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Storage Futures Study

Key Learnings for the Coming Decades

Nate Blair, Chad Augustine, Wesley Cole, Paul Denholm, Will Frazier, Madeline Geocaris, Jennie Jorgenson, Kevin McCabe, Kara Podkaminer, Ashreeta Prasanna, Ben Sigrin

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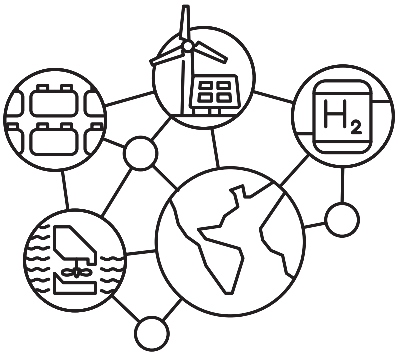

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NOTICE

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PREFACE

This report is the seventh and final publication from the National Renewable Energy Laboratory's (NREL's) Storage Futures Study (SFS). The SFS is a multiyear research project that explores how energy storage could impact the evolution and operation of the U.S. power sector.

The study examined the impact of energy storage technology advancement on the deployment of utility-scale storage and the adoption of distributed storage, as well as future power system infrastructure investment and operations. Some of the questions NREL sought to answer throughout this study included:

- How might storage cost and performance change over time?
- What is the role of diurnal energy storage in the power sector, even absent drivers or policies that increase renewable energy shares?
- How much diurnal grid storage might be economically deployed in the United States, both at the utility-scale and distribution-scale?
- What factors might drive that deployment?
- How might increased levels of diurnal storage impact grid operations?

Research findings and supporting data from the study have been published in a series of seven publications, which are listed in the table on the next page. Key learnings from throughout the study have culminated in this final report that helps shape the vision of energy storage moving forward.

The SFS series provides data and analysis in support of the U.S. Department of Energy's (DOE's) Energy Storage Grand Challenge, a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. The Energy Storage Grand Challenge employs a use-case framework to ensure storage technologies can cost-effectively meet specific needs, and it incorporates a broad range of technologies in several categories: electrochemical, electromechanical, thermal, flexible generation, flexible buildings, and power electronics.

More information, supporting data associated with this report, links to other reports in the series, and other information about the broader study are available at https://www.nrel.gov/analysis/storage-futures.html.

Table 1

Storage Future Study Series Reports		
Title	**Description**	**Relation to This Report**
The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System (Denholm et al. 2020)	Explores the roles and opportunities for new, cost-competitive stationary energy storage with a conceptual framework based on four phases of current and potential future storage deployment and presents a value proposition for energy storage that could result in cost-effective deployments reaching hundreds of gigawatts of installed capacity.	Provides broader context on the implications of the cost and performance characteristics discussed in this report, including specific grid services they may enable in various phases of storage deployment. This framework is supported by the results of scenarios in this project.
Energy Storage Technology Modeling Input Data Report (Augustine et al. 2021)	Reviews the current characteristics of a broad range of mechanical, thermal, and electrochemical storage technologies with application to the power sector. Provides current and future projections of cost, performance characteristics, and locational availability of specific commercial technologies already deployed, including lithium-ion battery systems and pumped storage hydropower.	Provides detailed background about the battery and pumped storage hydropower cost and performance values used as inputs to the modeling performed in this project.
Economic Potential of Diurnal Storage in the U.S. Power Sector (Frazier et al. 2021)	Assesses the economic potential for utility-scale diurnal storage and the effects that storage capacity additions could have on power system evolution and operations.	This report features a series of cost-driven grid-scale capacity expansion scenarios for the U.S. grid through 2050 and examines the drivers for storage deployment.
Distributed Storage Customer Adoption Scenarios (Prasanna et al. 2021)	Assesses the customer adoption of distributed diurnal storage for several future scenarios and the implications for the deployment of distributed generation and power system evolution.	Analyzes distributed storage adoption scenarios to test the various cost trajectories and assumptions in parallel to the grid storage deployments modeled in this report.
The Challenges of Defining Long-Duration Energy Storage (Denholm et al. 2021)	Describes the challenge of a single uniform definition for long-duration energy storage to reflect both duration and application of the stored energy.	Advances dialogue around the meaning of long-duration energy storage and how it fits into future power systems.
Grid Operational Implications of Widespread Storage Deployment (Jorgenson et al. 2022)	Assesses the operation and associated value streams of energy storage for several power system evolution scenarios and explores the implications of seasonal storage on grid operations.	Considers the operational implications of storage deployment and grid evolution scenarios to examine and expand on the grid-scale scenario results found with NREL's Regional Energy Deployment System model in this report.
Storage Futures Study: Key Learnings For the Coming Decades	**Synthesizes and summarizes findings from the entire series and related analyses and reports and identifies topics for further research.**	**This report.**

ACKNOWLEDGMENTS

We would like to acknowledge the contributions of the entire Storage Futures Study team (listed as coauthors) for this report, as well as our DOE Office of Strategic Analysis colleagues as core contributors, specifically Kara Podkaminer, Paul Spitsen, and Sarah Garman. Feedback and contributions also came from other NREL staff, including Gian Porro, Doug Arent, Karlynn Cory, Adam Warren, Chad Hunter, Evan Reznicek, Michael Penev, Greg Stark, Vignesh Ramasamy, David Feldman, Greg Brinkman, and Trieu Mai. We also would like to thank our technical review committee (see Table 2) for their input.

Finally, we acknowledge various technical experts at DOE, including Eric Hsieh, Alejandro Moreno, and many others, for their additional thoughts and suggestions throughout the Storage Futures Study, as noted in the individual reports.

Table 2

Technical Review Committee Members		
Doug Arent (NREL) –TRC *Chair*		
Paul Albertus (University of Maryland)	**Inez Azevedo** (Stanford University)	**Ryan Wiser** (Lawrence Berkeley National Laboratory)
Sue Babinec (Argonne National Laboratory)	**Aaron Bloom** (NextEra)	**Chris Namovicz** (U.S. Energy Information Administration)
Howard Gruenspecht (Massachusetts Institute of Technology)	**Arvind Jaggi** (NY Independent System Operator)	**Keith Parks** (Xcel Energy)
Kiran Kumaraswamy (Fluence)	**Granger Morgan** (Carnegie Mellon University)	**Cara Marcy** (U.S. Environmental Protection Agency)
Mahesh Morjaria (Terabase Energy)	**Oliver Schmidt** (Imperial College - London)	**Vincent Sprenkle** (Pacific Northwest National Laboratory)
	John Gavan (Colorado PUC Commissioner)	

LIST OF ACRONYMS

BESS	—	battery energy storage system(s)
DOE	—	U.S. Department of Energy
DR	—	distributed resource
FC	—	fuel cell
GW	—	gigawatts
GWh	—	gigawatt-hour
H2	—	hydrogen (as a storage fluid)
H2 Elec-salt cavern- CT	—	hydrogen storage using electrolyzers, salt caverns, and combustion turbines
H2 Elec-salt cavern- FC	—	hydrogen storage using electrolyzers, salt caverns, and stationary fuel cells
kW	—	kilowatt
kWh	—	kilowatt-hour (either a unit of energy or a unit of storage capacity)
LIB	—	lithium-ion battery
NG	—	natural gas
NREL	—	National Renewable Energy Laboratory
PV	—	photovoltaics
RE	—	renewable energy
SFS	—	Storage Futures Study
VRE	—	variable renewable energy

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THE COMING DECADES OF ENERGY STORAGE DEPLOYMENT

Energy storage is very likely to become a critical element of a low-carbon, flexible, resilient future electric grid.

In the past several years, there has been a dramatic increase of variable renewable generation in the U.S. power sector, and significant growth is anticipated in the future. In addition, there has been increased focus on the United States and globally on addressing numerous instances of power system disruptions and increased focus on research and analysis on power system reliability and resiliency with increasing amounts of variable renewable power—emphasizing the importance of clean energy deployment while maintaining a reliable power system.

At the same time, there have been significant cost declines in energy storage technologies (particularly batteries) over the past few years, and many more storage technologies are under development. These converging factors have increased attention on the potential role of energy storage as a critical asset for decarbonization and to ensure reliable electricity for the evolving grid.

Energy storage offers many potential benefits to the grid. It could provide generation to complement the deployment of wind and solar PV, providing capacity when these resources have reduced availability. When used in conjunction with renewable energy (RE) or other clean energy resources, energy storage has the ability to reduce greenhouse gas emissions.

Energy storage can also increase utilization of new and existing transmission lines, while offsetting the need to build new power plants to provide peaking capacity or operating reserves. Finally, distributed energy storage can reduce stress on the distribution grid during peak demand times. This flexibility will be important with the anticipated proliferation of electric vehicles and potential increased load from other end-use electrification.

As the cost of energy storage technologies continues to decline and the grid integrates more variable renewable generation, our modeling indicates significant increased deployment of energy storage deployment in the electric system in the coming decades. Questions arise, such as how could this impact how the grid operates and evolves over the coming decades?

Because energy storage can impact features of electricity generation, transmission, and distribution, quantifying the value of storage is more complicated than quantifying the value of other assets like solar PV or wind energy that are purely generation. Through the Storage Futures Study (SFS), the National Renewable Energy Laboratory (NREL) has aimed to increase understanding of how storage adds value, and how much, to the power system, how much storage could be economically deployed, and how that deployment might impact power system evolution and operations.

The Storage Futures Study started with defining a framework of four phases of increasing energy storage deployment and duration over time, moved on to create a set of long-term projections for diurnal (<12 hours) storage deployment in the United States, and then applied detailed production cost and agent-based modeling to better understand the role of storage. The key conclusion of the research is that deployment of energy storage has the potential to increase significantly—reaching at least five times today's capacity by 2050—and it will play an integral role in determining the cost-optimal grid mix of the future. Drawing on the analysis across the SFS, previous work, and additional analysis for this report, the study identified eight specific key learnings about the future of energy storage and its impact on the power system. These key learnings can help policy makers, technology developers, and grid operators prepare for the coming wave of storage deployment:

KEY LEARNING 1: Storage is poised for rapid growth.

KEY LEARNING 2: Recent storage cost reductions are projected to continue, with lithium-ion batteries (LIBs) continuing to lead in market share for some time.

KEY LEARNING 3: The ability of storage to provide firm capacity is a primary driver of cost-competitive deployment.

KEY LEARNING 4: Storage is not the only flexibility option, but its declining costs have changed when it is deployed versus other options.

KEY LEARNING 5: Storage and photovoltaics (PV) complement each other.

KEY LEARNING 6: Cost reductions and the value of backup power increase the adoption of building-level storage.

KEY LEARNING 7: Storage durations will likely increase as deployments increase.

KEY LEARNING 8: Seasonal storage technologies become especially important for 100% clean energy systems.

Each of the following sections provides additional insights into the eight key learnings, and we conclude with remaining uncertainties that could be explored to further advance understanding of the role of storage in the evolving U.S. power grid.

KEY LEARNING 1

Storage Is Poised for Rapid Growth

The SFS report *Economic Potential of Diurnal Storage in the U.S. Power Sector* (Frazier et al. 2021) demonstrates the growing cost-competitiveness of energy storage. Using a state-of-the-art national-scale capacity expansion model, we find that diurnal storage (<12 hours of duration) is economically competitive across a variety of scenarios with a range of cost and performance assumptions for storage, wind, solar PV, and natural gas (NG).

Figure 1 illustrates that across all scenarios, deployments of new storage ranges from 100 to 650 gigawatts (GW) of new capacity. This large range is driven by a variety of factors, including storage costs (Key Learning 2), natural gas prices, and renewable energy cost advancement, but even the most conservative case represents a fivefold increase compared to the installed storage capacity of 23 GW in 2020 (the majority of which is pumped storage hydropower).

It is important to note that significant deployments of both renewable energy and storage are deployed even without additional carbon policies, demonstrating their increasing cost-competitiveness as resources for provision of energy and capacity services.

Modeled scenarios result in significant, but not complete, decarbonization, where power sector emissions are reduced by 46%–82 % compared to 2005, and variable renewable energy (VRE) reaches shares of 43%–81% nationally by 2050. Durations with 4–6 hours are the most common, driven by the inherent synergy with PV (Key Learning 5), but longer durations are often deployed in the later modeled years (Key Learning 7). The primary drivers behind storage growth and the evolution of storage development were explored in Frazier et al. (2021) and other SFS reports—as highlighted in the following key learnings.

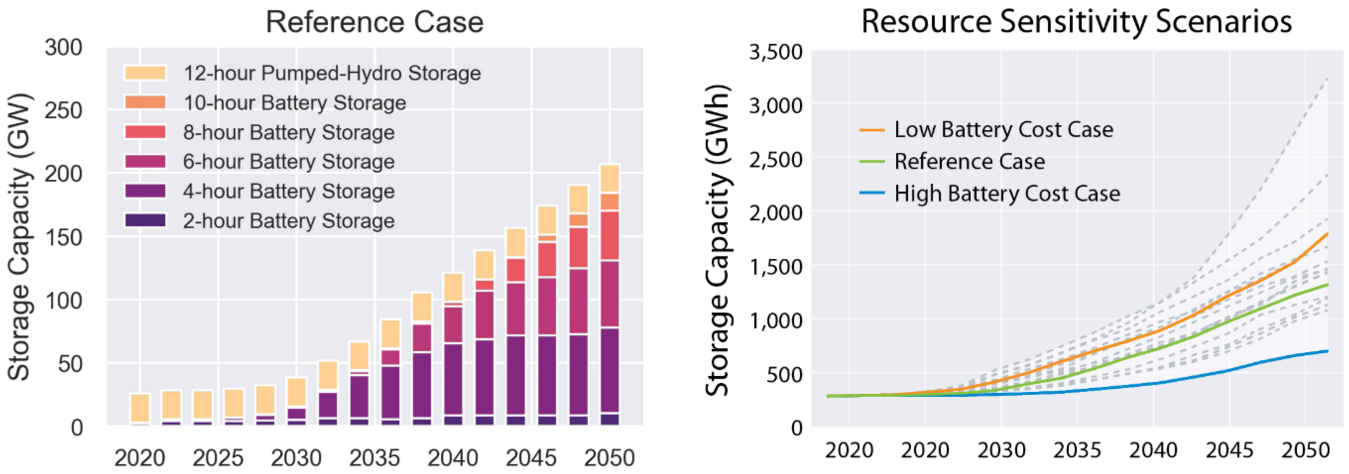

Figure 1. National storage capacity in the reference case grows to about 200 GW by 2050, deploying a range of durations (left) This translates to about 1,200 gigawatt-hours (GWh) of stored energy (right), with a wide range of deployments.

KEY LEARNING 2

Recent Storage Cost Reductions Are Projected To Continue, with Lithium-Ion Battery Continuing To Lead in Market Share for Some Time

The SFS report *Energy Storage Technology Modeling Input Data Report* discusses the future cost projections for utility-scale battery energy storage systems and other technologies that drive much of the anticipated growth identified in Key Learning 1.

Most of the stationary storage deployments that will occur in the near term are expected to be in the form of batteries, particularly LIBs. The dominance of LIBs, at least in the near term, has been driven by growth of this technology across multiple markets, including consumer electronics, stationary applications, and especially electric vehicles.

Figure 2 provides an example of historical and projected future costs of lithium-ion battery packs, illustrating a rapid decline in recent years. The chart also shows the vast majority of battery deployments are for transportation applications, which will likely be the most important drivers of battery technology development and battery cost declines in general.

We used a variety of future cost projections for utility-scale stationary battery energy storage systems (BESS) to evaluate total system cost, including inverter, balance of system, and installation. An example of a cost projection for batteries with 2–10 hours of usable duration that is used in the SFS reference scenario is shown in **Figure 3**.

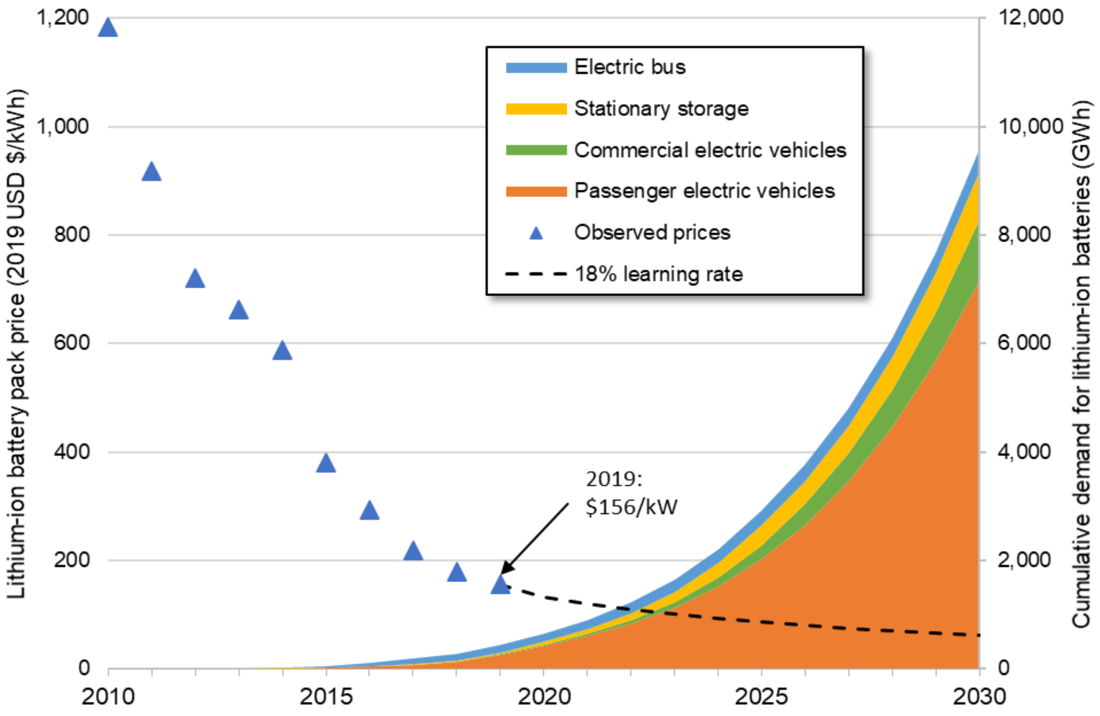

Figure 2. Lithium-ion battery pack costs have dropped by more than 80% over the past decade and are expected to continue to fall based on continued scale of production, driven largely by electric vehicle demand.

2021 values from BloombergNEF[3] are $132/kW. Data Source: Frith and Goldie-Scot 2019

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[3] *"Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite," BloombergNEF, November 30, 2021,* https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.

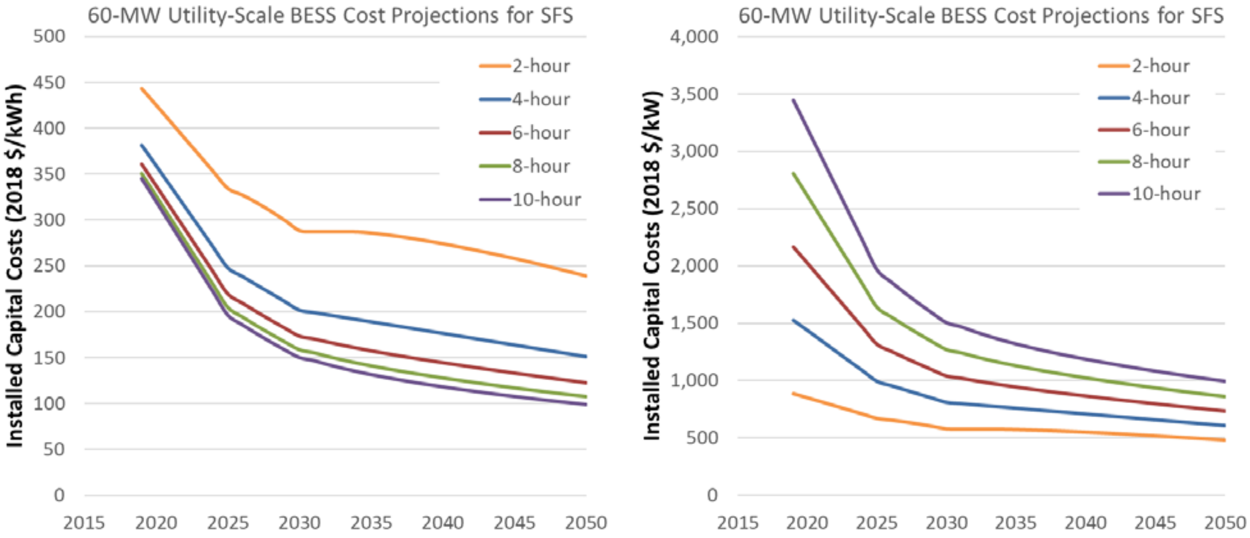

Figure 3. The utility-scale BESS Reference Scenario projects continued cost reductions. The left panel measures cost on a $/kWh (usable energy) basis, while the right panel measures costs based on $/kW (maximum direct current [DC] output power). Projections assume a 60-megawatt DC project.

The left curve shows the total cost per installed kilowatt-hour (kWh) of usable capacity, which is a common measure used in the battery industry. This is the total cost of installation, which for stationary applications includes both the power-related costs (associated with the equipment that converts grid electricity into stored electricity and back again) and the energy-related costs (the storage medium). The power-related costs typically do not scale with duration, meaning they are the same for a 2-hour system and a 10-hour system, which is why the costs per kWh decrease as duration increases (power costs are divided over a larger number of kWh). (This breakdown of costs for power and duration is illustrated in Figure 4.) The right curve shows the cost per kilowatt (kW), which is a more conventional measure of power plant costs used in the utility industry. By this measure, costs increase as a function of duration because for a fixed amount of power capacity, longer durations require additional module capacity. As durations increase, battery modules (the energy component) become the dominant source of costs. As module costs decrease over time (and projected module costs decrease at a greater rate than the power-related components), overall system costs decrease at a greater rate for longer-duration battery storage than shorter-duration battery storage.

While the majority of near-term storage deployments are expected to be LIBs, various technologies could enter the market as their costs fall or as longer-duration storage increases in value (Key Learning 7). **Figure 4** summarizes capital cost estimates for 15 energy storage technologies of different storage types and various stages of commercialization. To derive a total cost, the energy-related costs (x-axis) are multiplied by the number of hours (duration) and added to the power-related costs (y-axis). Figure 4 also delineates cost regions of this relationship that might be more or less appropriate for short or long duration. Using LIBs as a baseline, the blue lines indicate market segments where alternative technologies are (or could be) more cost effective as they are commercialized.

Note the distinction between these power- and energy-related components is not absolute for most technologies and isolating these components can be difficult. There are many additional important factors not illustrated in Figure 4, including round-trip efficiency and potential siting restrictions discussed in detail in Augustine (2021).

Because of the distinction between power- and energy-related costs, certain technologies may be more appropriate for different applications based on the duration needed. Technologies with low power-related

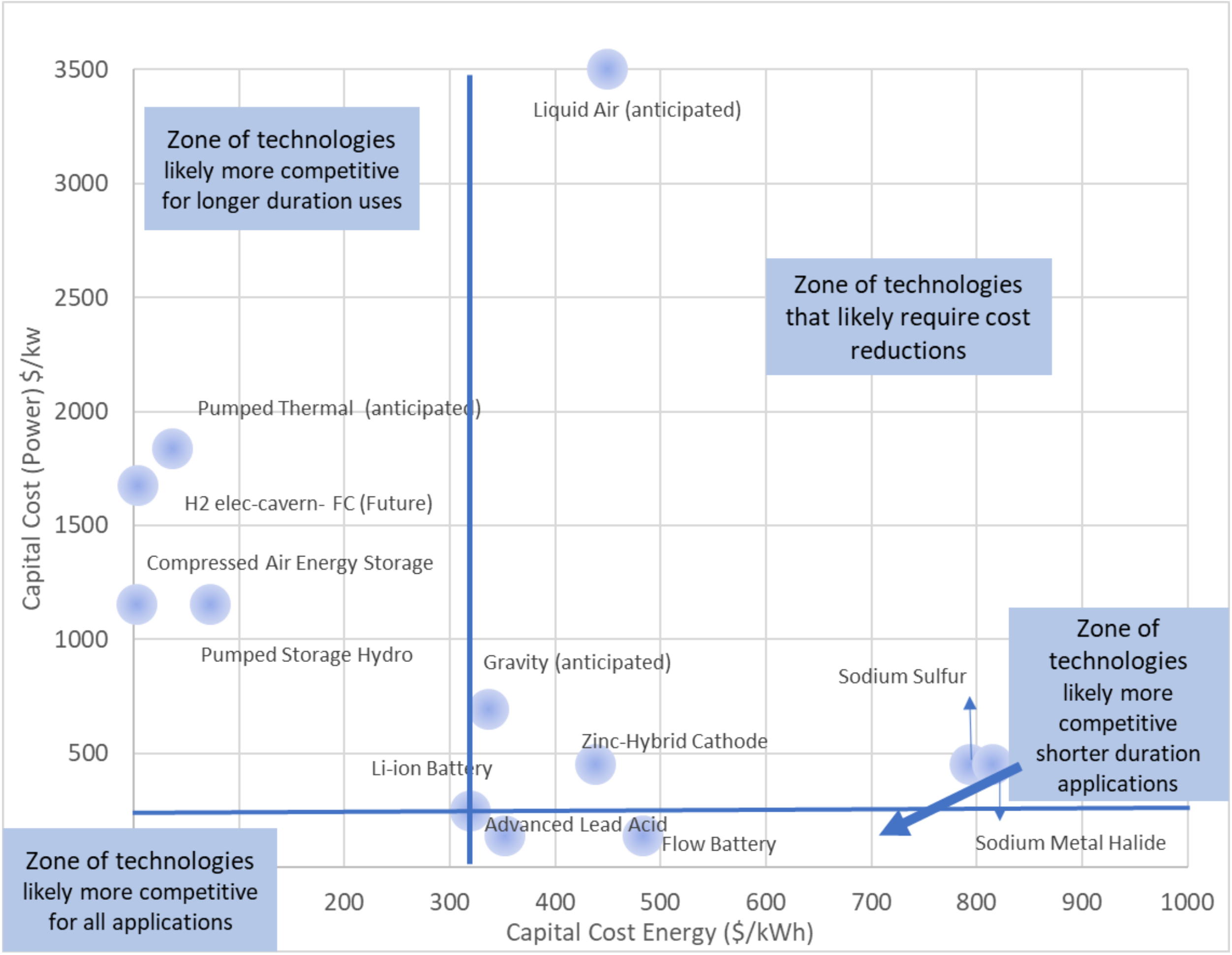

Figure 4. Capital cost for energy ($/kWh) versus capital cost for capacity ($/kW) for various technologies. Technologies with low power-related costs (but high energy costs) may be better suited for short-duration applications, whereas technologies with higher power-related costs and low energy related costs may be more competitive in longer-duration applications. Anticipated costs may change as technologies evolve and are commercialized.[2]

costs (but high energy costs) may be better suited for short-duration applications, while devices with higher power-related costs but low energy-related costs may be more competitive in longer-duration applications. The relative importance of various applications is discussed in Key Learning 3. As the grid evolves, there may be a growing role for longer-duration applications (Key Learning 7) that could increase opportunities for more technologies. The area in the far left of Figure 4 contains technologies with very low energy-related costs (utilizing underground caverns or reservoirs) that could be well-suited for seasonal storage applications (Key Learning 8).

Overall, LIBs are currently dominating storage installations and poised for future installations, but other storage technologies will likely continue to improve in the future. As the power system evolves and the role of storage changes over time, other technologies could have new opportunities if they can compete with LIB prices.

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[3] Shown in figures in this report as H2 Elec-salt cavern- CT implies a hydrogen electrolyzer stored in a salt cavern and then combusted in a combustion turbine. Label "H2 elec – cavern -FC" implies a hydrogen electrolyzer stored in a salt cavern and then converted to electricity via a fuel cell. Li-ion battery assumes 4-hour duration. Technology details are provided in Augustine et al. (2020).

KEY LEARNING 3

The Ability of Storage To Provide Firm Capacity Is a Primary Driver of Cost-Competitive Deployment

The SFS report *The Four Phases of Utility-Scale Energy Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System* discusses the multiple sources of value provided by energy storage that drive much of the anticipated growth identified in Key Learning 1.

The SFS modeling evaluates four general sources of value that storage provides to the grid:

- **Firm Capacity:** The ability to meet demand during system peak and replace conventional generators such as gas turbines.
- **Energy Time Shifting:** Storing low-value energy during periods of low net demand and discharging during periods of higher net demand. This includes avoiding unusable (curtailed) renewable energy generation.
- **Operating Reserve:** The rapid response to imbalances of supply and demand due to random variability and outages. Several reserve types include frequency regulation and spinning contingency reserve.
- **Avoided Transmission:** Offsetting the need for new transmission by installing storage in constrained regions and charging during periods of low transmission use and discharging during periods when the local transmission system is near or at maximum capacity. This also includes the ability to reduce new transmission needed for remote VRE resources.

Storage can provide multiple services, either simultaneously or at different times (often referred to as "value stacking"). To identify the relative value of these services in the evolving grid, we ran various scenarios, turning on or off the ability of storage to provide individual or combinations of reserve, capacity, and time shifting. While the value of transmission deferral is important (and included in the analysis), it is difficult to isolate, and very regionally specific (Jorgenson, Denholm, and Mai 2018), so we did not attempt to isolate deferred transmission value.

Figure 5 shows an example using the reference case (described in Frazier

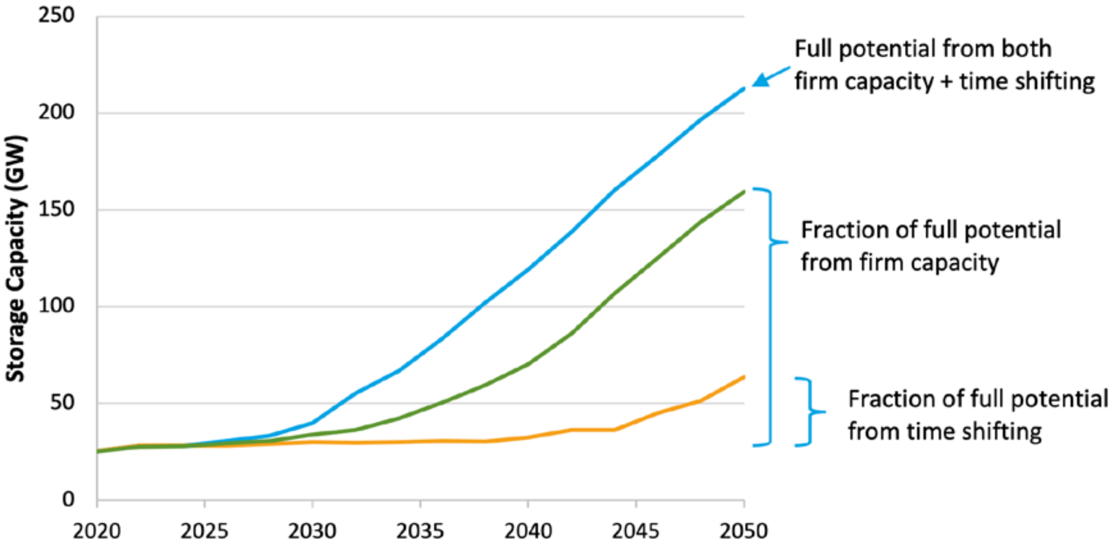

Figure 5. Restricting services that storage can provide shows capacity services are more important than time-shifting or operating reserves to achieve storage's maximum potential. Figure does not consider the impact of transmission-related benefits, which are important but very regionally specific.

et al. (2021), where storage that can provide all services achieves about 200 GW of deployment by 2050. When only providing time shifting, it achieves 30% of its "all four services" potential. However, if storage is economically valued for providing only firm capacity, 150 GW, or 75%, may be deployed. Providing operating reserves adds only a relatively small amount of deployment, driven in part by the limited operating reserves required (Denholm et al. 2021) and the saturation of reserve requirements that occurs from storage deployed primarily to provide capacity and time-shifting services.

Overall, this demonstrates that the ability of storage to provide firm capacity and offset the need for conventional generation to meet peak demand is critical to realizing its full potential. The actual ability of storage to provide firm capacity is largely determined by its duration and correlation with the duration of the net load peak in the region deployed. The duration of net load peak is affected by factors including solar and incremental storage deployment (Key Learning 5 and 7).

KEY LEARNING 4

Storage Is Not the Only Flexibility Option, but Its Declining Costs Have Changed When It Is Deployed Versus Other Options

The ability to improve the flexibility of the power system, meet peak demand, and help address the increased variability of net demand has often been expressed in terms of a flexibility supply curve. **Figure 6** provides an example of this concept, illustrating groups of resources that can provide flexibility services.

Historically, storage was seen as one of the most expensive options to increase grid flexibility. However, decreased costs are acting to potentially shift its relative position on the flexibility supply curve. Despite this shift, it is important to emphasize that storage is only one of several resources that

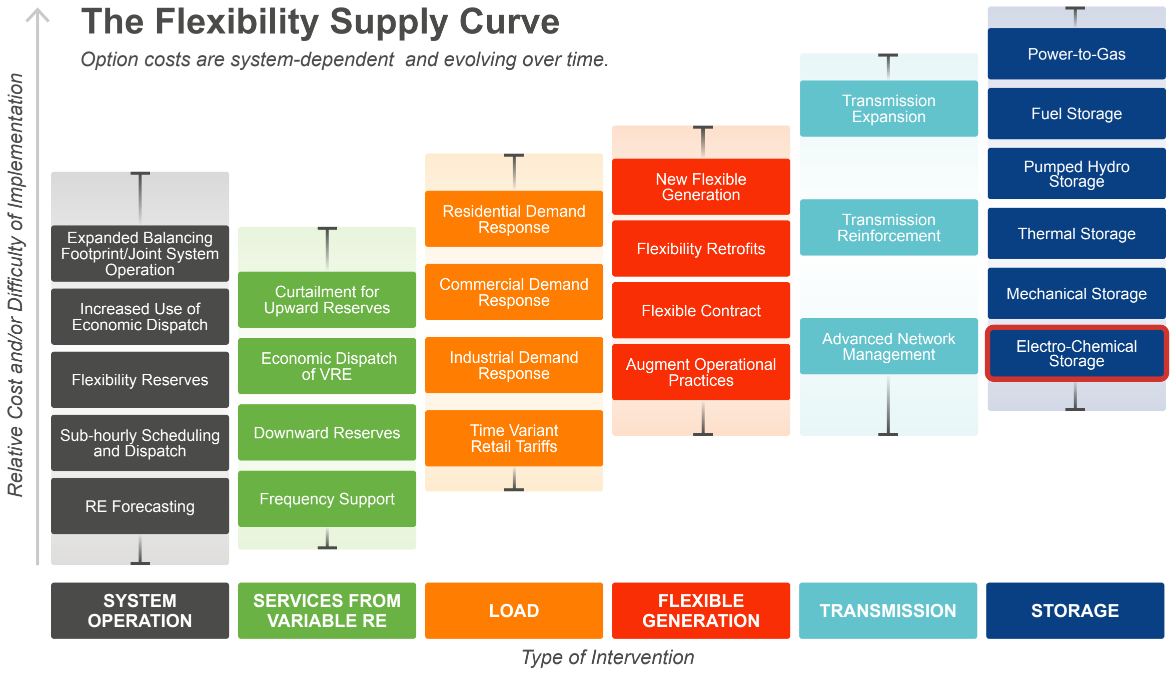

Figure 6. The flexibility supply curve

can provide flexibility to the grid to better align supply of generation with demand for electricity.

Cost-effective decarbonization will require consideration of all resources, including the largely untapped potential flexibility in end use electricity demand. Flexible demand—which can be implemented through a variety of mechanisms from price signals to colocation with distributed energy resources to flexible EV charging—can provide many of the same services as storage, including reduced peak net demand and shifting the timing of variable generation (Langevin et al. 2021; Dvorkin 2018).

Figure 7 shows the potential of both flexible demand and storage to be utilized significantly in the power sector. These results are from supplemental analysis performed for this report Columns 1 and 3 provide results from base scenarios in Frazier et al. (2021). Columns 2 and 4 assume additional demand response deployments to evaluate their impact on storage and overall investment decisions. In these cases, flexible demand reduces the overall need of firm capacity and the value of energy time shifting. As a result, storage deployment is reduced, particularly in the moderate storage cost scenario—highlighting potential competition between flexible demand and energy storage.

More research is needed to thoroughly understand the potential opportunities for demand response deployment, considering implementation costs, social acceptance, availability during periods of net peak (which may shift with increased variable generation deployment), and implementation mechanisms (Raman and Barooah 2020; Müller and Möst 2018; Parrish et al. 2019). While storage may be increasingly competitive against resources such as flexible demand, least-cost decarbonization requires analysis of the suite of flexibility options that can help enable VRE and other clean energy resources.

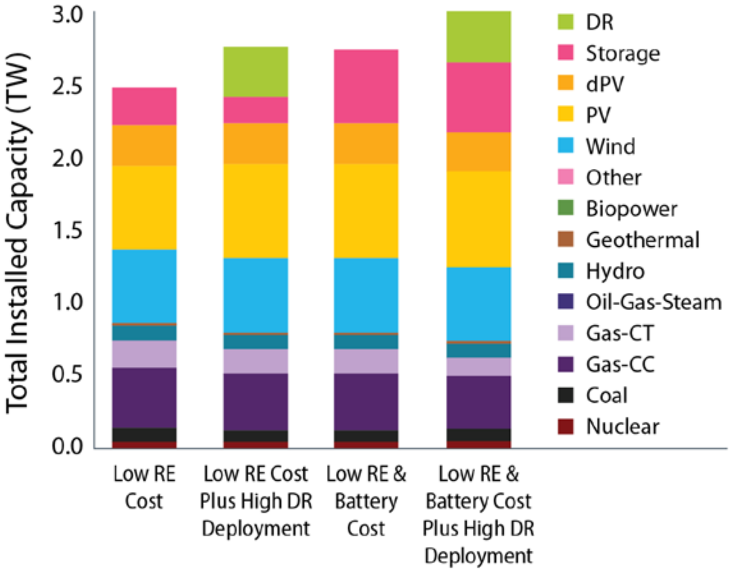

Figure 7. Increasing load flexibility and responsive demand reduces the need for storage capacity in 2050 for the low RE cost and low RE/battery cost scenarios with and without high demand response contribution.

KEY LEARNING 5

Storage and PV Complement Each Other

The SFS report *Grid Operational Impacts of Widespread Deployment* demonstrates the highly synergistic relationship between diurnal storage and variable generation, particularly with solar PV. As PV is deployed, it changes the shape of the net load (defined as the normal load minus the contribution of VRE resources).

Figure 8 illustrates an example of how the net load changes during a peak day in California where PV contribution increases from 0% to 20% of annual load. In nearly all locations that exhibit a midday to evening peak demand, a key result of increased PV deployment is the reduction in the length of the peak net load period. This decreases the duration of storage (and therefore costs) needed to provide firm capacity, which is a major source of value (Key Learning 3).

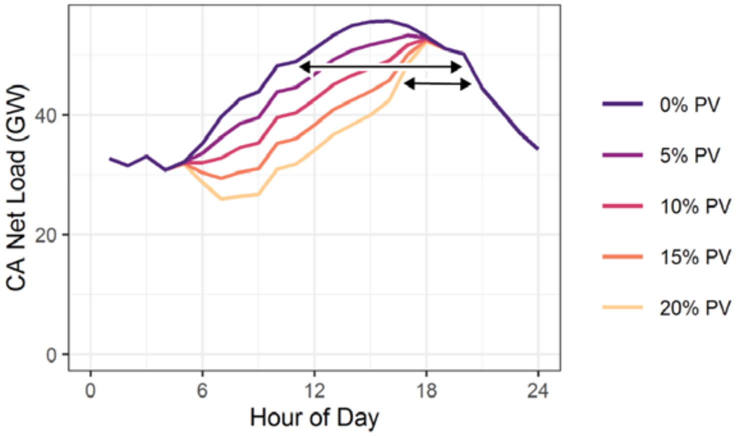

Figure 8. Increased deployment of PV demonstrates the reduced duration of net load peaks

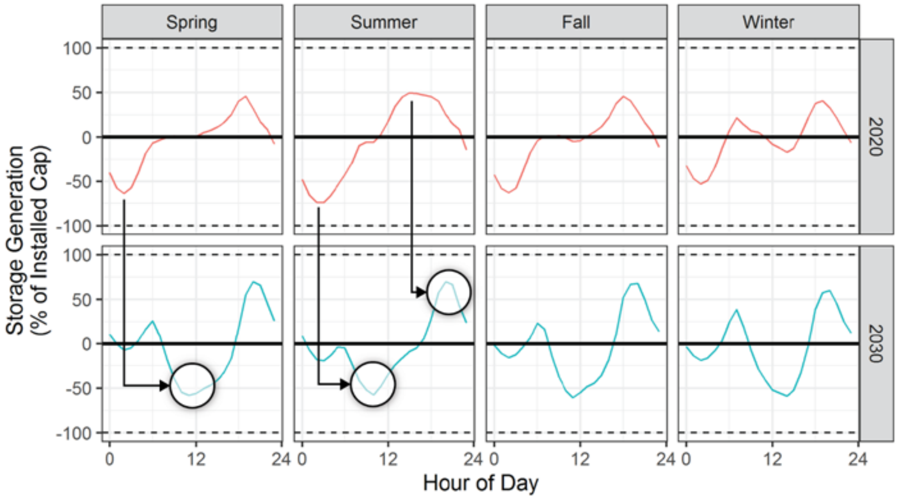

Figure 9. Increased deployment of PV demonstrates the reduced duration required for energy storage to provide firm capacity.

Figure 9 illustrates how the operation of storage can change in response to changing net load as PV deployment increases. The top curve shows the national average diurnal storage generation profile for the (simulated) 2020 conditions, where storage charges mostly at night, which corresponds to the lowest net load levels. The bottom panel shows the results from a 2030 case, where PV deployment has increased substantially. Storage charging has shifted mostly to the middle of the day, coincident with the availability of excess low-cost PV energy.

However, the most important change in terms of storage value occurs in the discharge pattern. During the summer peak in 2020, the storage must discharge for longer duration at partial output (on average), reducing its ability to reduce the system peak. In the 2030 case, the storage can discharge at closer to full output (on average) due to the solar creating a narrower peak later in the day.

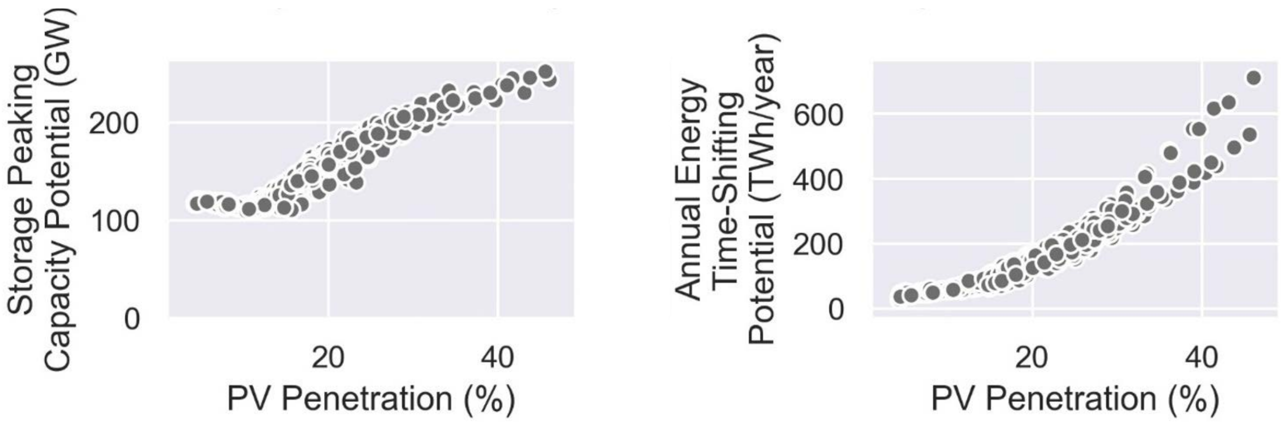

Figure 10. National peaking capacity potential for diurnal storage (up to 12 hours) as a function of PV contribution (left) and national diurnal energy time-shifting potential as a function of PV contribution (right).

The change in the peak net load shape increases the potential for storage to serve peak demand and increases time-shifting opportunities. **Figure 10** (left) shows the national potential for diurnal storage (<12 hours) to provide peaking capacity in each year of each scenario, plotted as a function of PV contribution. This curve represents the ability of storage to reliably provide firm capacity during periods of high demand and potentially replace conventional peaking capacity. The national peaking potential of storage doubles relative to 2020 levels at about 35% PV contribution. It ultimately plateaus as net load peaks in many regions are shifted to winter periods of low PV output.

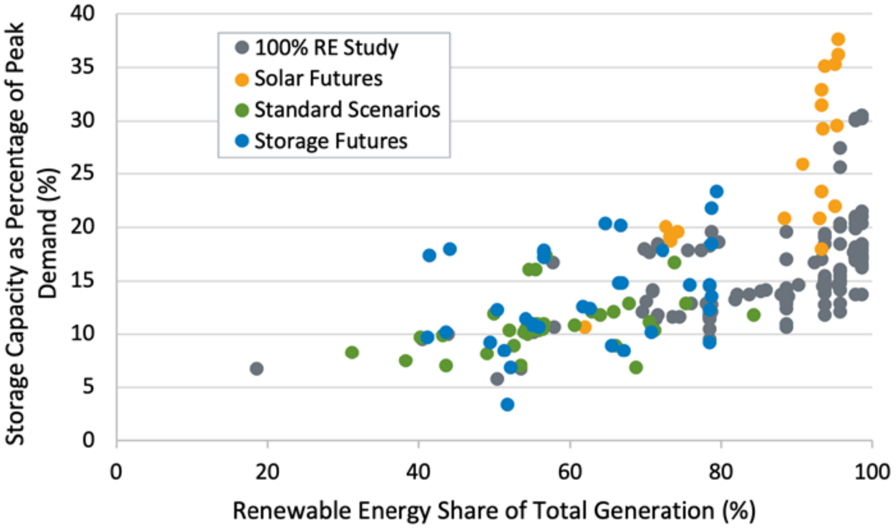

Figure 11. Storage capacity as a function of renewable energy contribution (%).

100% RE Study: Quantifying the Challenge of Reaching a 100% Renewable Energy Power System for the United States (Cole et al. 2021)

Solar Futures: Solar Futures Study (DOE 2021)

Standard Scenarios: 2020 Standard Scenarios Report (Cole et al. 2020)

Storage Futures: Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector (Frazier et al. 2021)

As PV deployment increases, it also increases the potential for energy storage to provide time-shifting potential, shown in Figure 9. The relationships between wind and diurnal storage are less correlated, as wind does not exhibit a consistent daily pattern, and the synergies between wind and storage occur across longer time periods. There are also important relationships between wind and the ability of storage to provide transmission benefits (Jorgenson, Denholm, and Mai 2018), making the overall interaction between storage and wind more complicated than the interaction between storage and PV.

The increase in value and opportunities for energy storage translates into increased storage deployments as the role of VRE in the power sector increases.

Figure 11 shows total storage power capacity as a function of renewable energy contribution for a range of assumptions and constraints across scenarios from multiple studies. Collectively, this set of studies considered more than 200 scenarios, with renewable energy contributions ranging from 20% to 100%, showing the strong relationship between VRE and storage deployment across a large number of scenarios with varying assumptions and constraints.

KEY LEARNING 6

Cost Reductions and the Value of Backup Power Increase the Adoption of Building-level Storage

The SFS report *Storage Futures Study: Distributed Solar and Storage Outlook: Methodology and Scenarios* discusses how the adoption of distributed (behind-the-meter) PV paired with battery storage systems may evolve in the coming decades (Prasanna et al. 2021). The study uses new capabilities in NREL's Distributed Generation Market Demand (dGen) model[3] to project customer adoption of PV-plus-battery systems for the contiguous United States out to 2050. Collectively, the results of the examined scenarios characterize the future potential for behind-the-meter storage and identify the key drivers of adoption.

As modeled, there is significant economic potential for distributed battery storage systems (coupled with PV) under all studied scenarios, ranging from 85 GW of 2-hour duration LIB storage to 244 GW (170 GWh to 490 GWh). However, customer adoption potential is much lower due to long payback periods. Lower battery costs and higher perceived value of backup power increase customer adoption in the modeling.

Lower cost of PV also significantly impacts adoption of PV-plus-battery storage systems and, additionally, storage adoption can be nonlinear with PV cost reductions. In addition to the main scenarios presented in the report, we evaluated a scenario with breakthrough (very low) PV cost projections *and* low battery costs (consistent with costs in the Advanced Battery Cost Scenario from the Solar Futures Study [DOE 2021]). Under this scenario, projected adoption of distributed battery storage systems surpasses 40 GW (82 GWh), as shown in **Figure 12**—more than double the projected adoption in the 2x Backup Value + Advanced Cost Batteries Scenario.

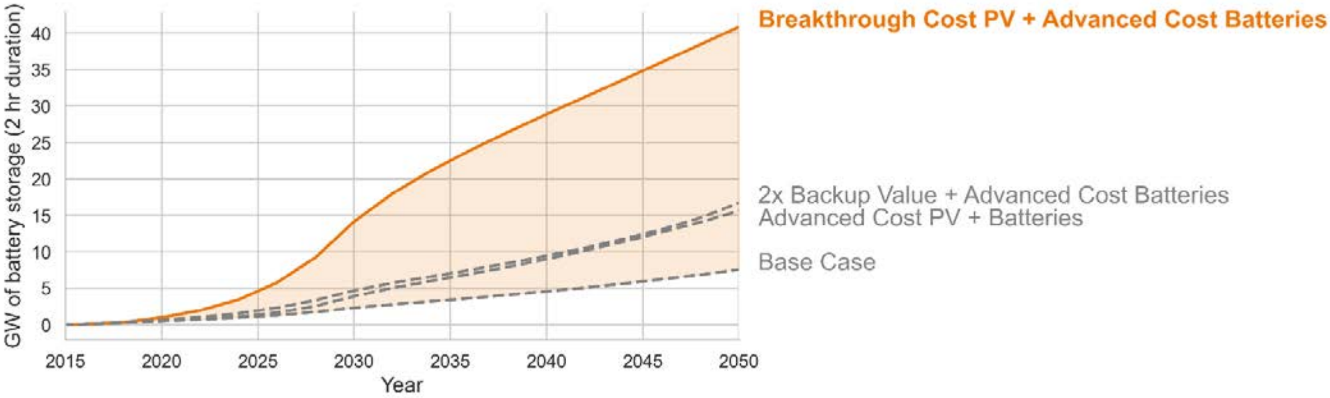

Figure 12. Projected adoption of distributed storage (GW of 2-hour duration storage systems coupled with PV) increases over time as costs decrease, with a significant jump if there are breakthrough PV costs.

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[3] *"Distributed Generation Market Demand Model," NREL,* https://www.nrel.gov/analysis/dgen/.

KEY LEARNING 7

Storage Durations Will Likely Increase as Deployments Increase

Key Learning 3 demonstrated the importance of providing firm capacity toward economic deployment. A key element of determining the cost-competitiveness of storage in providing firm capacity is determining the minimum duration required. In much of the United States, local market operators have determined that 4 hours of duration is sufficient to meet the summer peaks as detailed in Denholm et al. 2021b.

As storage deployment increases, the net peak load periods become wider, requiring more stored energy (longer duration) to provide the same level of firm capacity. **Figure 13** shows nationwide net demand during a three-day period of high demand with varying amounts of storage in the reference 2050 Storage Futures Scenario. It also shows the net demand in sensitivity cases with more or less storage. Increased levels of storage deployment widen the peak periods (producing a flatter net load) and thus increases the amount of stored energy required to provide firm capacity and continue reducing the net peak demand.

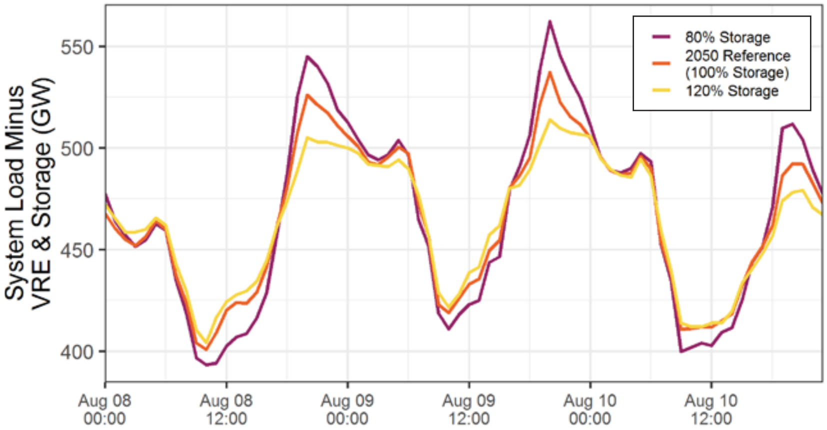

Figure 13. As storage deployment increases, the net load peak widens, requiring longer-duration storage to provide firm capacity.

Key Learning 5 demonstrated that increased PV deployment helps offset this effect; however, there are limits to this benefit, and at some point, shorter-duration storage is anticipated to be derated (reducing value), which provides additional incentive for deployment of longer-duration storage.

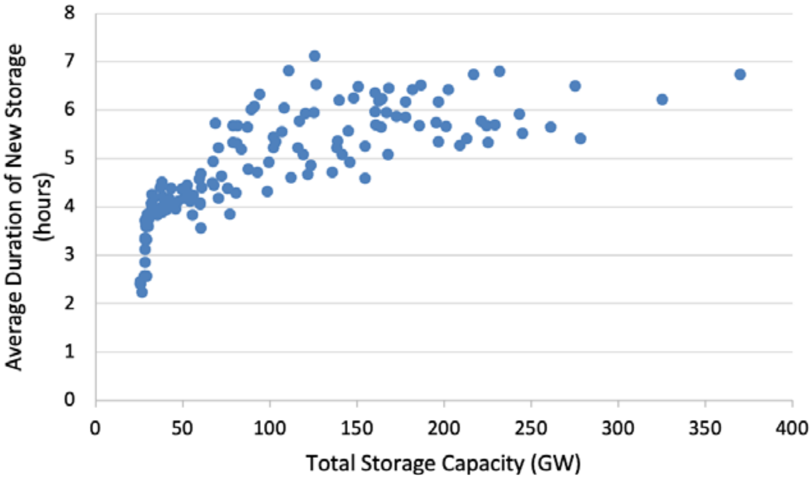

Figure 14. The average duration of new storage deployments increases as the total amount of storage capacity grows, up to approximately 200 GW (using reference storage costs).

Source: Frazier et al. 2021

This effect is observed in the SFS results. **Figure 14** shows the average duration of new storage deployments versus total storage capacity in the scenarios with reference battery costs. Initially, deployments are largely 2–4 hours, resulting from narrower peaks that primarily occur during summer afternoons. These peaks are maintained as PV deployments create the narrowing effect discussed in Key Learning 4. Storage duration increases as storage deployment grows to meet the longer-duration peaks. This presents opportunities for emerging technologies capable of longer durations, or even for the next generation of existing long-duration technologies such as pumped storage hydropower.[4]

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[4] *As discussed in the SFS report The Challenge of Defining Long-Duration Energy Storage (Denholm et al. 2021a), there is no universally agreed-upon definition of long-duration storage, but 10–100 hours is often used.*

KEY LEARNING 8

Seasonal Storage Technologies Become Especially Important for 100% Clean Energy Systems

The main SFS scenarios evaluate significant, but not full, decarbonization. Yet these scenarios, along with scenarios evaluated in related work point toward the potential role of multiday storage or seasonal storage as systems move to very high renewable energy contributions (>90% VRE) (Cole et al. 2021).

Figure 15 shows the challenge of meeting the seasonal mismatch as the contribution from VRE increases. These results are derived from a set of analysis evaluating 100% decarbonization scenarios (Jorgenson et al. 2022). In these scenarios, 94% of national demand is met by VRE plus hydropower and geothermal, where the remaining 6% of demand is met by renewably-fueled thermal resources such as combustion turbines burning hydrogen and biofuels. The top panel shows the patterns of the remaining

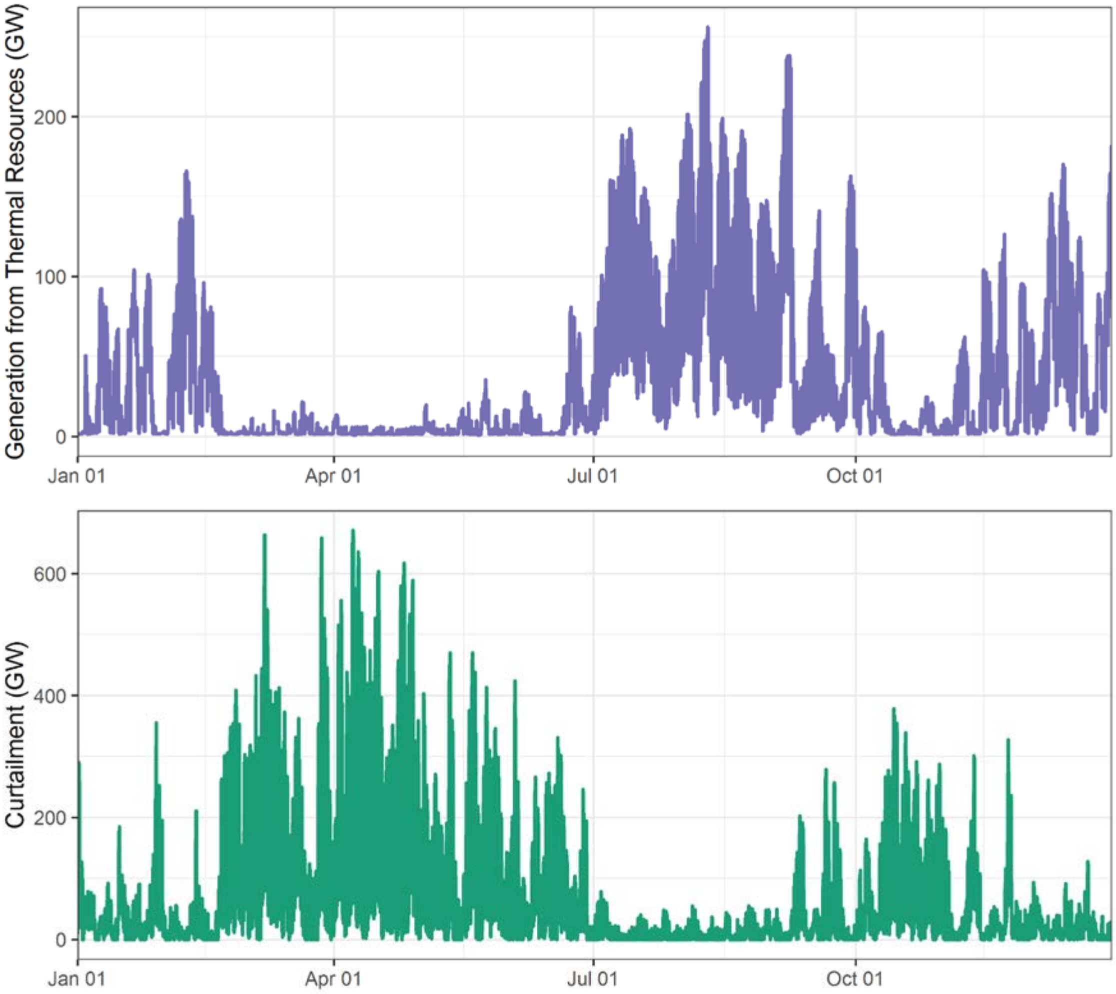

Figure 15. Seasonal mismatch of renewable energy supply and electricity demand demonstrates the potential opportunity for seasonal storage. The top graph indicates significant thermal resource usage in the summer while renewable energy curtailment is dominant in the spring in the lower graphic.

hourly demand and significant use of these thermal resources, particularly in the summer during periods of relatively low wind output and in the winter during periods of relatively low solar output.

The ability of VRE and diurnal storage to meet this demand economically is reduced, as the supply of electricity is already saturated during much of the year, illustrated by the amount of curtailment shown in the lower panel. Any additional diurnal storage will sit idle during most of the year, reducing its cost-effectiveness. Seasonal storage may provide an economic alternative by storing excess generation in the spring and fall and shifting it to summer and winter.

Figure 16 shows the results from an additional set of national cases, evaluating 100% clean energy scenarios (Cole et al. 2021). In these cases, seasonal storage was simulated in the form of combustion turbines using renewably derived fuels such as hydrogen. In these scenarios, large amounts (greater than 400 GW) of seasonal storage technologies are deployed, demonstrating the value of having a technology that can overcome the seasonal mismatch in renewable energy production and electricity demand systems. Significant levels of storage of all durations could be deployed. If sufficiently cost-competitive, other seasonal storage technologies could also play this role in high renewable energy futures.

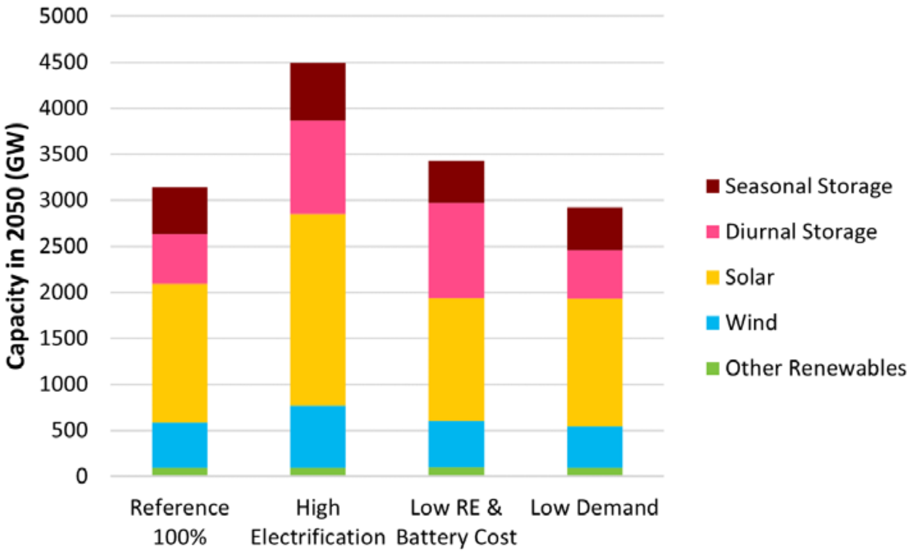

Figure 16. Capacity and generation in 2050 for the scenarios that reach the 100% requirement.

CONCLUSIONS AND REMAINING UNCERTAINTIES

The eight key learnings identified in the Storage Futures Study highlight important elements to help key stakeholders prepare for the evolving grid and the potential roles and value of storage assets. While results from the SFS indicate that storage solutions are poised to potentially grow by five times by 2050, several uncertainties remain that could alter the trajectories for storage growth and evolution identified in this study. Remaining uncertainties include:

Storage Growth and Compensation: Key Learning 1 summarizes the main conclusion from research throughout the Storage Futures Study, pointing to significant economic deployments of energy storage under various scenarios of grid evolution. Even without carbon policy, energy storage is highly competitive as a new source of peaking capacity, with many projections of significant growth (also beyond the SFS in the general literature). However, it is still important to recognize that technology or policy changes could impact the growth of storage. Despite important modifications to regulatory frameworks over the past decade, storage remains a challenging technology to appropriately value and compensate, particularly in restructured markets. If storage is not compensated fairly, it could result in nonoptimal storage deployment.

Technology Evolution: Key Learning 2 shows near-term dominance of LIBs in the storage market. However, significant R&D efforts have been underway to improve many energy storage technologies. Multiple technologies could emerge as competitive with LIBs, particularly for longer-duration applications. Stakeholders will likely benefit from considering future opportunities for emerging technologies and the next-generation of existing technologies (e.g., closed-loop pumped storage hydropower).

Storage as a Capacity Resource: Key Learning 3 demonstrates the importance of storage as a capacity resource. This value, along with storage deployment, depends on appropriately valuing and compensating storage—which relies on market rules that reflect the ability of storage to provide firm capacity with increasing deployment of storage and renewables. Rules could account for the impact of marginal-price-based markets on revenue to ensure it is sufficient to support the socially optimal amount of storage.

The Role of Flexible Loads: Key Learning 4 indicates that in order to decarbonize the power sector at least cost, leveraging a variety of flexibility resources, some of which may be lower cost than energy storage remains important. Establishing better characterization of demand response, flexible loads' realistic contribution potential, and cost is critical to better understanding the opportunities for energy storage.

Storage and Renewable Energy: With increasing goals to decarbonize the grid, Key Learning 5 highlights storage as an important enabling technology for deployment of clean electricity generation. We find significant synergy between diurnal storage and PV, but this could change due to several factors. Potential widescale electrification of heating could shift the peak load to the winter for much of the United States, which would create longer peaks that are more difficult to meet with storage and PV. This shift could increase the value of wind generation and longer-duration storage. Lower-cost longer-duration storage and its ability to increase transmission utilization could also present more synergistic opportunities for wind and storage.

Distributed Storage: Key Learning 6 shows there is significant economic potential for distributed storage under all studied scenarios, but customers are likely willing to buy systems only when their investments pay off more quickly. Emerging value streams and evolving compensation mechanisms for distributed energy resources could incentivize greater adoption. In addition, electrification could impact storage adoption positively or negatively. For example, a widescale shift to electric heating could dramatically increase the value of backup power for building owners during cold climate outages. Conversely, increasing adoption of electric vehicles and their potential to provide backup power could limit adoption of distributed storage. More research on customer behavior in this area is needed to understand these nuances.

Evolving Storage Duration: Key Learning 7 shows a general trend of increasing storage duration, with a high initial value for 4-hour storage given its ability to serve the summer peak demand. As storage deployments increase, longer durations generally become more competitive, although this trend is driven by multiple factors, such as even lower-cost short-duration storage that could offset the declining value of capacity. Alternatively, longer durations could provide additional services, such as grid resilience or providing a supplement or alternative to new transmission.

The Role of Seasonal Storage: Key Learning 8 suggests storage could have an increasingly important role as power systems approach 100% clean energy, and it could play multiple roles in the transformed power system. Key seasonal storage technologies involve the production and storage of renewably derived fuels, which can be used for multiple applications within industry or transportation. Therefore, seasonal electricity storage—or at least fuels used seasonally for electricity production—could share the infrastructure cost with other applications. This could even act to offset the amount of shorter-duration storage needed. The cost of these seasonal technologies and the trade-offs associated with efficiency and the interactions with shorter-duration storage need further study.

While significant uncertainty remains, the key learnings indicate the future energy system will likely include dramatic increases in electricity storage as a strong complement to renewable energy.

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