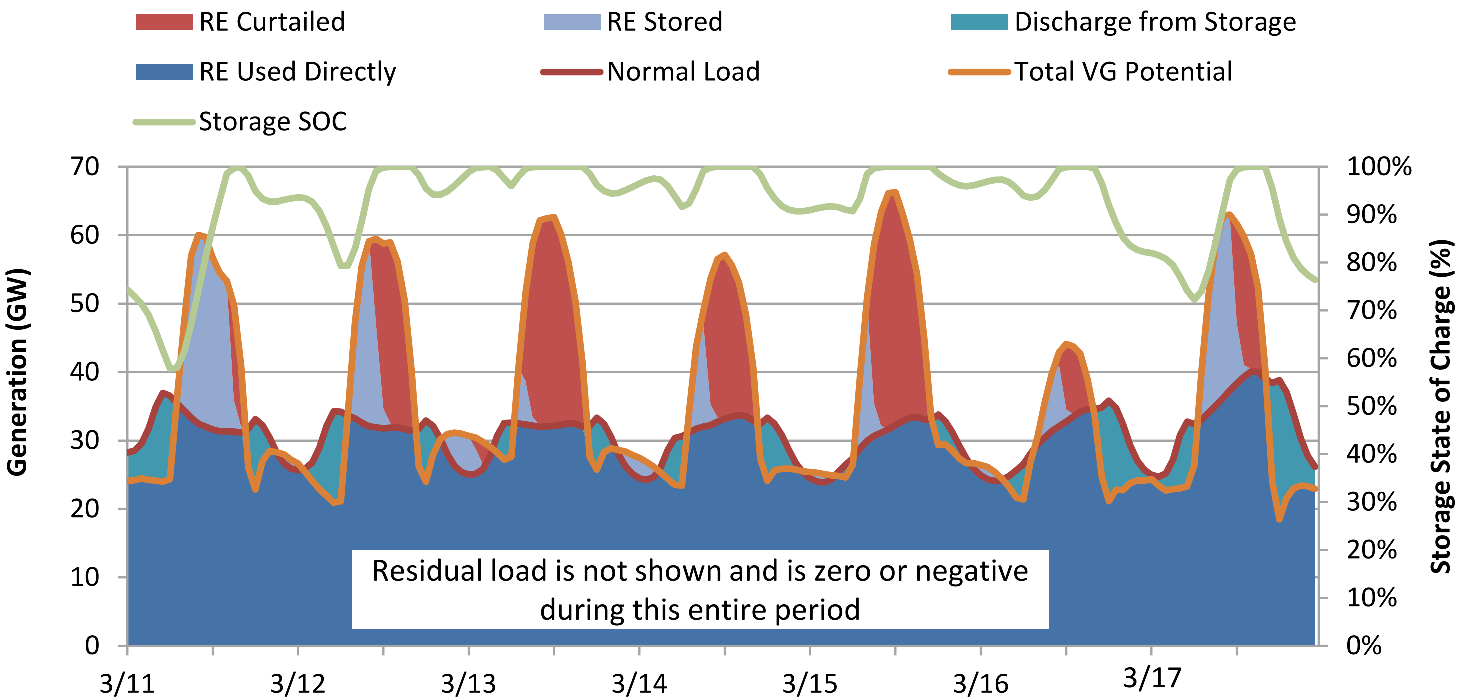
Simulated flattened loads in ERCOT at 80% RE



Decline in capacity value due to a flattened net load

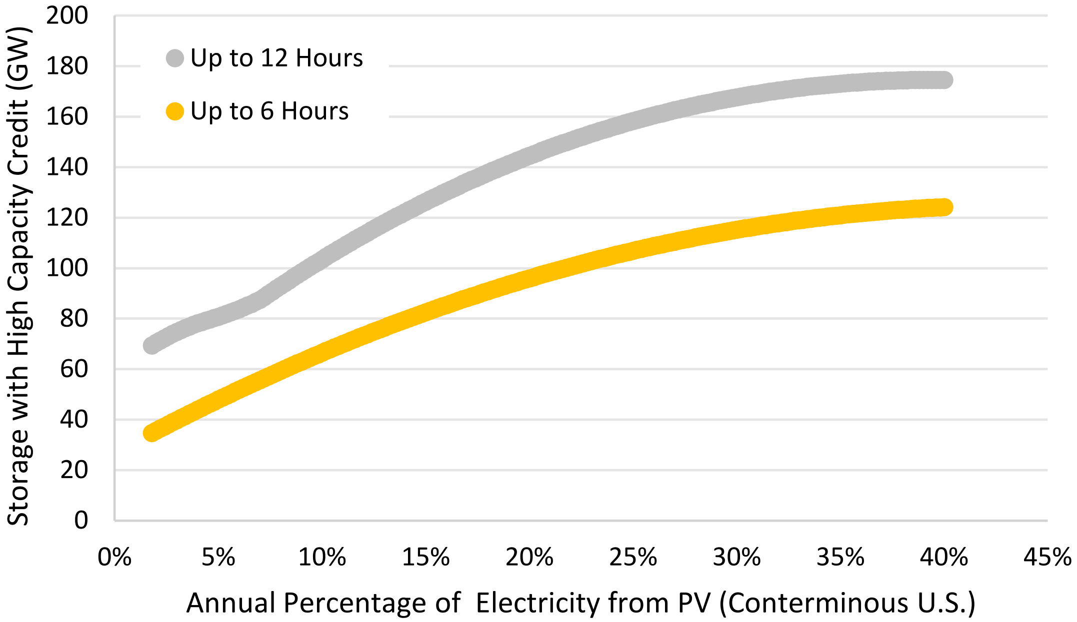
Phase 3: Ultimate Limits Due to Seasonal Mismatch

Simulated flattened loads in ERCOT at 80% RE



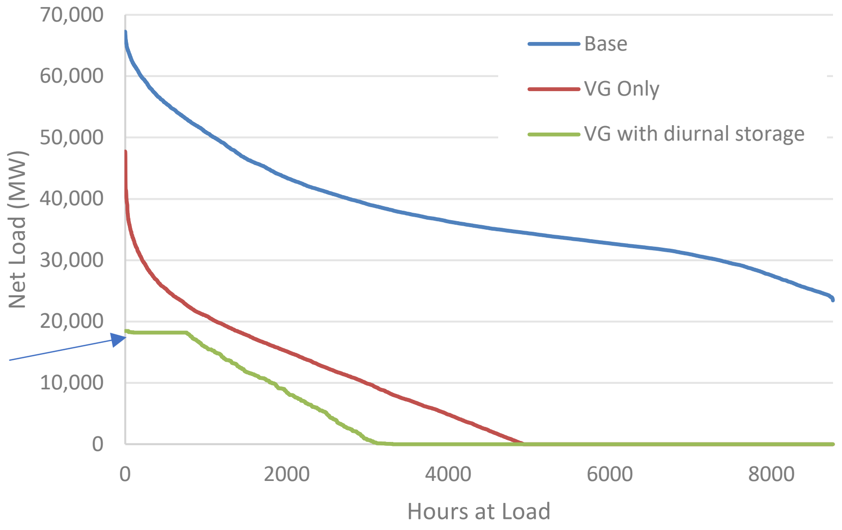
Decline in time-shifting value due to zero net load.

Phase 3 Opportunities



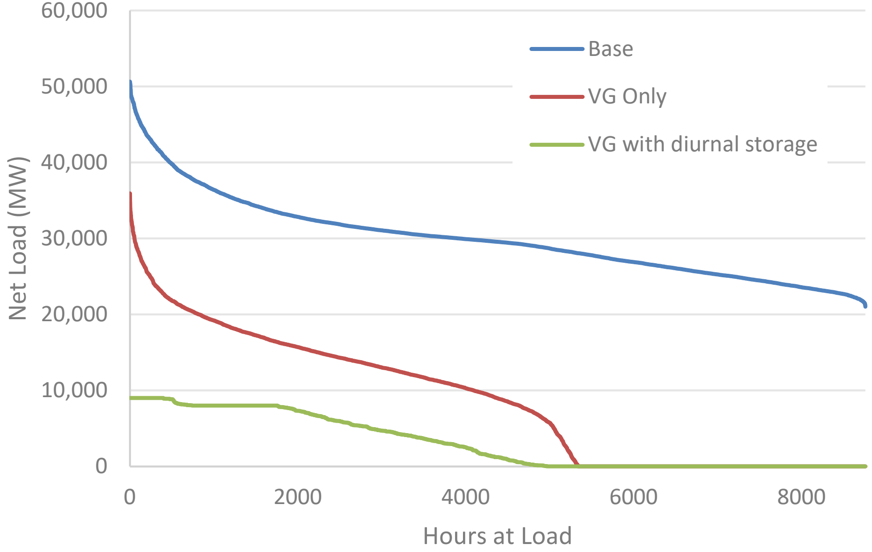
National opportunities for long-duration (up to 12-hour) storage providing capacity services in Phase 3

Phase 4: The Need for Residual Capacity



Firm capacity needed to meet net peak demand and serve remaining 10%

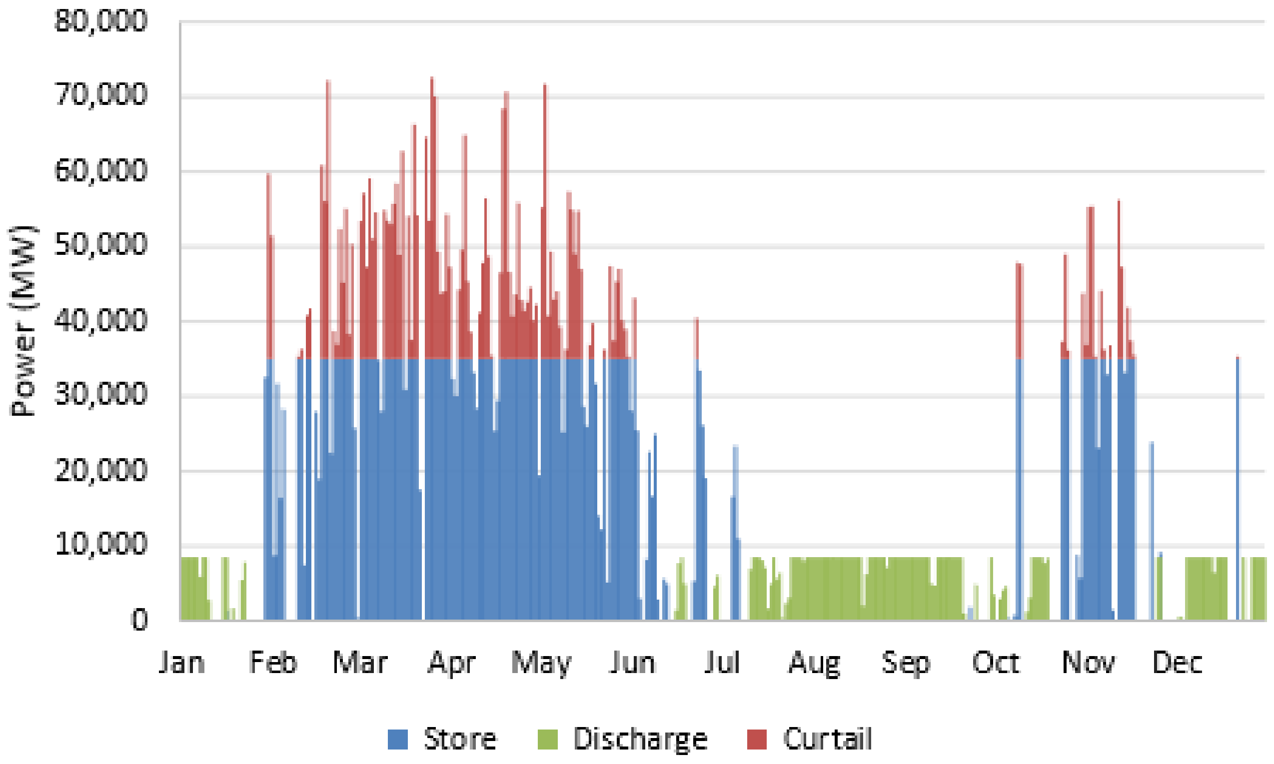
ERCOT



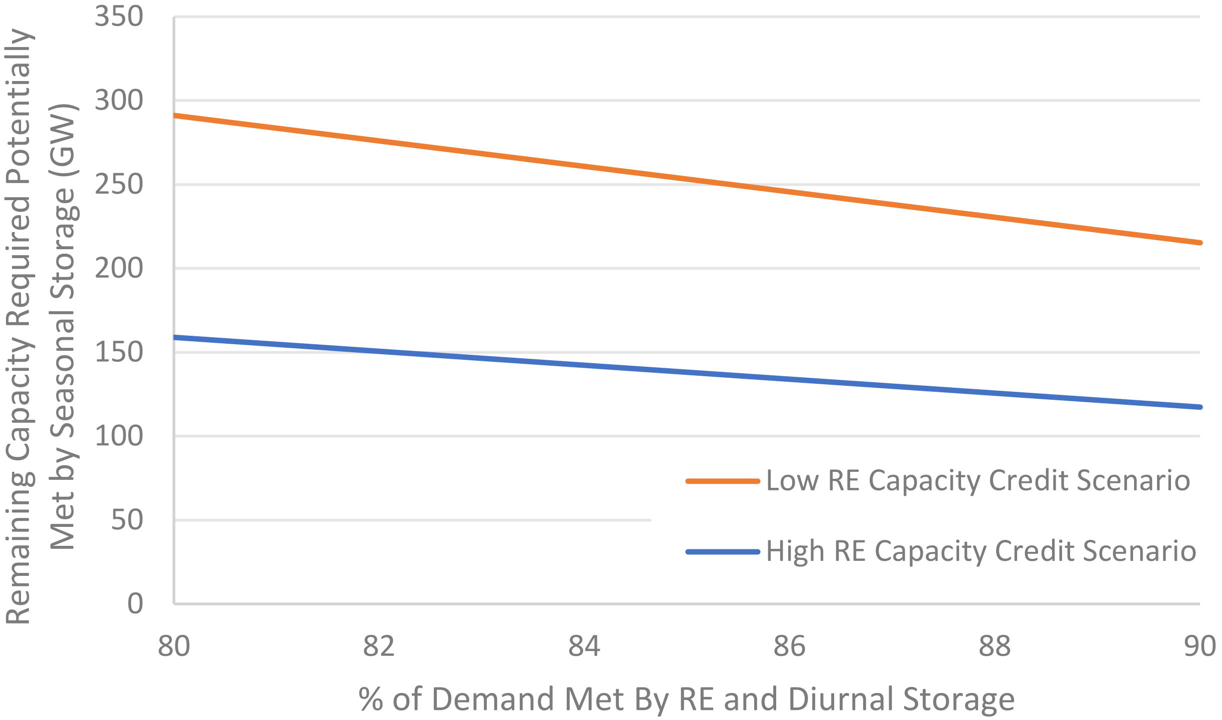
California

Residual load duration curves at 90% RE showing the need for significant firm capacity

Seasonal Storage Operation at 98% RE



Phase 4 Opportunities



Bounding the size of Phase 4 by estimating the national residual capacity requirements under 80%–90% RE scenarios

The Four Phases of Storage Deployment

Phase	Primary Service	National Potential in Each Phase	Duration	Response Speed
Deployment prior to 2010	Peaking capacity, energy time shifting and operating reserves	23 GW of pumped hydro storage	Mostly 8–12 hr	Varies
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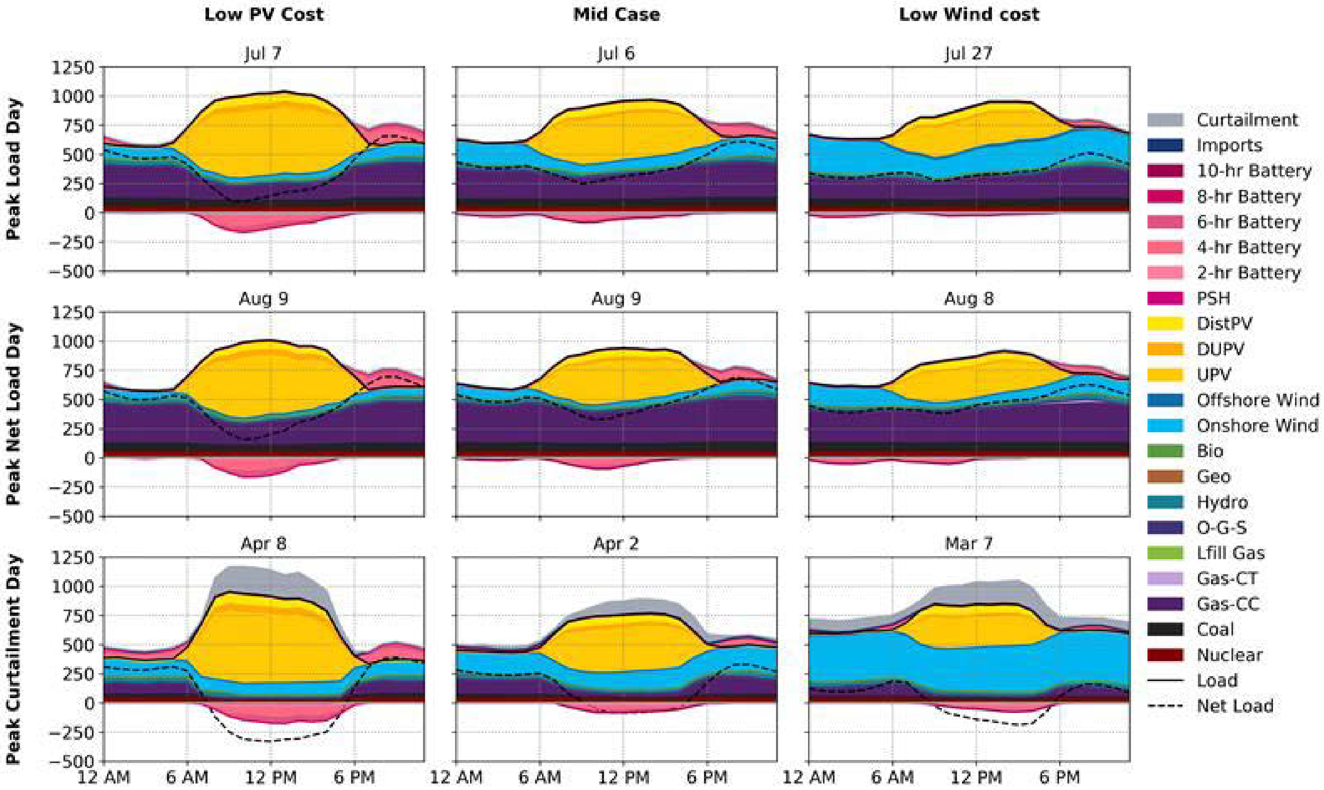
While the Phases are roughly sequential there is considerable overlap and uncertainty!

Grid-Scale Diurnal Storage Scenarios

Combinations of these sensitivities are used to create a total of 19 scenarios

Variable Renewable Energy Cost	Storage Cost	Natural Gas Price	Transmission cost
• *Reference Cost* • Low Wind Cost • High Wind Cost • Low PV Cost • High PV Cost	• *Reference Cost* • Low Battery Cost • High Battery Cost	• *Reference NG price* • High NG price • Low NG price	• *Reference transmission cost* • High transmission cost

Improvements to Storage Representation in ReEDS

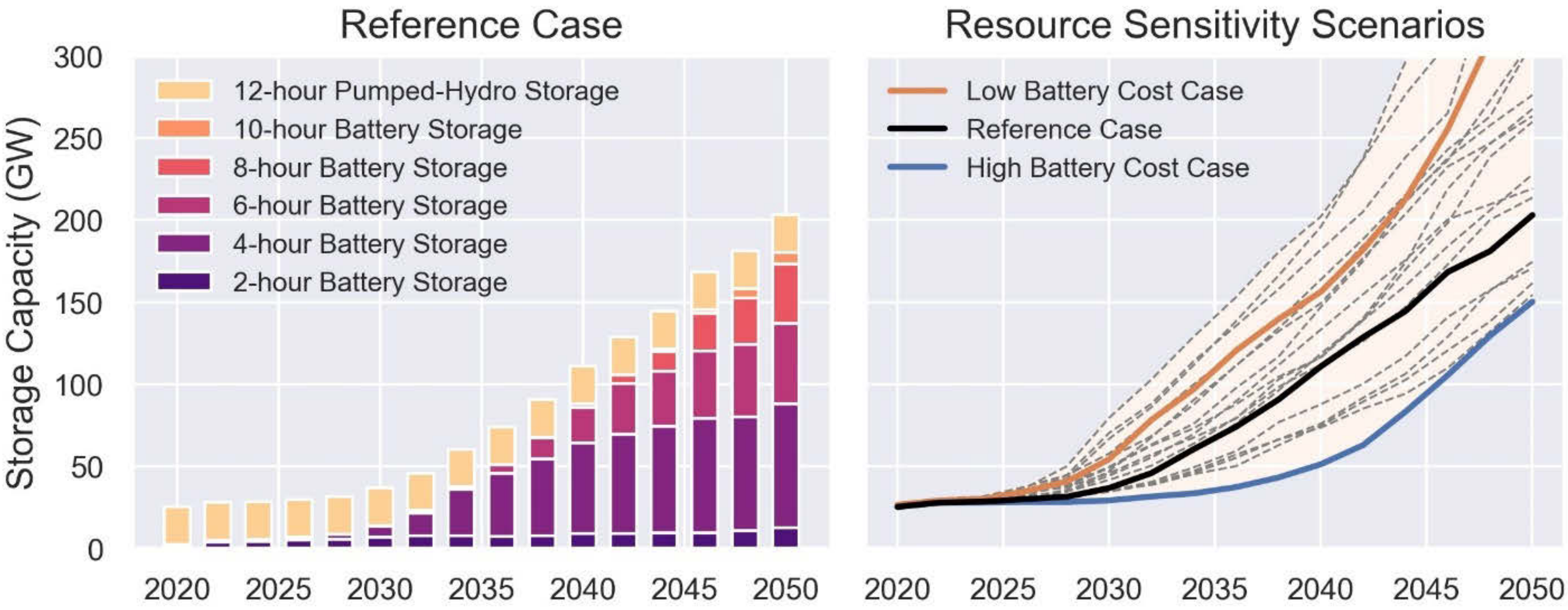


7 years of weather and load data for analyzing system reliability

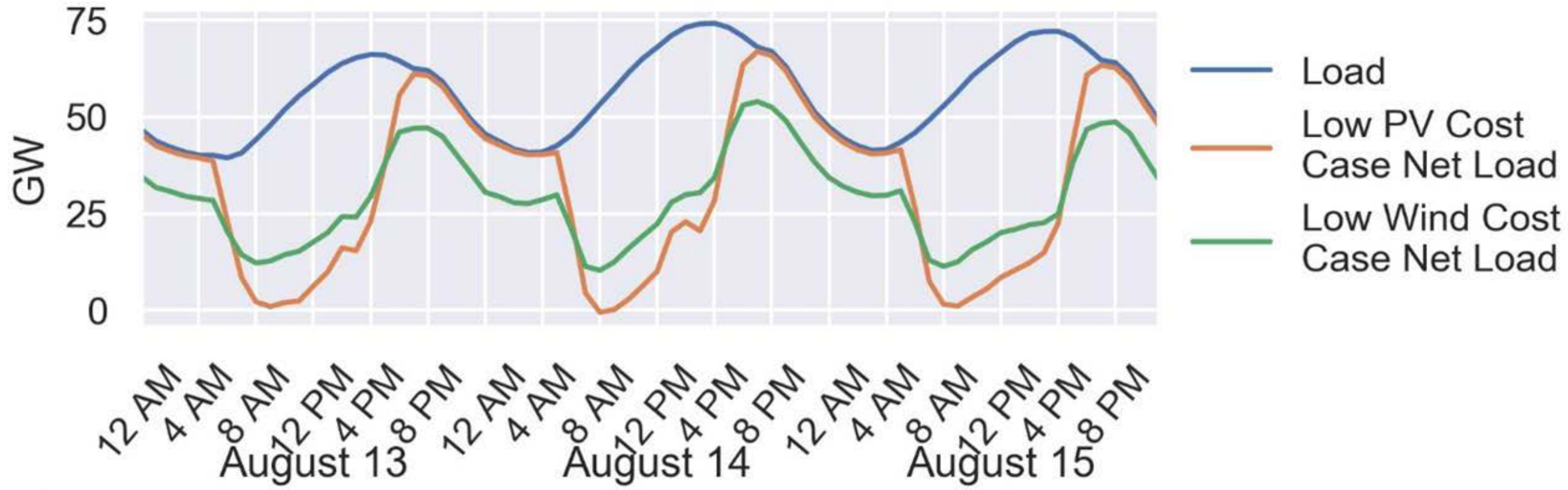
Storage resources are split out by duration to capture the relationship between duration, capacity provision, energy arbitrage, and cost

Dispatch of generation, storage, and transmission **simulated for each hour of year** to inform investment decisions

Modelled storage deployment in ReEDS



Interaction of Storage and Net Load (2050 in California)

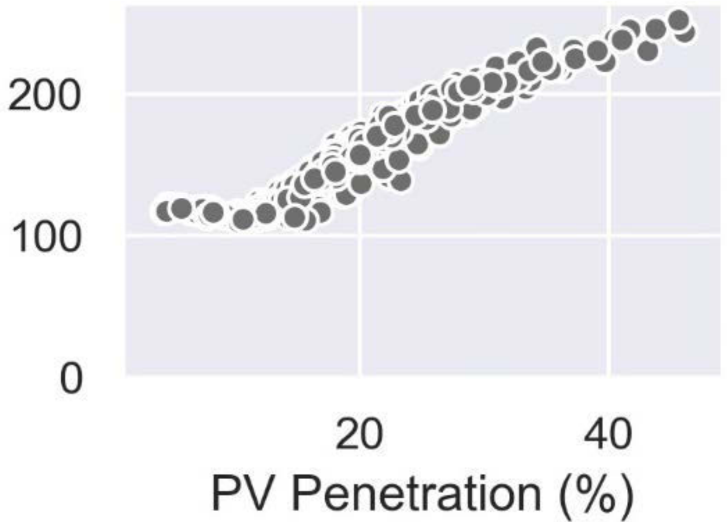


Net load profiles → inform capacity value of storage

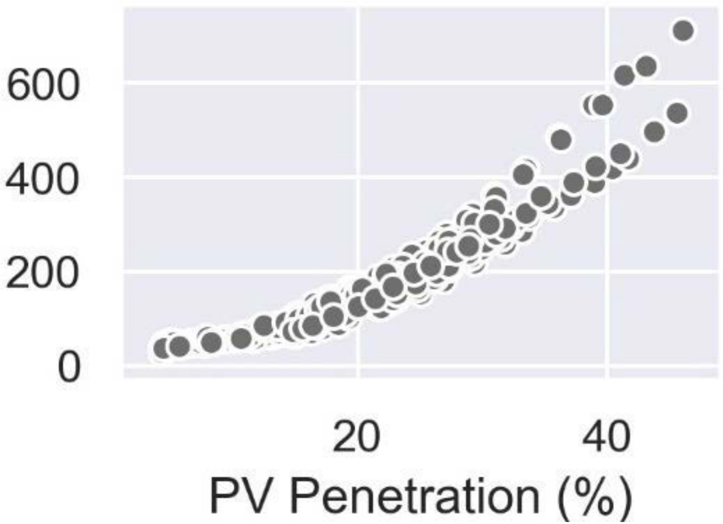
Energy price profiles → inform energy time-shifting value of storage

Storage Correlates with PV More than Wind

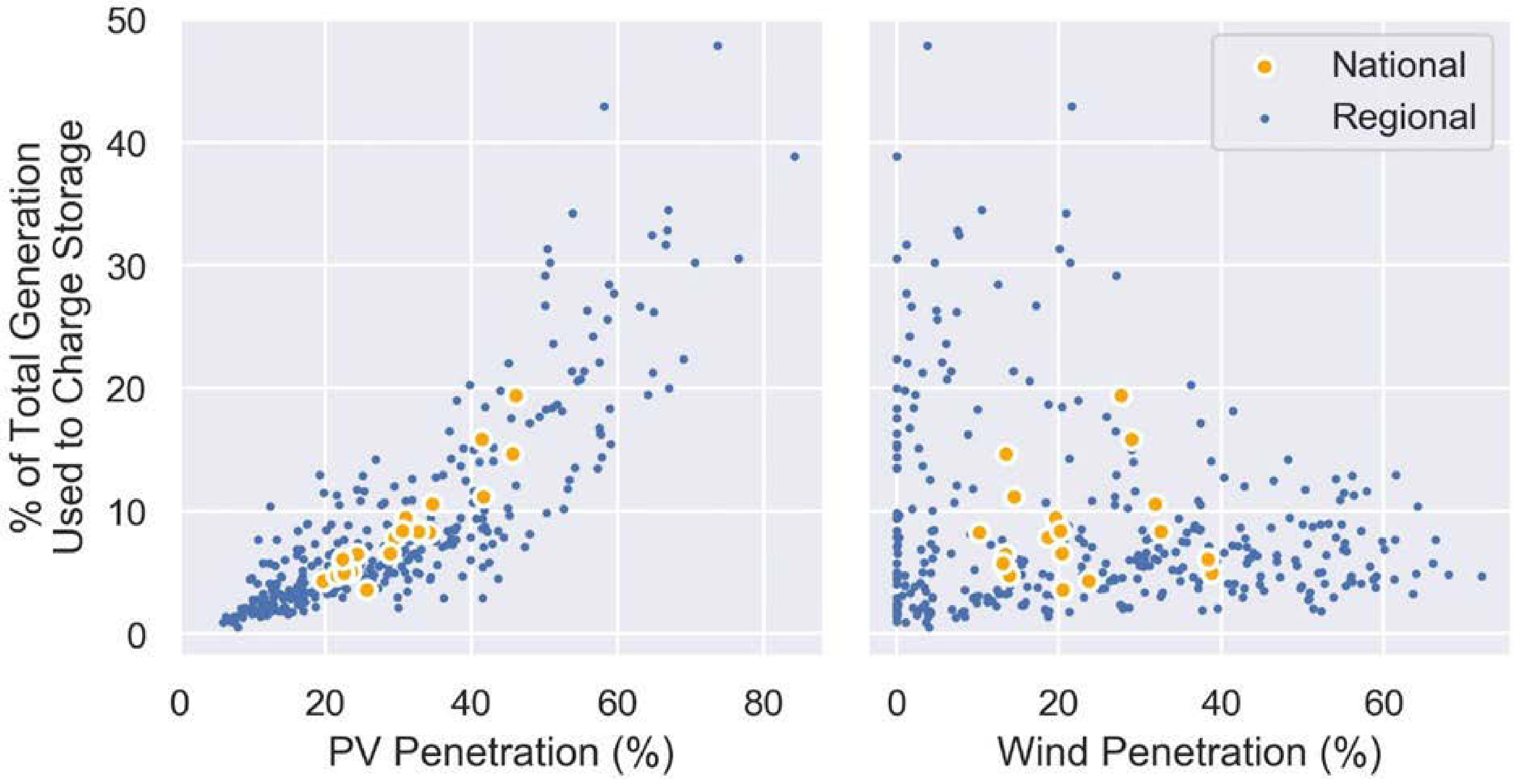
Peaking capacity potential (GW)
(determined by net load shape)



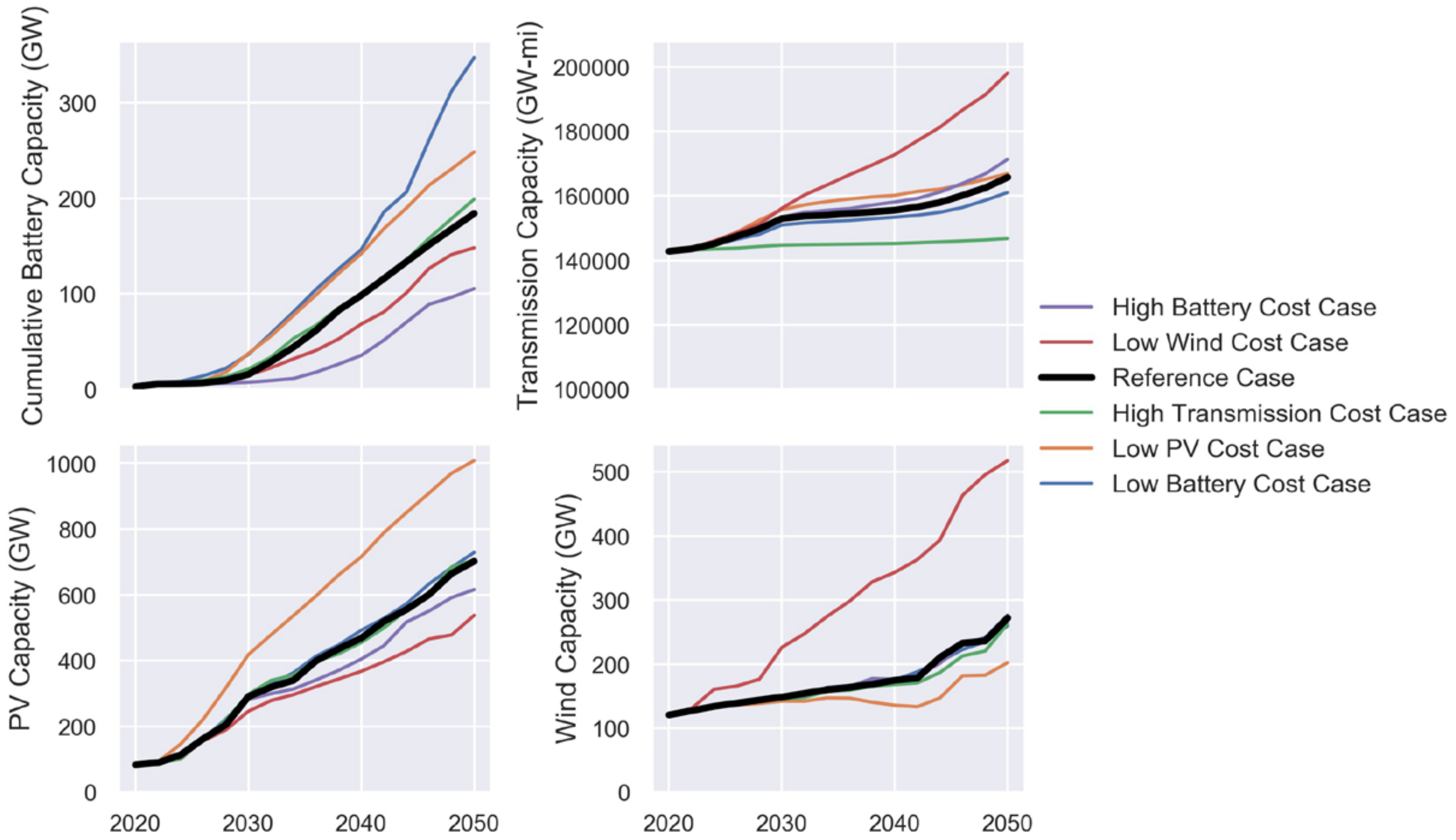
Energy time-shifting potential (TWh)
(determined by energy price profiles)



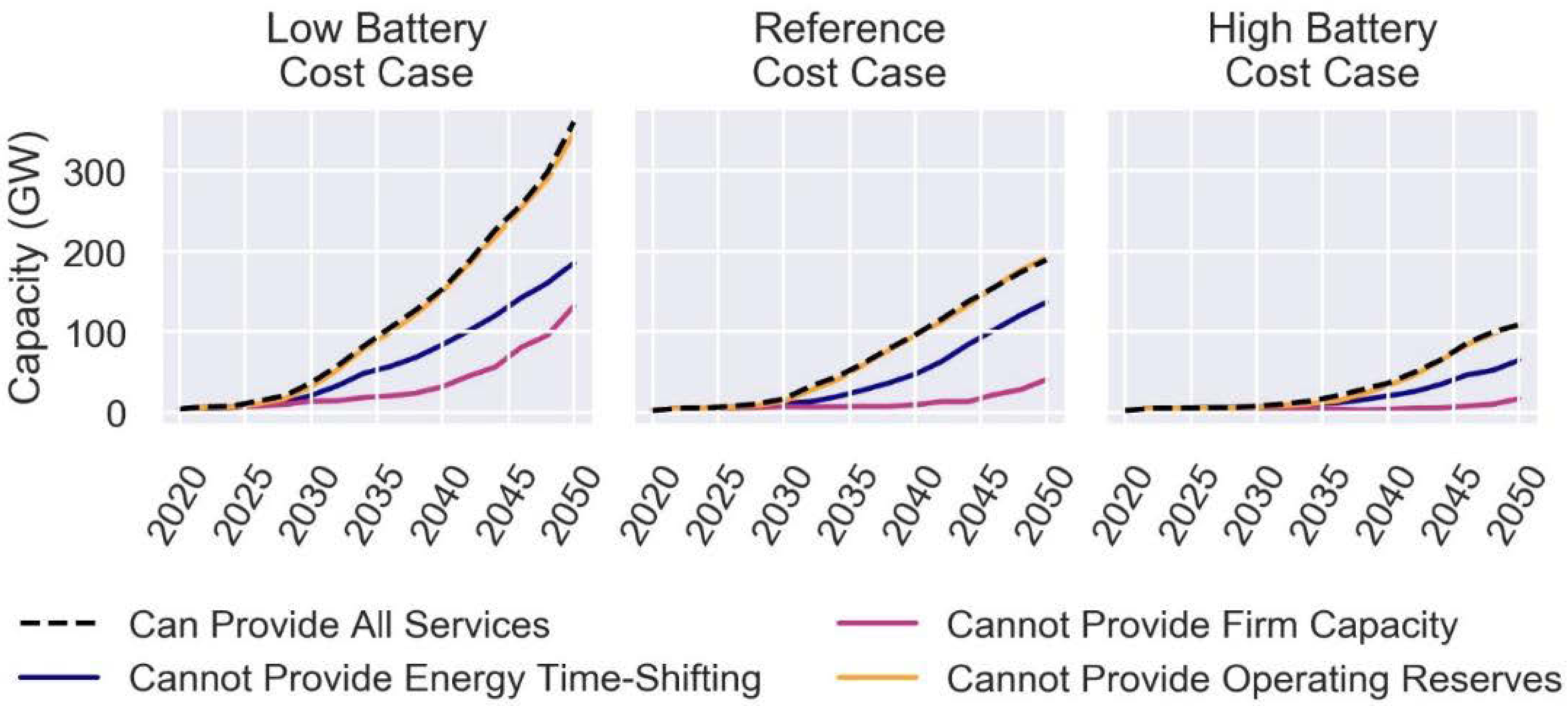
Amount of Generation that Goes through Storage



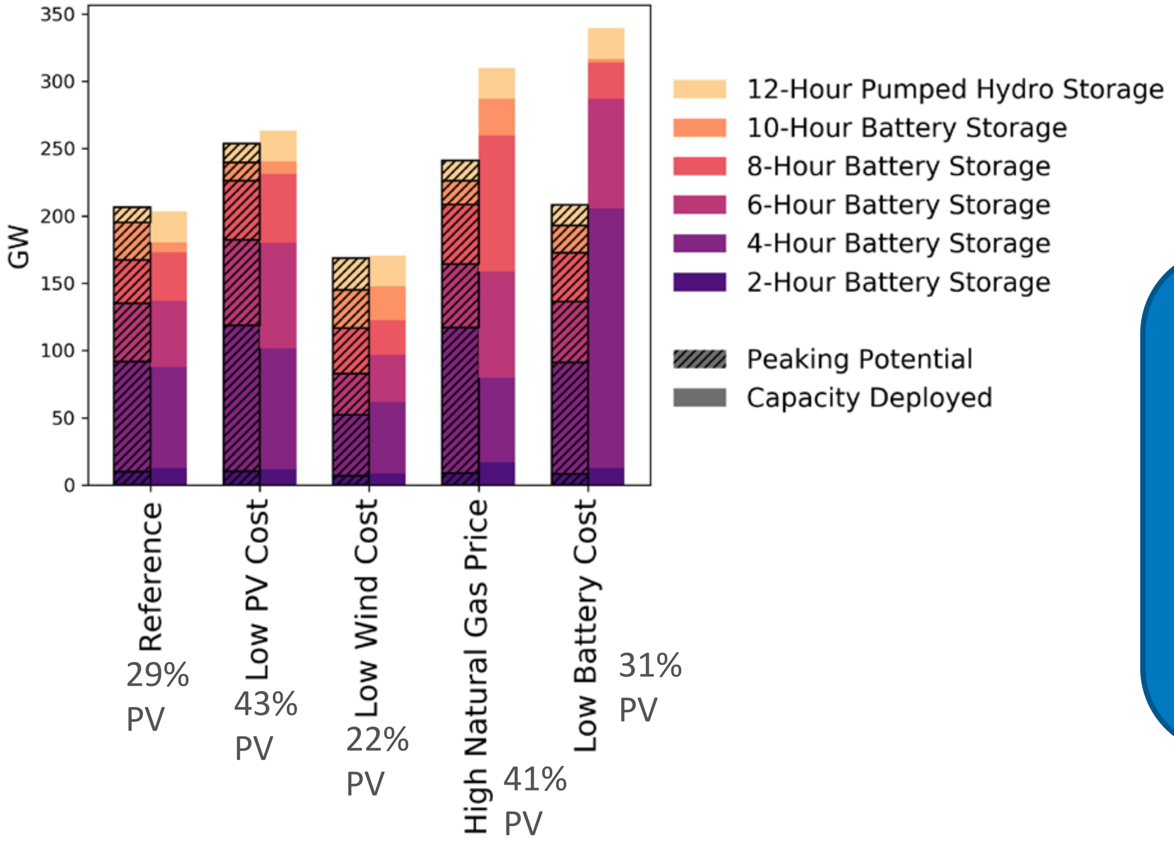
Transmission Correlates More with Wind



Relative Value of Storage Services



Economic Deployment versus Peaking Capacity Potential



Storage is optimized based on the relationship between:

- capacity value
- energy value
- storage duration
- storage cost & performance

Grid-Scale Diurnal Storage Scenarios Key Takeaways

- Capacity value drives deployment, but energy arbitrage value is needed to realize optimal deployment
- Diurnal storage adds value to PV penetration more than with wind penetration
- Significant storage growth (>125 GW) in all scenarios
- Any storage technology that can meet the cost and performance values used in this paper will be competitive

Questions and Discussion

https://www.nrel.gov/analysis/storage-futures.html

NREL/PR-5C00-80366

Encouraging everyone to share/forward NREL outreach on social media

- https://www.nrel.gov/news/program/2021/nrel-launches-storage-futures-study-with-visionary-framework-for-dramatic-increase-in-deployment.html
- NREL also posted items on Linkedin, Twitter, etc.

www.nrel.gov

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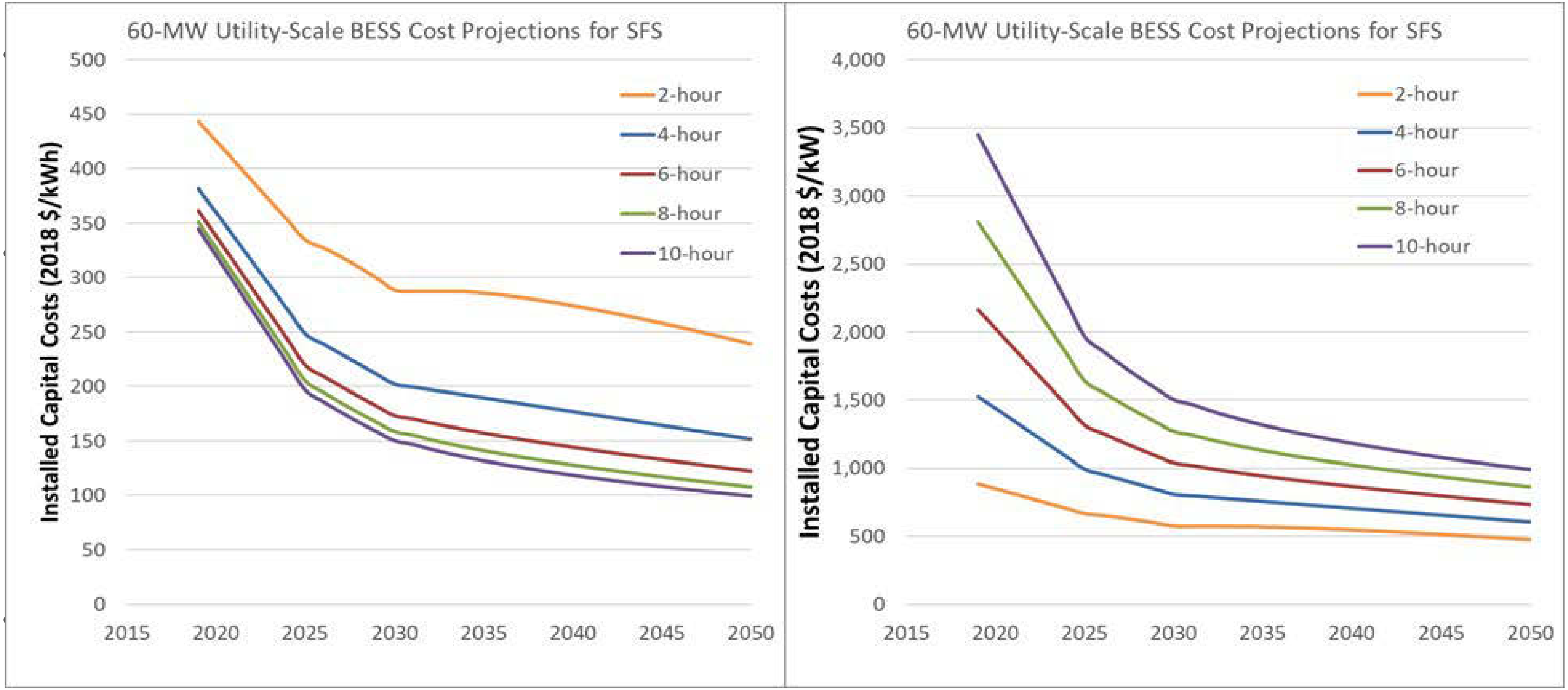
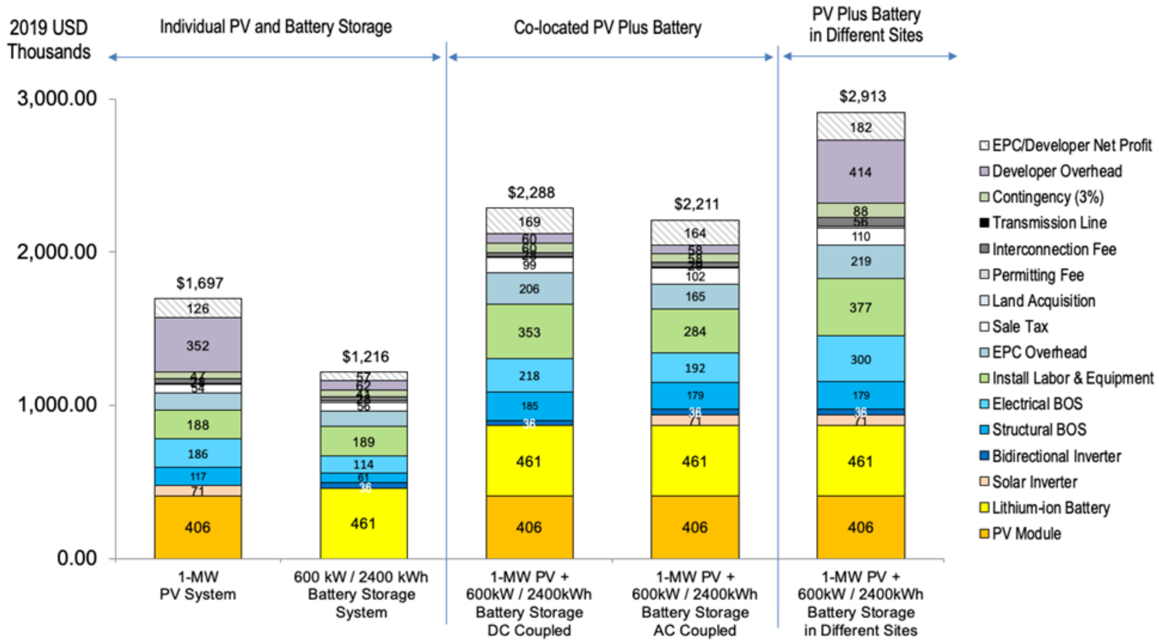
Future Battery Costs by Cost Scenario - Moderate



*https://atb.nrel.gov/

Current Battery Costs – Residential

- Stand-Alone Battery Energy Storage System (BESS)
  - Based on methodology used in NREL PV and BESS cost benchmarking study*
  - Assumes $176/kWh battery pack (BNEF 2020)
  - Installation, overhead and profit margin assumptions aligned with NREL Residential PV model
  - Costs converted to linear equation based on battery power and energy capacity for use in dGen



*Feldman et al. 2020 (forthcoming) U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2019, NREL/TP-6A20-75161

Future Battery Costs by Component

- Battery pack costs decline much faster than other cost components
- Must account for this or will skew BESS costs as a function of duration
- Determined current year cost breakout by component for all durations and then applied cost reductions by component