Storage Futures Study: Four Phases Framework and Modeling

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Speakers:
Paul Denholm, Four Phases Lead Author
Will Frazier, ReEDS Diurnal Storage Lead Author
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

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 scenarios on 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
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!
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
Four Major Categories of Bulk Power System Storage Services

<table>
<thead>
<tr>
<th>Service</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Firm capacity</td>
</tr>
<tr>
<td>Energy</td>
<td>Energy shifting/dispatch efficiency/avoided curtailment</td>
</tr>
<tr>
<td>Transmission</td>
<td>Avoided capacity, congestion relief</td>
</tr>
<tr>
<td>Ancillary services</td>
<td>Operating reserves, voltage support</td>
</tr>
</tbody>
</table>
Phase 1: Short-Duration Storage for Operating Reserves
## Reserve Types

### Timescale

<table>
<thead>
<tr>
<th>mS</th>
<th>S</th>
<th>Min</th>
<th>Hr</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Frequency Responsive Reserves</td>
<td>Inertial Response</td>
<td>Primary Frequency Response</td>
<td>Fast Frequency Response</td>
<td></td>
</tr>
<tr>
<td>2. Regulating Reserves</td>
<td>Regulating Reserves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Contingency Reserves</td>
<td>Spinning Reserves</td>
<td>Non-spinning Reserves</td>
<td>Replacement Reserves</td>
<td></td>
</tr>
<tr>
<td>4. Ramping Reserves</td>
<td>Ramping Reserves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Normal operation provided by “energy and capacity”</td>
<td></td>
<td>Economic Dispatch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Services currently not procured via markets**
- **Proposed or early adoption market services**
- **Currently procured via markets**
Example Value

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

<table>
<thead>
<tr>
<th>Region</th>
<th>Deployment (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alaska &amp; Hawaii</td>
<td>27</td>
</tr>
<tr>
<td>California</td>
<td>139</td>
</tr>
<tr>
<td>Non-CAISO Western Interconnection</td>
<td>29</td>
</tr>
<tr>
<td>Texas</td>
<td>108</td>
</tr>
<tr>
<td>PJM</td>
<td>182</td>
</tr>
<tr>
<td>New York &amp; New England</td>
<td>66</td>
</tr>
<tr>
<td>Other Regions in the Eastern Interconnection</td>
<td>171</td>
</tr>
<tr>
<td>Total</td>
<td>721</td>
</tr>
</tbody>
</table>

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
### Regional Energy Storage Duration Requirements in response to FERC 841

<table>
<thead>
<tr>
<th>Market Operator</th>
<th>Duration Minimum (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO-NE</td>
<td>2</td>
</tr>
<tr>
<td>CAISO</td>
<td>4</td>
</tr>
<tr>
<td>NYISO</td>
<td>4</td>
</tr>
<tr>
<td>SPP</td>
<td>4</td>
</tr>
<tr>
<td>MISO</td>
<td>4</td>
</tr>
<tr>
<td>PJM</td>
<td>10</td>
</tr>
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</table>

[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](https://www.pjm.com/directory/etariff/FercDockets/5832/20201030-er21-278-000.pdf).) FERC 841 [https://www.ferc.gov/media/order-no-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
Example of the total and marginal value of energy time-shifting using 2019 energy market values
Example of the total and marginal value and of a battery storage system providing peaking capacity.
Example of the Benefit/Cost ratio of a battery storage system providing peaking capacity
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
The potential opportunity of Phase 2: National potential of 4–6 hour batteries with high capacity credit.
Phase 3: The Era of Ubiquitous Storage?

Example of Phase 2:
9,000 MW with 4.5-hour average duration

Net load peak is about 7 hours wide after Phase 2

Example of Phase 3:
7,000 MW with 8-hour average duration

Net load peak is about 10 hours wide with example Phase 3 deployments

Demand (MW)

- Load
- Net Load w/VG
- Net Load with 4- and 6-Hr Storage (Phase 2)
- Net Load with 8-Hr 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

Phase 3: Continued Deployment of <8 Hr storage?

VRE supply and net load during two spring days

Supply of VG exceeds electricity demand

Residual curtailment after Phase 2 storage deployments

PV Stored
PV Used Directly
PV Curtailed

Curtailment lasts 6 hours

Stored with Phase 2 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
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.

Residual load is not shown and is zero or negative during this entire period.
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%

Residual load duration curves at 90% RE showing the need for significant firm capacity
Seasonal Storage Operation at 98% RE
Bounding the size of Phase 4 by estimating the national residual capacity requirements under 80%-90% RE scenarios.
# The Four Phases of Storage Deployment

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Grid-Scale Diurnal Storage Scenarios

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

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<th>Storage Cost</th>
<th>Natural Gas Price</th>
<th>Transmission cost</th>
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<td>• Reference NG price</td>
<td>• Reference transmission cost</td>
</tr>
<tr>
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<td>• Low Battery Cost</td>
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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

Reference Case

Resource Sensitivity Scenarios

- 12-hour Pumped-Hydro Storage
- 10-hour Battery Storage
- 8-hour Battery Storage
- 6-hour Battery Storage
- 4-hour Battery Storage
- 2-hour Battery Storage

Storage Capacity (GW)

Year:
- 2020
- 2025
- 2030
- 2035
- 2040
- 2045
- 2050

- Low Battery Cost Case
- Reference Case
- High Battery Cost Case
Interaction of Storage and Net Load (2050 in California)

Net load profiles \(\rightarrow\) inform capacity value of storage
Energy price profiles \(\rightarrow\) 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

- **PV Penetration (%)** vs. % of Total Generation Used to Charge Storage
- **Wind Penetration (%)** vs. % of Total Generation Used to Charge Storage

- **National**
- **Regional**
Transmission Correlates More with Wind

![Graphs showing cumulative battery capacity, transmission capacity, PV capacity, and wind capacity over time for different cost cases.](image-url)
Relative Value of Storage Services

Low Battery Cost Case

Reference Cost Case

High Battery Cost Case

Can Provide All Services

Cannot Provide Firm Capacity

Cannot Provide Energy Time-Shifting

Cannot Provide Operating Reserves
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

Encouraging everyone to share/forward NREL outreach on social media

- NREL also posted items on Linkedin, Twitter, etc.
Future Battery Costs by Cost Scenario - Moderate

• Use same cost projections for 4-hour BESS as in Cole & Frazier 2020*
  – Projections based on literature review of 16 projections
• Adjusted cost projections for other durations to account for reductions at component level
  – BNEF data for component-level reductions
  – LIB pack costs reduce faster than rest of component costs
• Compared here to EPRI, BNEF and Schmidt

*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

• 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