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ISSUE BRIEF

THE ROLE OF LONG-DURATION ENERGY STORAGE IN DEEP DECARBONIZATION: POLICY CONSIDERATIONS

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EXECUTIVE SUMMARY

Highlights

- Growth in targets for ambitious clean energy use and net zero greenhouse gas (GHG) emissions has increased interest in the role of utility-scale storage, including long-duration energy storage, to achieve deep decarbonization of the power sector.
- In future deep-decarbonization scenarios, storage holds potential to address multiday weather-related events that lower renewable production, as well as seasonal differences in renewable energy resource availability that can last for weeks.
- Today's storage technologies provide only hours of storage, though with design and operational changes, compressed air energy storage and pumped storage hydro may be stretched into days.
- Other less mature storage technologies may evolve to provide long-duration storage that will compensate for seasonal variations in renewable energy supply, for example, technologies that create hydrogen through low-carbon processes.
- Recent storage deployments in the United States have been driven by state storage mandates, utility investment, frequency regulation markets, and declining battery costs.
- Policymakers can play a role in driving innovation, encouraging cost reductions, and assessing the benefits of storage to provide greater options for maintaining reliability in future deeply decarbonized grids through research and development, demonstration projects, and regional studies. New approaches to financing, planning, and procurement could reduce barriers to the adoption of long-duration storage technologies.

LIST OF ABBREVIATIONS

APS	Arizona Public Service	MWh	megawatt-hour
ARPA-E	Advanced Research Projects Agency–Energy	NYPA	New York Power Authority
BEST Act	Better Energy Storage Technology Act	O&M	operations and maintenance
CAES	compressed air energy storage	PCM	phase change material
CAISO	California Independent System Operator	PSH	pumped storage hydro
CCS	carbon capture and storage	PSB	polysulfide bromide
CCUS	carbon capture, utilization, and storage	PUC	public utilities commission
CEC	California Energy Commission	PV	solar photovoltaic
CPS	clean peak standard	P2G2P	power to gas to power
CPUC	California Public Utilities Commission	RD&D	research, development, and demonstration
CSP	concentrating solar power	RFP	request for proposals
CSP-TES	concentrating solar power with thermal energy storage	RPS	renewable portfolio standard
DAYS	Duration Addition to Electricity Storage program	RTO	regional transmission organization
DOE	U.S. Department of Energy	SCE	Southern California Edison
EIA	U.S. Energy Information Administration	SGIP	Self-Generation Incentive Program
EV	electric vehicle	SMES	superconducting magnetic energy storage
FCEV	fuel cell electric vehicle	T&D	transmission and distribution
FERC	Federal Energy Regulatory Commission	TES	thermal energy storage
GHG	greenhouse gas	UPS	uninterruptable power supply
GW	gigawatt	VRB	vanadium redox flow battery
GWh	gigawatt-hour	VRE	variable renewable energy
IOU	investor-owned utility	ZBR	zinc-bromine
IRP	integrated resource planning		
ITC	investment tax credit		
LCOE	levelized cost of energy		
LCOS	levelized cost of storage		
MW	megawatt		

Context

The landscape for U.S. energy storage technology is changing rapidly. The vast majority (91 percent) of installed storage capacity is pumped storage hydro installed decades ago. However, the United States has experienced rapid percentage growth in battery storage deployments in recent years, bringing installed capacity to roughly one gigawatt. Economies of scale spurred by electric vehicle expansion have accelerated growth in lithium-ion battery storage and enhanced the ability to build battery storage projects rapidly. Deployment of lithium-ion batteries for utility-scale storage is projected to double or triple annually in terms of capacity over the next several years.

State and utility interest in storage is being driven in part by recent clean energy and net-zero GHG emissions targets. Interest is growing in the future role of utility-scale long-duration energy storage as U.S. electricity grid regions get closer to achieving deep-decarbonization levels targeted by these goals. In recent years, new storage capacity has been driven by state storage mandates in about a half dozen states, utility contracts, and frequency regulation markets, particularly in the PJM interconnection region.¹ Some states and utilities are exploring ways to encourage a more diverse set of new longer-duration storage technologies to help them integrate renewable energy technologies and ensure grid reliability. There is no universally agreed definition of long-duration storage, but the term often refers to storage that can discharge for longer than 10 hours. As renewable energy, such as solar and wind power, increasingly penetrates the grid, longer-duration storage could be used to meet electricity demand during weather events that reduce renewable production for days. As renewable energy reaches higher grid penetrations of 80 percent or above, long-duration storage that can extend to weeks could be used to smooth seasonal fluctuations in renewable energy availability—if it can economically compete with alternative approaches to managing supply and demand on the grid.

About This Issue Brief

Our objective is to inform policymakers about the state of storage technologies and how utility-scale storage, including long-duration storage, can support a decarbonized grid. We hope to spark conversation and further analysis that can help policymakers better understand future needs and consider how policy can support development of the

storage technologies that could help maintain reliability in the future grid. This issue brief begins with a description of the role of storage technology today, the mix and characteristics of storage technologies in use, and current policy drivers for storage. It then explores future grid needs and the potential use of long-duration storage to maintain grid reliability in deep-decarbonization scenarios.

Methodology

The findings and recommendations in this issue brief were developed through a review of current literature, expert interviews, and an expert convening. The literature review covered recent articles in academic journals and trade publications, as well as reports and factsheets from relevant trade associations, departments in the U.S. government, research organizations, storage developers, consultants, utilities, and nonprofits. Drawing from the same organization types, experts were interviewed directly early in the research process and invited to an in-person meeting to review research findings midway through research. Direct expert interviews were designed to identify useful data sources, discuss trends related to long-duration needs and technologies, and develop potential policy recommendations. Similarly, the in-person meeting was designed to surface insights on the same topics and review the current state of storage in the United States.

Findings

Most current storage technologies can store energy for less than one day. Most of the battery energy storage being installed today has the ability to operate for about four hours, which is likely to be sufficient for near-term power system needs (e.g., peak demand and ramping) and to provide grid services to maintain system reliability (e.g., frequency regulation). Most of the existing pumped storage hydro capacity operates for up to 10 hours, though with operational changes some plants could operate for one or more days, albeit at reduced capacity. Markets for storage to supply grid services (e.g., frequency regulation) are relatively small and the need for these services is likely to be fully met in the near term.

Long-duration storage has the potential to support deep decarbonization of the U.S. power sector. Storage could play an expanded role in providing sufficient capacity and energy to meet demand at all hours as more variable renewable energy sources come online. Modeling studies

of 100 percent clean energy and deep-decarbonization scenarios suggest that long-duration storage technologies could help address future grid needs when storm events reduce renewable generation for days and when seasonal variability of renewable supply extends for weeks. However, many studies show a greater need to address these issues when wind and solar exceed 50–60 percent of generation and that shorter-duration storage (four-hour batteries) could address near-term grid needs.

Long-duration storage will need to compete economically with alternative technologies and operational strategies, and the ability to increase long-duration storage capacity will depend on achieving significant cost reductions. Studies show that seasonal storage technologies would have to decrease substantially in cost—potentially by several orders of magnitude—to compete with alternative solutions such as dispatchable clean energy generation, load shifting, excess renewables capacity, conventional generating capacity with carbon capture, and transmission.

Several technologies can provide mid-duration storage of 8–12 hours or longer. Options include pumped storage hydro, thermal energy storage, batteries, compressed air energy storage, and liquid air. These technologies vary in their readiness level and cost for widespread mid-duration application. Very-long-duration storage (weeks) could potentially be met by technologies that serve multiple markets, enabling scaling as costs for additional applications decrease, and making use of existing infrastructure. Hydrogen and ammonia, which are commercially viable commodity products today, are both efficient energy carriers that could be integrated into existing delivery infrastructure in the future and provide long-duration storage in the process.

Recommendations for Policymakers

Encourage further development of long-duration storage to widen the range of options available to address grid needs in coming years. Achieving deep decarbonization of the power sector will require a suite of technologies, and solutions will likely vary by region. While it is unclear today which technologies will be most cost effective and deployed in the long term, policymakers should encourage further development of long-duration storage.

Drive improved understanding of regional grid needs and how storage could contribute to deep decarbonization. Improved methodologies for

modeling and assessing the benefits and costs of storage options are needed to effectively evaluate options. In addition, new regional modeling efforts can increase our understanding of grid needs and the relative costs of alternative solutions.

Support and encourage innovation in storage technology for future grid applications. Given the rapid change in grid needs and technologies, demonstration projects can play an important role in understanding technology options, performance, and cost. In addition, investments in research and development are important to continue to help drive down costs of technologies that could help meet future grid needs.

Develop new financing and procurement models that better match the needs of long-duration storage assets. As long-duration storage can be capital intensive and operate less frequently than storage used in other applications, financing approaches similar to those needed for infrastructure investments (such as transmission) may be needed. New procurement models may also be needed to encourage the deployment of assets that may not be financially viable in existing market contexts.

1. INTRODUCTION

The United States' electricity system is undergoing a rapid transformation to cleaner energy resources and more advanced low-carbon technologies. This shift is occurring along the entire electricity grid, which includes electricity generating units, transmission and distribution lines used to transport and deliver electricity, and consumers connected to the grid. To maintain steady, uninterrupted electricity supply, utilities and grid operators manage this infrastructure to keep the power placed onto the grid and drawn from the grid in constant balance. Storage technologies, which now allow electricity to be captured and available for use later, can profoundly impact how the grid functions.

Energy storage resources include a suite of evolving technologies that provide a wide variety of services,² many of which can aid the transition to a low-carbon grid. Battery energy storage has been expanding in the United States because of falling battery prices and increasing deployment of variable renewable energy (VRE) technologies. Fifteen states (plus the District of Columbia) and more than a dozen utilities have announced goals to achieve net-zero greenhouse gas emissions³ from electricity

generation or 100 percent clean energy between 2040 and 2050. To meet these goals, many utilities have planned to deploy substantial new VRE and storage capacity over the next decade. Already, many regional transmission organizations (RTOs)⁴ are undertaking market reforms that enable storage participation, while states are setting storage goals and other supportive policies. Policymakers are seeking to better understand the potential role of storage in grid decarbonization over the near, medium, and long terms as well as the policy support needed to guide technology development.

The roles of energy storage in grid decarbonization will change over time and vary geographically. Already, grid decarbonization has taken different paths across the country because of regional differences in infrastructure, resource potential, and regulatory context. Currently, new storage capacity—mostly battery storage—is being deployed in some regions to provide grid services such as frequency regulation (which has traditionally been provided by conventional electricity generators), address the daily variability of wind or solar energy, and reduce curtailment of these VRE generators. Over the mid-term,⁵ more advanced forms of energy storage that can operate for longer periods (days or up to a week) could help address grid issues resulting from higher VRE penetrations, such as extended VRE outages due to storm events. As we move toward a decarbonized grid, strategies that rely heavily on higher levels of VRE could experience seasonal differences in wind or solar availability that reduce generation for weeks at a time. Throughout the paper, we define “seasonal storage” as storage with a duration of weeks, as opposed to longer-duration storage more generally (with hours of discharge time and power ratings of at least tens of megawatts).

The extent to which storage technologies fit into the decarbonized grid depends on their cost relative to other solutions as well as the maturity and evolution of their technical characteristics. As clean energy deployment continues to rise, the future grid will require different forms of storage than those being deployed today—particularly for long-duration challenges and, eventually, seasonal-capacity challenges. No existing storage technology can yet meet seasonal storage needs economically, but some chemical energy storage technologies hold more promise than others. In addition, energy storage is not the only approach to addressing grid needs. The levels of transmission, dispatchable clean generating capacity, demand response, overall ability to balance generation to

load under uncertainty (grid flexibility), and—in the case of battery storage—management of safety concerns will influence the future role of storage.

This issue brief aims to help policymakers understand the current state of utility-scale energy storage in the United States, current policy drivers, and future storage needs. It provides policy recommendations that can facilitate long-duration storage development in support of deep grid decarbonization. We focus on utility-scale storage because long-duration storage needs are likely to be met by large-scale projects, rather than smaller distributed storage projects. Although energy storage can facilitate decarbonization in other sectors—such as transportation and heating for buildings—those sectors are also outside the scope of this paper.

2. OVERVIEW OF UTILITY-SCALE ENERGY STORAGE SYSTEMS

This section summarizes the main types of storage technologies, the roles that storage can play on the grid, the technologies currently deployed to meet grid needs, and the relative costs of each technology.

2.1 Storage Technology Characteristics and Roles

Energy storage systems can be categorized broadly into mechanical, electrochemical, electrical, chemical, and thermal technologies (see Figure 1), although some types of storage may cross multiple categories.⁶ Storage technologies can also be classified according to whether they store and dispatch electricity to be consumed immediately or act as “energy carriers.” For example, electricity discharged from pumped storage hydro and batteries, if not consumed immediately, must be transmitted and face “line losses” if transmitted over long distances. As energy carriers, technologies such as hydrogen and ammonia store energy and can be transported for consumption elsewhere (Brasington 2019).

The grid services a storage technology can provide are determined by the technology’s characteristics, including the electricity discharge duration, system size, instantaneous output, ability to cycle, operational lifetime, and other operating constraints. For example, very short discharge durations are needed for grid reliability functions, such as voltage or frequency regulation, while durations on the order of hours are needed for load shifting, peak

FIGURE 1

CLASSIFICATION OF ENERGY STORAGE TECHNOLOGIES BY THE FORM OF STORED ENERGY

Source: Argyrou et al. 2018.

FIGURE 2

ROLES OF STORAGE BY POWER, ENERGY, AND DURATION CHARACTERISTICS

Note: RES stands for renewable energy sources.

Source: Adapted from Argyrou et al. 2018.

shaving, and integrating VRE (Figure 2). No existing storage technology can play all these roles.

Figure 3 aligns storage technologies with the grid functions they may be best suited to provide, based on their discharge time and power rating. For example, several battery technologies have relatively low power ratings that suit them for providing frequency and power quality support, while many other technologies have moderate

power ratings well suited to supporting grid transmission and distribution. The dashed magenta box in Figure 3 highlights technologies most applicable to long-duration storage, with power ratings of at least tens of megawatts and hours of discharge time. Other technologies will need unforeseen technological and cost breakthroughs to reach weeks of storage duration at necessary power levels.

FIGURE 3

ENERGY STORAGE TECHNOLOGIES BY POWER CAPACITY, DISCHARGE TIME, AND MARKET SEGMENT

Note: TES: thermal energy storage; ZBR battery: zinc-bromine battery; VRB battery: vanadium redox flow battery; PSB battery: polysulfide bromide battery; NaS battery: sodium-sulfur battery; NaNiCl: sodium-nickel chloride battery; NiCd battery: nickel-cadmium battery; NiMH battery: nickel metal hydride battery; SMES: superconducting magnetic energy storage; KW: kilowatt; MW: megawatt; GW: gigawatt.

Source: Adapted from Argyrou et al. 2018.

2.3 Current and Near-Term Roles for Utility-Scale Storage

Compared with the range of potential roles for utility-scale storage discussed in Section 2.1, the roles of storage in today's grid systems have been limited to the following:

- Load Shifting and Generation Capacity:** Energy storage can be located in ways that either help the grid balance supply and demand across wide geographic areas, respond to shortages of electricity supply on the grid, or reduce load from the grid during “peak demand” periods, when demand is highest. Storage can reduce peak demand through “load shifting,” enabling specific loads to be met by
- Grid Management:** Energy storage can discharge power onto the grid to help balance the flow of grid electricity, rather than meet demand. Such “ancillary services” increase grid stability and security. Examples include frequency regulation (immediate power to counteract dips or surges in frequency that occur around normal load fluctuations), spinning/non-spinning reserves (power infrequently needed to

respond to the loss of a line or generator), voltage support (immediate power to keep grid voltage within a tight tolerance range), or “blackstart” (the ability to restart a shutdown generator without help from the grid).

- **Renewable Integration:** Energy storage can smooth VRE output using services called “ramping and load following,” which adjust for hourly changes in VRE output or electricity demand. Today, storage is used to address the daily variability of wind and solar on the grid, such as by enabling solar generation to meet peak demand even after sunset.
- **Transmission and Distribution Congestion Reduction and Investment Deferrals:** Storage assets deployed in key locations can often mitigate grid congestion caused by constrained capacity. Storage that improves transmission or distribution operation can be deployed to defer infrastructure investments. To date, storage has played a limited role in deferring transmission and distribution. However, storage is an increasingly attractive option because its costs are falling, and it requires shorter build times and a smaller physical footprint than transmission or distribution infrastructure.
- **Energy Price Arbitrage:** Storage resources can be charged during low- or negative-priced hours and discharged during higher-priced hours to reduce dispatch from generators with high fuel costs and variable operations and maintenance (O&M) costs.

The current full list of roles for storage is larger if distributed (customer-site) projects are taken into account; however, the focus of this paper is utility-scale projects.

The near-term need is to ensure that storage projects can provide multiple services, can compete with traditional resources (such as fossil fuels), and are properly compensated for all the services they provide (Hledik et al. 2017). The markets for some near-term storage services may evolve rapidly. For example, the storage capacity needed for ancillary services is small compared with the energy requirements for peaking and load-shifting. The total size of the frequency regulation market (which is only a portion of ancillary services) in RTO markets has been estimated at about three gigawatts (GW) (Denholm 2019). With such a shallow market, there will be strong competition for whatever ancillary services compensation evolves in regional markets.

Longer-term grid needs include storage resources that can provide days or weeks of discharge needed to aid renewable integration, provide backup power and resiliency, and defer transmission development substantially. There is no widely accepted definition of long-duration storage, and one may not yet be needed. For now, the U.S. Department of Energy’s (DOE) work on transformative technologies considers long-duration storage to refer to technologies dispatching within the range of 10 to 100 hours, a definition we use in this issue brief. Longer-term approaches to storage will differ from current approaches and are covered in Sections 4 and 5.

2.4 Current U.S. Utility-Scale Energy Storage Installations

In 2019, the United States had energy storage equivalent to nearly 25 GW of rated power, including utility, commercial and industrial, and residential deployments (Figure 4). Pumped storage hydro (PSH) constituted approximately 22.8 GW (91 percent) of this capacity. Almost all of the 42 existing pumped storage hydro projects were built decades ago to help nuclear facilities operate more continuously by using nighttime generation to pump water when loads are low. Today, PSH also helps balance the grid.

In recent years, U.S. deployment of utility-scale battery storage systems, particularly lithium-ion (Li-ion) batteries, has surged, reaching over 1,500 megawatts (MW) of installed capacity in 2019 (EIA 2020a). As of March 2019, California, Illinois, and Texas had the largest utility-scale battery storage capacities, collectively accounting for nearly half of all U.S. installations. Growth in battery installations is expected to accelerate because rising electric vehicle (EV) sales have driven down the price of lithium-ion batteries (BNEF 2019). The U.S. Energy Information Administration (EIA) projects that installed capacity will more than double in 2021 (EIA 2019b). Other estimates project even faster growth over the next five years (Wood Mackenzie 2020).

Several other storage technologies have been deployed in smaller quantities across U.S. markets. These include 405 MW of concentrating solar power with thermal energy storage (CSP-TES), 110 MW of compressed air energy storage (CAES), and 17 MW of flywheels. (see Figure 5) (EIA 2019a). Trends in U.S. storage deployment have mirrored global trends. Li-ion battery deployments have surged internationally in recent years, with South Korea and China leading the way. Global battery energy storage

FIGURE 4

HISTORICAL AND PROJECTED CAPACITY OF U.S. UTILITY-SCALE BATTERY STORAGE POWER

Note: Operating capacity in dark red refers to the cumulative deployments each year.

Source: EIA 2019b.

FIGURE 5

U.S. ELECTRICITY STORAGE CAPACITY BY TYPE OF STORAGE TECHNOLOGY, 2019

Note: Battery storage category includes lithium-ion, flow batteries, nickel-based batteries, sodium-based batteries, lead-acid batteries, and other technologies. Lithium-ion, however, represents 93 percent of batteries deployed. CSP stands for concentrating solar power, and CAES for compressed air energy storage.

Source: EIA 2019a.

capacity reached 8 GW, or 20 gigawatt-hours (GWh), in 2018 (St. John 2019), with Li-ion batteries making up nearly 85 percent of all new capacity installed (IEA 2019). Although PSH still accounts for 97 percent of total worldwide storage capacity (NHA 2018), the demand for Li-ion batteries for stationary storage and EVs has grown exponentially since 2016.

2.5 Relative Costs of Current Storage Technologies

Table 1 compares the capital and operating costs of today's storage technologies; see the appendix for more detailed technology comparisons. There is no single "cost of storage." A relatively new term, levelized cost of storage (LCOS) encompasses several cost metrics that collectively reflect important storage cost considerations. These considerations depend upon use case or application and role in the electricity marketplace, which define operational parameters (e.g., wholesale, transmission and distribution, commercial and industrial, residential). Key cost metrics include energy (measured in dollars per kilowatt-hour) based on annual energy output; capacity (dollars per kilowatt-year) based on operating costs per year; capital cost (dollars per kilowatt-hour) based on system cost per rated energy; and capital cost (dollars per kilowatt) based on system cost per rated power output.

Among these technologies, Li-ion batteries were on the steepest cost-reduction curve through much of the 2010s, and future costs are projected to continue declining, albeit at much lower rates (e.g., 4–7 percent per year). PSH and CAES have had few domestic deployments in recent decades, resulting in known operational costs for fully depreciated systems and greater uncertainty and range on current installed costs. CSP-TES is currently the highest-cost technology—cost reductions are projected but depend on continued deployments; economies of scale; and research, development, and demonstration (RD&D) gains (NREL 2019).

Compared with other generation sources, hybrid projects with co-located storage and photovoltaic (PV) or wind systems can add substantial value premium to projects. Modeling conducted by the Lawrence Berkeley National Laboratory found that adding storage to stand-alone PV or wind projects can result in a value add of between \$5 and \$29 per megawatt-hour (/MWh). Market differences, rather than the type of technology used, affect the ultimate value add more heavily. Co-located projects in California, for example, are shown to add \$26–29/MWh, while co-located projects in Texas add anywhere between \$5 and \$7/MWh (Ela et al. 2020).

RELATIVE COSTS OF CURRENT ENERGY STORAGE TECHNOLOGIES

TABLE 1

Technology	Power (GW)	Energy ^a (TWh)	Capital Cost ^b		Operating Cost ^b	
			(\$/kW)	(\$/kWh)	(\$/kW-year)	(\$/kWh)
Pumped hydro storage (PSH)	22.3	~20-60 TWh	\$2,638	\$165	\$15.90	\$0.0000025
Concentrating solar power with thermal energy storage (CSP-TES)	1.7	3.6 TWh	\$7,550	\$141 ^c	\$77.50 ^c	N/A
Lithium-ion (Li-ion) battery	1.3 ^d	1.5 TWh ^e	\$1,876	\$469	\$10.00	\$0.00003
Compressed air energy storage (CAES)	0.1	0.003 TWh	\$1,669	\$105	\$16.70	\$0.0021

Note: GW: gigawatts; TWh: terawatt-hours; \$/kW: dollars per kilowatt; \$/kWh: dollars per kilowatt-hour; \$/kW-year: dollars per kilowatt-year.

Sources:

^a EIA 2019a, Table 4.3, "Existing Capacity by Energy Source, 2018 (Megawatts)," and Table 4.7.B, "Net Summer Capacity Using Primarily Renewable Energy Sources and by State, 2018 and 2017 (Megawatts)."

^b Pumped storage hydro and CAES data: Mongird et al. 2019.

^c Lazard 2019.

^d Wood Mackenzie 2019.

^e Estimate per data in Cabral 2018.

3. CURRENT POLICY, MARKET, AND REGULATORY DRIVERS OF UTILITY-SCALE STORAGE

Opportunities for utility-scale storage are currently shaped by state policy and regulation, regional electricity markets, and federal policies—and they vary geographically. As of 2017, much of the U.S. energy storage capacity, including two-thirds of all utility-scale battery storage, was located in California and the PJM territory⁷ (EIA 2018a). This section summarizes some state actions and experiences.

3.1 State Policy and Regulation

States have driven utility-scale storage deployment through measures including procurement targets, financial incentives, demonstration projects, and changes to utility regulations. Institutional arrangements can influence storage deployment. For example, California's battery storage installations are largely utility-owned and provide energy-oriented services (serving demand for electricity), whereas PJM's large-scale batteries are owned by competitive generators and provide regulation services (managing the stability of electricity flow on the grid). Table 2 summarizes state-level actions.

TABLE 2

STATE-LEVEL STORAGE POLICY

STATE	FINANCIAL INCENTIVE	DEMONSTRATION PROJECT	PROCUREMENT TARGET	UTILITY REGULATION	STATE INITIATED STORAGE STUDY
AZ	●		●	●	
CA	●		●	●	●
CO				●	
MD	●	●	●	●	●
MA				●	
MI				●	
MN				●	●
NV	●		●	●	●
NJ	●		●		●
NM				●	
NY	●	●	●		●
NC					●
OR				●	
UT		●			
VT	●				●
VA	●	●	●	●	●
WA		●		●	

Source: Adapted from Twitchell 2019.

3.1.1 Procurement Targets

California enacted the first U.S. energy storage legislation in 2010, enabling the California Public Utilities Commission (CPUC) to set storage procurement targets for its three large investor-owned utilities, totaling 1,325 MW by 2020 (Table 3). To diversify technologies and use cases, CPUC limited PSH projects to 50 MW and broke the target into subcategories by point of connection, to include storage connected to transmission, distribution, and customer-sited applications (Twitchell 2019). The California Independent System Operator (CAISO), California Energy Commission (CEC), and CPUC partnered to develop a state energy storage roadmap addressing storage revenue opportunities, integration and connection costs, and project development timelines (CPUC 2014). Cumulatively, the regulated utility procurements have reached the state target and have satisfied almost all of the domain-specific requirements. However, many of these projects are scheduled to come online closer to the 2024 deadline (CPUC n.d.).

In 2016, when a leak at the Aliso Canyon natural gas storage facility threatened to cause blackouts, the CPUC prioritized electricity storage resources (as well as renewables and demand response) as a solution and allowed Southern California Edison (SCE) to procure four-hour duration energy storage projects on an emergency basis to meet capacity needs (Munsell 2017).

As of April 2019, five states had established procurement targets as mandates or goals, which together are expected to bring more than 14,000 MW of additional storage capacity by 2030 (Twitchell 2019). Many of these goals have been paired with studies of the potential for battery storage in these states (Hledik et al. 2018) or possible use cases. States are also increasingly considering the emerging concept of a clean peak standard (CPS) to drive storage deployment. Massachusetts has begun to establish a CPS, which would require utilities to procure clean resources to meet a certain percentage of their peak demand, including clean resources shifted using storage resources, much like a renewable portfolio standard (RPS). This policy has been examined by California, Arizona, and North Carolina (DiFelice 2020).

3.1.2 Financial Incentives

In 2016, the California legislature passed three bills focused on distributed storage and a fourth bill addressing the role of long-duration storage in renewable energy integration. The Self-Generation Incentive Program

TABLE 3

STATE TARGETS AND MANDATES FOR ENERGY STORAGE

State	Mandate Type	Amount	Year
CA ^a	Mandate for IOUs-utility scale	1,325 MW total (1% of 2020 annual peak load)	2020
	Mandate for IOUs-distributed storage	500 MW	N/A
MA ^a	Goal	1,000 MWh	2025
NJ ^a	Goal	2,000 MW	2030
NY ^b	Goal	3,000 MW	2030
OR ^a	Mandate per utility	10 MWh total (5 MWh per utility)	2020
VA ^b	Mandate per utility	3,100 MW total (2,700 MW and 400 MW, respectively)	2035
AZ ^b	Proposed goal	3,000 MW	2030
NV ^c	Goal	1,000 MW	2030

Notes: IOU: investor-owned utility; MW: megawatts; MWh: megawatt-hours.

Source:

a. Twitchell 2019; b. Baldwin 2020; c. Stanfield, J. 2020.

(SGIP) was updated to award incentives in relation to dollars per watt-hour instead of dollars per watt. This incentivized the development of projects capable of dispatching energy for longer than two hours, which was the average in the market (Ola 2016). Today, storage projects in California tend to provide a wider array of services than projects in other regions and are shifting toward long duration because of these, and other, state actions (EIA 2018b).

Several states use financial incentives—such as utility rebate programs approved by public utilities commissions (PUCs), state property tax incentives, income tax incentives (currently offered only by Maryland), and grants—to stimulate storage investments. Arizona's battery incentive is structured to encourage long-duration storage, offering the full incentive only for storage longer than five hours and prorating it for storage of shorter durations (Twitchell 2019). The incentive is directed to large industrial and commercial customers and requires customers to allow the utility to collect data on battery performance (SRP 2020).

3.1.3 Demonstration Projects

The degree of state involvement in demonstration projects varies greatly. For example, the New York Power Authority (NYPA) took a strong role by hosting an “innovation challenge” that led to a demonstration of zinc-air technology for providing long-duration storage and facilitating renewable integration (New York State 2019). California recently announced an \$11 million solicitation for a diverse set of storage technologies, indicating that new technologies are needed “because [current] technologies do not have the energy density, daily cycle capability, longevity, safety, and price to be viable for the diverse set of applications that will be needed in the state” (Balaraman 2020).

3.1.4 State-Initiated Storage Studies and Utility Regulation

State regulation of utilities can provide other levers to drive storage deployment, particularly regulations shaping utility asset ownership, rate recovery and avoided-cost determination, interconnection, permitting, renewable energy procurements, and resource planning. North Carolina’s recent report on storage options, required by House Bill 589, encourages development of a coordinated statewide energy storage policy that recognizes the complexity of the current policy environment (Shipman 2018).

Requiring utilities to consider storage in long-term resource planning processes has become a key lever; 15 states have implemented such regulations. Many utilities are also working to develop more advanced integrated resource planning (IRP) modeling to fully understand the contributions of storage. This enhanced modeling requires better data on storage costs, sub-hourly modeling, development of “net-cost” analysis to value flexibility, and other improvements (ESA 2018). Although California’s IRP process is unique in beginning with a review of state-level needs (whereas most IRPs focus on utility territory needs), it illustrates the importance of resource planning to better identify future storage needs. In 2020, a California resource planning document concluded that, in addition to 8,873 MW of battery storage projected by 2030, 1 GW of long-duration storage would be needed for the state to meet its clean energy goals (Spector 2020). In addition, recent request for proposals (RFP) for storage to support Hawaii’s 100 percent renewable energy goals have similarly seen a shift to longer-duration storage, with a recent project reaching eight hours in duration (Parkinson 2020).

3.2 Organized Wholesale Electricity Markets

Organized wholesale electricity markets—managed by RTOs and regulated by the Federal Energy Regulatory Commission (FERC)—impact energy storage by defining the ways in which storage projects can participate in markets and their ability to earn revenues. This is important because multiple studies have found that the ability of a storage project to “value stack”—optimize its operation to earn revenues by providing multiple types of service—will be key to properly valuing storage in the market (RMI 2015).

PJM offers one example of how market rules can drive storage deployment by influencing how storage could earn revenue. In 2012, PJM implemented the rules of FERC Order 755, enacted in 2011, which increased compensation for fast-acting resources such as batteries or flywheels bidding into frequency regulation service markets. From 2012 to 2016, this order alone contributed to a 236 MW increase in installed storage capacity in the PJM region (Energy Policy Council 2019). This capacity is owned by independent power producers, has relatively large capacities and short durations, and provides power-oriented frequency regulation (EIA 2018b). The battery deployment⁸ quickly saturated the market, reducing the potential revenues from providing this service, and investment has dropped off. The rapid cycling of batteries participating in these markets has decreased their useful lives, highlighting the limits of current technology and the disconnect between wholesale market signals and storage asset optimization. One potential approach could be market compensation that offsets decreased battery life.

Order 755 is one of several major FERC orders that affected storage development. The landmark Order 841, issued in February 2018, requires each RTO to revise its tariffs to remove barriers that prevent storage from participating in wholesale electricity markets.

TABLE 4

FERC ORDERS AFFECTING ENERGY STORAGE DEPLOYMENT

FERC Order	Year	Name	Highlights
755	2011	Frequency Regulation Compensation in the Organized Wholesale Power Markets	Requires separate compensation structure for fast-acting resources such as batteries bidding into frequency regulation service markets
784	2013	Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies	Requires utility transmission providers to consider speed and accuracy—which storage excels at—when assessing regulation resources, and improves accounting for storage
841	2018	Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators	Requires regional transmission organizations to define rules for storage to participate in markets
845	2019	Reform of Generator Interconnection Procedures and Agreements	Revises the definition of <i>generating facility</i> to explicitly include electricity storage and gives storage projects more options when requesting interconnection

Source: FERC 2020.

3.3 Federal Policies and Incentives

There are currently no federal tax credit incentives specific to stand-alone storage, although new storage tax credits have been proposed, and there are opportunities to use the solar investment tax credit for projects pairing solar with storage. Stand-alone storage and storage paired with renewable energy can also use accelerated depreciation (the Modified Accelerated Cost Recovery System) tax reduction, which, based on tax rates, can be converted into an equivalent capital cost reduction of about 20 percent (Elgqvist et al. 2018). Storage is also eligible for Opportunity Zone incentives, which provide tax incentives for projects located in low-income areas. To date, however, developers have found these federal programs highly complex and difficult to leverage, so the programs have not been widely used (Deign 2019).

The solar investment tax credit, together with cost reductions for PV modules and inverters, has driven tremendous growth in U.S. PV installations across the utility-scale, commercial, and residential sectors during the past decade. In the case of commercial or utility-scale PV-plus-storage systems, if the storage system is charged by solar power at least 75 percent of the time, it is eligible for a commensurate share of the investment tax credit applied to the cost of the energy storage system (SEIA n.d.). The investment tax credit for PV plus storage will progressively fall from 26 percent in 2020 to 22 percent in 2021 and 10 percent in 2022, after which it will expire (SEIA n.d.).

Finally, federal legislation and agencies can drive the RD&D investment needed to develop more diverse storage technologies or target longer-duration storage options. Box 1 provides an example of legislation that can drive RD&D funding across federal agencies. Currently, the DOE supports storage RD&D through its Office of Science, Office of Electricity Delivery, and Office of Energy Efficiency and Renewable Energy. Specific efforts such as the Advanced Research Projects Agency–Energy (ARPA-E) and Joint Center for Energy Storage Research support innovation in storage technology. Energy storage experts have argued that this work is underfunded relative to its strategic importance and that expanded federal RD&D is needed (Hart 2019).

THE PROPOSED BETTER ENERGY STORAGE TECHNOLOGY ACT

On May 23, 2019, the House Committee on Science, Space and Technology introduced the Better Energy Storage Technology (BEST) Act, which requires the DOE to establish an energy storage system research and development program and authorizes \$300 million between 2020 and 2024 to fund up to five demonstration projects for grid-scale energy storage systems. This bill specifically calls for the following:

- Highly flexible power systems with a minimum duration of six hours and a lifetime of at least 8,000 cycles of discharge at full output and 20 years of operation
- Long-duration storage systems with power output of 10 to roughly 100 hours, with a lifetime of at least 1,500 cycles and 20 years of operation
- Seasonal storage systems that can store energy over several months and address seasonality concerns

The BEST Act also does the following:

- Establishes a prize competition at DOE to advance the recycling of critical energy storage materials such as lithium, cobalt, nickel, and graphite
- Establishes a program at DOE to assist electric utilities with identifying, evaluating, planning, designing, and procuring storage
- Requires the Federal Energy Regulatory Commission (FERC) to conduct a rulemaking to develop standard processes for utilities to recover storage system costs in FERC-regulated rates

In February 2020, the House Committee on Science, Space and Technology ordered the bill to be amended by voice vote.

4. THE LONG-TERM ROLE OF STORAGE IN A DECARBONIZED GRID

Current storage technologies and roles are far more limited than they might become in highly decarbonized grid systems of the future. This section briefly reviews some important aspects of longer-term storage.

4.1 Penetration of Variable Renewable Energy Sources

The long-term roles of storage will vary with regional mixes of resources and decarbonization targets, infrastructure buildouts, transmission investments, electrification impacts, and many other factors. The likely trend is toward longer storage durations, constrained by

storage costs relative to the costs of other resources that provide similar services. Shorter storage durations of up to 10 hours are typically able to cover the daily variability of renewable generation by, for example, extending solar production after sunset to cover evening peak demand periods or ramping up generation quickly as wind or solar falls off. However, with higher amounts of renewables on the grid, the impact of storms and weather-related reductions in output will be commensurately greater. Longer-duration storage has the potential to address the needs created by low production periods, which could last many days.

At very high penetrations of renewables, seasonal differences in output can affect electricity supply, due to substantial overgeneration of electricity in some months and very low production levels in other months. The relative dependence on solar or wind also matters because in some cases a mix of wind and solar can be complementary—windier conditions at night compensating for lack of sun, for example.

4.2 Modeling the Future Role of Storage

General energy outlooks often do not consider storage (Koshinen and Breyer 2016). However, studies designed to examine deep decarbonization of electricity systems (carbon dioxide emissions reductions of roughly 80–100 percent) can provide insights into potential future storage needs. Many of these studies examine interactions between types of energy resources, including “firm” resources that provide stable electricity in all seasons, VRE resources that offset carbon-intensive resources but have limited dispatchability, and “flexible” resources that do not provide firm power but can reduce demand or increase the ability to use VRE resources. In deep-decarbonization scenarios, storage can provide flexible capacity, backup power, and transmission and distribution grid deferrals, and increase resilience in the face of power outages following catastrophic events. However, the integration, modeling, and valuation of storage has been limited, even in deep-decarbonization studies.

Some studies allow a broad range of resources to aid decarbonization, whereas others limit the energy portfolio to renewable resources. Studies that target a 100 percent renewable energy supply balance these resources using geographic aggregation via transmission expansion, load shifting, dispatchable generation using a zero-carbon

FIGURE 6 SEASONALITY OF WIND AND SOLAR RESOURCES, BASED ON MONTHLY GENERATION ESTIMATES IN CALIFORNIA WITH 80% RENEWABLE PORTFOLIO STANDARDS

Note: This graph illustrates the seasonality of renewable resources by showing what monthly production of wind and solar looks like based on estimates from the California Independent System Operator (CAISO). This estimate assumes an 80 percent renewable portfolio standard that is met by equal amounts of wind and solar.

Source: Brick 2017.

fuel (hydrogen, synthetic methane, ammonia, biogas), and/or heavy investment in storage.

The goals, geography, and assumptions about resources in deep-decarbonization scenarios impact the optimal mix of resources. A meta-analysis reviewed 30 deep-decarbonization studies that targeted an 80–100 percent reduction in carbon dioxide (CO₂) emissions, including 100 percent renewable energy pathways (Jenkins and Thernstrom 2017). It concluded that grids meeting CO₂ targets of 50–80 percent⁹ require a different set of generating resources compared with zero- or nearly zero-carbon electricity grids. At targets around 50–80 percent, most of the portfolio can be made up of VRE, such as wind and solar, and power can be balanced with a range of low-carbon resources, including nuclear power, bioenergy, and natural gas plants that capture CO₂. At higher targets, the optimal contribution from clean, firm resources grows, and depends on the specific geography modeled. In one study, as the carbon limit approaches zero, the optimal contribution from wind and solar is as low as 30–50 percent of system energy (for a northern region) or as high as 60–70 percent of system energy (for

a southern region). The rest of the energy mix is provided by a combination of clean, firm resources (such as flexible nuclear power plants, hydro plants with high-capacity reservoirs, flexible coal and natural gas plants with carbon capture and storage [CCS], geothermal power, and biomass- and biogas-fueled power plants) with support from energy storage and transmission (Sepulveda 2018).

Deep-decarbonization studies that assumed a range of resources beyond VRE resulted in cheaper decarbonization even when continued deep reductions in wind, solar, and storage costs were assumed. These studies also yielded physically smaller grid systems, because they did not overbuild VRE and transmission to meet seasonal demand. In these studies, energy storage has a role, but optimal durations are smaller, in the 4-to-16-hour range. Studies targeting only renewable energy required storage durations of several weeks because of seasonal differences in renewable production (Denholm 2019).

The cost-effectiveness of such long-duration storage is an open question owing to low utilization rates and high per-unit costs based on projected battery costs

(Denholm 2019). Other studies achieved long durations via advancements in underground thermal energy storage, advancements in electrolytic hydrogen production, and/or production of synthetic natural gas (Jenkins and Thernstrom 2017). Development of cost-effective technology that can provide days to weeks of storage would alter the role of storage on the future grid, enabling it to provide firm resources. More research is needed to establish the cost and performance parameters required for long-duration storage to play a significant role (Jenkins et al. 2018).

Some studies have examined different strategies to get to 100 percent renewable energy that will work best in each region. Analysis conducted by McKinsey & Company, for example, finds that mature heavy-thermal markets such as PJM may need to invest in carbon capture, use, and storage (CCUS) technology, while large, diversified markets such as CAISO may require overbuilding of solar-plus-storage hybrid projects to meet demand, or the use of technologies like power to gas to power (P2G2P), which involves using excess electricity to produce hydrogen to be stored in the gas network (Finkelstein et al. 2020).

4.3 Assessing Costs and Value of Storage Technologies in Evolving Grid Systems

Policymakers and regulators need new frameworks to assess the anticipated costs and value of future storage technologies within evolving grid systems. The frameworks currently used to assess generation technologies are not sufficient to evaluate emerging storage technologies that can play multiple roles. Emerging frameworks for evaluating storage are geared toward understanding current technologies and use cases. A comprehensive evaluation framework for future storage should consider all storage costs (costs of the storage technology, stored energy, and energy lost during conversion), the multiple services storage may provide, the value of incremental carbon reductions, the speed of those reductions, and competing strategies for realizing the reductions. It is key to recognize that storage may not always be powered by free renewable energy that would otherwise be curtailed.

Future storage systems that address seasonal needs likely will be large projects whose stored energy is not discharged often. Such projects would not offer the same economic return paradigm as a more conventional energy arbitrage with a value-stacking storage mechanism that competes in wholesale markets. In addition, location and

timing affect “deliverability” of these projects (the ability to deliver power when and where needed), which also affects the economic returns. Since long-duration storage is uncharted territory, operational strategies and practices are likely to change over time to meet the functional needs of an evolving grid, and positively or negatively impact costs and expected financial returns. Given these factors, it may become more appropriate to consider long-duration storage as an infrastructure investment rather than a capital venture based on return on investment.

5. PATHWAYS FOR THE EVOLUTION OF STORAGE TECHNOLOGY

This section discusses the evolution of technological options as storage shifts toward long-duration and seasonal applications.

5.1 Clean Energy Projections

Long-duration storage needs will emerge in a region as VRE reaches very high grid penetration levels, as already seen in California. Current national penetrations are 7 percent for wind and 2 percent for solar. As VRE penetrations increase beyond 20–25 percent, peak demand, ramp management, load shifting, and curtailment reduction will increasingly be handled by PSH (6–10 hours) and Li-ion batteries (1–4 hours), which provide the necessary operational flexibility. CSP-TES (6–16 hours) will also play a role.

Long-term projections of electric-sector evolution vary widely. The EIA’s reference scenario projects that VRE generation will overtake natural gas generation in the 2040s, with declining VRE costs and state goals continuing to drive development. By 2050, the total renewable energy supplied is just under 40 percent, with solar and wind representing about 30 percent of all energy generation (EIA 2020). Other projections that assume more aggressive state policies and local actions show renewable energy making up as much as 49 percent of generation as early as 2030 (Bloomberg Philanthropies 2019) and as much as 80 percent by 2050 (NREL 2012).

A recent study investigated whether or not a 90 percent clean energy scenario could be achieved by 2035 and found that the current low cost of renewable energy and storage made this target possible with policy reforms. The study estimated the need for 600 GWh of storage

(150 GW for four hours) for grid balancing, equivalent to about 20 percent of daily electricity demand (UC Berkeley 2020). The study found that using natural gas generation to meet the remaining 10 percent of demand avoided the need to build excess renewable energy capacity or longer-duration storage, but that even with substantial deployment of four-hour storage, 14 percent of renewable generation was curtailed annually. The authors noted that only four-hour storage was considered because of modeling limitations and that new long-duration storage technologies could potentially reduce curtailment.

5.2 Near-Term Storage Technology Evolution

Over the next decade, technologies in use today could expand to meet future storage needs, but few technologies could evolve to meet seasonal needs. PSH could be more efficiently or widely deployed to provide long-duration storage if financial compensation were increased and permitting streamlined, but significant planning and permitting would be needed to reach durations of days. CSP-TES can currently provide durations up to 16 hours, but it is unlikely to achieve multiple days of discharge or to be deployed widely across the United States. Battery technology is transforming as new grid services and markets open, but it is also unlikely to provide seasonal storage owing to size and cost constraints. There is more uncertainty surrounding the technology evolution pathways for CAES and liquid air, but they are discussed briefly due to their potential.

5.2.1 Pumped Storage Hydro

Currently, PSH is the only technology with the potential for cost-effective bulk energy storage that can provide storage durations of around 12 hours to three days. However, only about 20 percent of U.S. PSH plants store enough water for such durations, and those plants—like most PSH plants—typically generate in much shorter cycles to meet peak demand. In coming years, there is potential to more fully use existing PSH plants by replacing the fixed speed generators in most plants with variable speed generators; increase PSH production from existing plants; and develop new PSH plants as new storage assets or adding generation and pump back to existing non-powered dams.

Optimizing PSH to more fully utilize its capacity is complex, possibly requiring advanced modeling and/or enabling technologies (Koritarov 2017). PSH reservoirs could be enlarged by raising water levels or adding

pump-back capabilities to conventional hydropower dams (as done at Grand Coulee Dam in Washington State). This might be challenging given the difficulties of permitting systems sized for only 6–10 hours of storage and the high costs of such changes. PSH deployment could potentially be increased by 16.2 GW by 2030 (DOE 2018). Few new PSH projects have been commissioned in the past 25 years, but more than 60 projects are now in the FERC queue for licensing and permitting, representing over 51 GW of potential. This queue indicates that developers have found potentially viable pumped storage hydro sites after working through locational barriers.

In addition to the potential for 16.2 GW of PSH expansion by 2030, another 19.3 GW could be added by 2050 (DOE 2018). Such additions would provide more storage capacity in the conventional 6-to-10-hour timeframe, but considerable re-planning and re-permitting would be needed to provide one to three days of storage.

Environmental concerns, permitting, and finance are barriers to future PSH development. The initial FERC licensing process (which includes environmental permitting) takes three to five years, while other required federal and state permits and construction timelines of three to five years all contribute to making financing difficult and expensive to obtain.

5.2.2 Concentrating Solar Power with Thermal Energy Storage

As of 2019, 19 CSP plants totaled approximately 1.8 GW of capacity. All plants are located in the Southwest owing to the region's abundant sunshine and low humidity (EIA 2020). The dominant technologies are power towers and parabolic troughs, with molten salt as a common heat-transfer fluid. CSP systems are complex and must be large to enable economies of scale. More recent plant installations (2013–15) include 405 MW of storage capacity. Going forward, CSP-TES of 6–12 hours of storage will need to halve costs by 2030 to compete with PV, although other applications (e.g., using CSP for desalination) may provide market opportunities while costs decline (Murphy et al. 2019).

CSP-TES is well-suited to meet the ramping caused by California's shifting load profile referred to as the "duck curve." Solar increases on the grid mid-day, decreases net load, and then drops off quickly in the evening. This rapidly increases load at sunset and creates a net load shape that resembles a duck with a long neck. Resources must

ramp up production quickly to meet this spike; however, CSP-TES can reduce some of the ramping need as it can be sized to provide electricity well after sunset (Branke 2018). However, even if cost-reduction thresholds are met, CSP-TES will always be a regional energy storage solution whose serviceable territory may extend into several other southern states, but whose storage duration could likely not be prolonged much beyond current designs.

5.2.3 Batteries

Annual growth in U.S. electricity-sector battery deployment is projected to grow dramatically, even after adjusting for the impacts of the Covid-19 pandemic, increasing from 523 MW in 2019 to almost 7,000 MW by 2025 (Figure 7). The rise of EV technologies has driven development of Li-ion batteries with high power and energy densities, with economies of scale contributing to annual double-digit percentage declines in Li-ion battery costs between 2010 and 2016. Lower annual price reductions of 4–7 percent are projected through 2025 (Wood Mackenzie 2019). Lower Li-ion battery prices

have opened opportunities across the utility-scale, distributed, and residential electricity storage markets, as has the availability of the investment tax credit for systems charged via VRE (NREL 2018).

However, despite increasing deployment, current Li-ion battery technologies have faced significant barriers related to their safety. Many electrochemical storage technologies are relatively new and have risks associated with their operating characteristics. Li-ion batteries are associated with significant fire risks and incidents have caused concern among regulators. Arizona Public Service (APS), for example, has experienced two Li-ion-related fires (in 2012 and 2017) thought to be caused by a lack of proper ground from electrical shocks, insufficient management of the operation environment, poor installation, and a lack of integrated control and protection systems (Weaver 2019). These incidents led to concerns at the regulatory commission that Li-ion's release of hydrogen fluoride posed a drawback compared with other storage technologies and prompted a review of safety codes, standards, best

FIGURE 7 ELECTRICITY-SECTOR BATTERY ANNUAL DEPLOYMENT AND PROJECTIONS, 2012–2025

Note: U.S. energy storage annual deployment forecast for 2012–2025E (estimated) in megawatts (MW).
Source: Wood Mackenzie 2019.

practices, and procedures in place (Arizona Corporate Commission 2019). While management systems for storage assets will improve, safety concerns will continue to shape regulators' assessments of various technologies.

A key advantage of battery technology is the ability to extend duration by building projects modularly. Although the cost and performance of Li-ion technology currently suggests a duration of four hours as the sweet spot for grid and commercial applications, additional units can be stacked to reach longer durations. This approach, however, means costs increase linearly as duration increases; the cost and size of battery installations reaching seasonal capacity may be unfeasible. For now, grid storage is a secondary market for Li-ion technology, behind the EV market, where the technology has clear advantages over alternative batteries.

Other batteries, such as flow batteries and sodium sulfur technologies, are also unlikely contenders for long-duration storage. Redox flow batteries (vanadium or zinc bromine) are readily scalable by adding more electrolyte solution tanks. However, compared with Li-ion batteries, they have a very low energy density (roughly one-eighth) and lower efficiency (67 percent versus 86 percent), although they have about three times the cycle life. The energy density of sodium sulfur batteries is about half that of Li-ion batteries, and their costs are about double. Round-trip efficiencies for sodium sulfur batteries are about 75 percent, compared with 86 percent for lithium-ion batteries.

5.2.4 Compressed Air Energy Storage

CAES technology pumps compressed air into large underground sites, preferably salt caverns but also potentially natural aquifers or depleted natural gas sites, and then releases the pressurized air to regenerate electricity when needed. Much like PSH, the physical constraints of screening and siting these projects remain a large barrier. Screening criteria can be complex and include prioritization of proximity to natural gas pipelines or transmission, previous exploration drilling nearby, and the presence of geologic traps (natural reservoirs in which air can be confined) that are deep, thick, and laterally extensive (Mongird et al. 2019). A few U.S. CAES projects exist: one operating plant in an excavated salt cavern in Alabama and another underway in Utah that will use several storage technologies at once, including CAES sited in salt caverns.

5.2.5 Liquid Air

Liquid air storage technologies clean and compress air, liquefy it, and store it in aboveground, cold-insulated tanks. When power is needed, the air is warmed, which causes it to expand and power a turbine to generate electricity, achieving durations of up to eight hours. The first U.S. project is planned in Vermont, with at least 50 MW of capacity, and may help mitigate the region's transmission congestion. Liquid air benefits from fewer siting constraints than CAES and can exploit existing supply chains for compression equipment (Balaraman 2019).

5.2.6 Other Storage Technologies

Some additional technologies that bear mention are gravity storage, and ice (low temperature) and PV (mid to high temperature) thermal storage. Tables A1 and A2 in the appendix examine these technologies as well as others we have covered and highlight why these technologies could be game changers or may be limited in their ability to meet long-duration storage needs.

Gravity storage functions similarly to PSH but instead replaces water with heavy blocks that are lifted to store energy and released to generate electricity using kinetic energy. Energy Vault technologies, for example, explains that its gravity technology does not face the complex siting requirements of some other technologies (Energy Vault 2020).

In the CSP-TES example earlier, heat generated from CSP is used to heat a medium, usually molten salt. There are other thermal-based technologies, such as thermal ice storage, which generates ice blocks, or solid-state thermal storage, which heats a block of material. Antora Energy, for example, is developing thermal storage technology based on heating carbon blocks that later radiate heat to specially designed thermophotovoltaic panels to absorb (Davis 2018).

5.3 Evolving Storage Technology for Seasonal Needs

Based on current and near-term trends and considerations, energy storage using chemical technologies may hold the most potential for providing seasonal storage. Emerging energy carriers—including hydrogen, hydrogen within biomethane, and ammonia—have potential to provide storage and generation at scales far greater than other storage technologies. They also have potential to overcome key cost and development barriers because they could use existing infrastructure and thus require

less investment to commercialize. These technologies can be housed in standard aboveground facilities and are therefore less geographically limited than PSH and CAES. Unlike batteries, these energy carriers entail no degradation concerns; they can also be used to provide other, non-storage services.

Hydrogen is currently a \$10 billion market in the United States, used primarily for methanol and ammonia production and petroleum refining. It is extracted from methane via steam methane reforming. An alternative production method uses electrolysis to separate hydrogen from oxygen in water; if renewable electricity is used, this clean process results in “green hydrogen.” High electrolysis costs are projected to decline as the price of electrolyzers and the levelized cost of energy (LCOE) of VRE also fall. Hydrogen costs could drop from \$6 per kilogram (/kg) to \$2–3/kg by 2025 or 2030 (Hydrogen Council 2020). In 2019, the pipeline for green hydrogen plants of over 100 MW surged, and 19 projects are under way worldwide (Deign 2020).

Hydrogen can be used to power light- and heavy-duty fuel cell electric vehicles (FCEVs). California currently has 6,300 FCEVs and 39 public hydrogen fueling stations, with another 25 under development and plans for 200 by 2030 (Descant 2019). Stationary fuel cells can convert hydrogen to electricity for backup power or grid consumption. California’s simultaneous promotion of FCEVs and electric-sector energy storage suggests potential for hydrogen synergy in that state, although infrastructure costs for current hydrogen stations are much higher than for EV charging stations.

A new approach, biomethanation, uses microorganisms to convert carbon dioxide and hydrogen (derived via electrolysis with renewable energy) into pipeline-grade natural gas (Hicks 2017). Biomethane can use existing natural gas infrastructure (from extraction through transport and delivery) until biomethane production scales up to replace extraction, and the end product can serve multiple sectors that already use natural gas.

Finally, like hydrogen, ammonia can serve as an energy carrier with potential applications for electricity, heating, and vehicle fuel. Ammonia is commonly used as a chemical in the fertilizer, refrigeration, and oil-processing industries. It can be safely stored as a dense liquid at 25 degrees Celsius in standard steel tanks. Although ammonia contains no carbon, ammonia combustion creates

oxides of nitrogen, which are greenhouse gases and pollutants. Ammonia is commonly used in other industries, so supply chains and familiarity with transporting the fuel already exist (Deign 2018).

5.4 Evolution of Storage Markets and Technologies

The evolution of long-duration and seasonal storage will not only depend on the characteristics of storage technologies but also be influenced by related technologies, synergies with other applications, and deployment in niche markets. For example, Li-ion technology started in watch batteries before progressing to laptops and phones, EVs, and then utility-scale storage systems. If EVs continue to proliferate as expected, they will significantly impact storage development in the future electricity system. This section explores markets that could make technologies with a storage duration of one to three days economically viable.

Potential near-term markets that could serve as entry points for long-duration storage technologies include essential backup power (e.g., for data centers) and more remote locations such as island jurisdictions with very small balancing areas, particularly those with clean energy resources. For example, although a storage system capable of providing one to three days of storage for a data center may appear prohibitively expensive, when compared with the cost of losing power—and thus losing data and customers—even a rarely used storage system may still be cost-effective for a company whose primary product absolutely requires 24/7 power. Industrial and commercial frozen food warehouses could also be an entry point for long-duration storage.

Some large corporate customers are interested in using energy storage to meet 24/7 renewable goals. Google, for example, is moving away from purchasing enough renewable energy annually to offset its total electricity consumption and instead ensuring that power consumed by Google facilities is clean at any given hour. Google will use a range of clean energy plants producing at different times, sourcing energy and investing in storage closer to its facilities. Another entry point could be siting storage to defer grid transmission and distribution, reducing congestion and increasing reliability more cheaply than building out the grid.

Such market-driven needs could stretch the storage duration of existing or emerging storage technologies, which

could eventually be used for resilience during grid outages and to address systems with high VRE penetrations. Both ARPA-E's Duration Addition to electricity Storage (DAYS) program and DOE's recently announced Energy Storage Grand Challenge (Moreno 2020; delivered by Litzelman) target 10-to-100-hour storage capability (about one-half to four days). These programs indicate that initial efforts should focus on extending current storage duration limits. The need for seasonal storage is not yet clearly defined or visible on the near-to-mid-term horizon.

6 CONCLUSIONS AND POLICY RECOMMENDATIONS

As electric grids decarbonize over the next two decades, new roles for storage will likely emerge. Storage could play an expanded role in maintaining reliability and providing firm capacity for future grids, but its longer-duration uses (days or longer) will depend on technology improvements, its cost relative to other grid solutions, and the mix of generation sources deployed on the grid.

While a number of technologies hold the potential to provide cross-day or multiday storage—including PSH, CAES, batteries, thermal storage, and liquid air—the leading candidates today for very-long-duration storage (weeks) are energy carriers, such as hydrogen. Substantial cost reductions and new evaluation metrics may be needed to make these technologies economically viable.

Studies of electricity grids with large amounts of renewables find that mismatches in renewable energy supply and customer demand can be addressed through a variety of approaches other than storage, including expanding the use of dispatchable renewables, maintaining some conventional gas generation with carbon capture, building excess renewables capacity with curtailment, shifting loads, and building new transmission lines. Thus, storage will need to compete with alternatives on cost and address regionally specific grid needs, and the mix of solutions will vary with regional grid characteristics.

Policymakers can play a role in driving innovation, encouraging cost reductions, and assessing the benefits of storage to provide greater options for maintaining reliability in future deeply decarbonized grids. Efforts to encourage longer-duration storage technologies are already under way in California and Hawaii, where renewables are currently supplying substantial fractions of the energy used on the grid. Concerns about safety

are also driving interest in technology diversity in some regions, given the fire-related risks of commonly deployed battery technologies. Because of regional grid differences, a suite of solutions will likely be needed to meet aggressive decarbonization targets.

To encourage the evolution of storage technologies and increase options for meeting future needs of deeply decarbonized grids, policymakers can take the following near-term steps:

- **Establish New Targets and Procurement Models for Long-Duration Storage:** Much like current ancillary services markets, utility procurement that focuses on current and future services needed from storage can help drive the right investments. Expanding state procurement targets to also focus on services, and not just overall power capacities, can support long-duration storage development. Targets based on technology characteristics or technology-specific carve-outs may be helpful as well. Emerging technologies may not be economically viable without procurements directed at specific characteristics. Regulators can also support innovation in the utility procurement process itself by encouraging the use of all-source requests for proposals (RFPs). All-source RFPs identify needs and solicit proposals for creative alternatives that could fulfill those needs, providing utilities with more insight into how storage can be leveraged and fostering innovation among developers (Wilson et al. 2020).
- **Encourage Innovation in Utility Resource Planning:** As a first step, it is important for state regulators to require that utilities consider storage in their integrated resource planning or other long-term plans. State regulators could also remove barriers to storage by supporting more robust reviews of storage and innovation in IRP processes. IRPs that include storage can still fall short on cost data or operational assumptions, the range of storage services and benefits considered, and transparency around storage modeling. Near-term improvement can be made by incorporating sub-hourly modeling into IRPs to capture grid interactions. New modeling techniques may be needed for long-duration storage evaluation. Information sharing and analysis of how to improve consideration of storage technologies in IRPs will more quickly reduce planning barriers across utilities.

- **Fund High-Value Demonstration Projects That Advance Learning and Help Commercialize New Storage Technologies:**

Demonstration projects that provide valuable data on technology performance, cost, and value will be essential if new technology solutions are to emerge. A narrow focus on battery systems or low-cost technologies for today's applications will not drive technologies that can serve future grid needs. Federal support for field demonstrations across the United States can harness needed data for new technologies and applications and provide regional context as well. Federal support can also target high-value and high-risk demonstration projects in which venture capitalists may not yet be ready to invest (UCS 2018). States could support utility demonstration projects that provide data on the operational characteristics and benefits of new technologies and share these data across the industry. Collaborations among government, industry, utilities, and states can help bring technologies to commercialization.

- **Maintain Reliable Funding for Storage RD&D:**

The federal government can play a strong role in supporting long-duration storage RD&D that cannot be undertaken by utilities and other stakeholders. Continued support for storage RD&D can create a pipeline of technology improvements to drive down costs, clarify performance and value propositions, and improve operating characteristics. ARPA-E's DAYS and other programs within DOE will be key to filling this need. Additional programs within the U.S. Department of Defense specifically targeting long-duration storage can leverage the department's experience with storage and provide resilience benefits to its defense operations. Finally, RD&D can be strategically deployed to encourage technology diversity and support technologies at different stages of development.

- **Conduct Screening Assessments for Potential Sites:**

The federal government and states can support screening of potential sites for geographically limited resources such as CAES. Screening assessments would provide insight into how and where these projects could be developed as well as reduce costs and risks for developers. Understanding specific land-use issues related to future long-duration storage technologies as they emerge will be key to preventing new barriers related to siting approvals and public opposition.

- **Drive Sophisticated Modeling of Storage Services and Promote Regional Studies of Storage Needs:** In addition to the need for IRP modeling, additional analyses with more advanced modeling techniques are needed to understand when long-duration storage could provide benefits, the types of benefits it could provide, and the trade-offs between storage and other mechanisms for integrating VRE. State-level assessments of storage needs and opportunities should continue, and assessments should expand to the regional level. Region-specific modeling, and increased coordination within each region, is needed to understand needs and options that differ based on grid characteristics, consumption patterns, and resource mixes. In addition, deep-decarbonization studies that model interactions between resource types and predict future needs under low-carbon futures should robustly model storage contributions and important interactions with non-utility sectors.
- **Enable Financing That Better Matches the Needs of Long-Duration Storage Assets:** Policymakers should try to match financing mechanisms with storage applications and their benefits to the grid. Long-duration storage will operate very differently from the batteries deployed for ancillary services today. Providing days or weeks of storage will require capital-intensive infrastructure, with higher financial risk, that is dispatched infrequently and thus will need to recoup costs over fewer operating hours. This model for cost recovery is more similar to infrastructure investments. To finance long-duration storage assets with longer lifetimes and lower utilization rates, models used for infrastructure, such as electrical transmission infrastructure, may be more appropriate.

These recommendations are a starting point for policymakers to help long-duration storage evolve, better understand potential seasonal needs, and facilitate deep decarbonization. Additional policies, such as innovation-focused tax credits and financial incentives, may also play a role. As decarbonization progresses, more work is needed to clarify technological evolution, the future roles of storage, and policy action.

APPENDIX. COMPARISON OF STORAGE TECHNOLOGIES

TABLE A1

TECHNOLOGIES WITH POTENTIAL TO BE GAME-CHANGERS FOR LONG-DURATION STORAGE

Technology	General Configuration	Beneficial Characteristics	Challenges	Potential for Long-Duration Storage, Days to Weeks
Hydrogen (H₂), fuel cells	<ul style="list-style-type: none"> Hydrogen is an energy carrier made from methane, biomass, or electrolysis 33% of H₂ for transport is renewable 44 fueling stations in California to 100 by 2022 to support 68,000 FCEVs 	<ul style="list-style-type: none"> Can be combusted for heat or electricity Applied as fuel cell for transport with water as by-product Electrolyzer can provide ancillary services H₂ from methane in FCEV is twice as efficient as gas-powered car and 55% cleaner Multi-market product—used in oil refining, ammonia for fertilizer, chemicals, among others 	<ul style="list-style-type: none"> Requires high pressure tanks and piping Low total efficiency (multiple conversions) High-cost Infrastructure—production, transport, and end use Electrolysis with renewables is becoming increasingly cost effective 	<ul style="list-style-type: none"> High cost Need new infrastructure Can serve multi-market transport and electricity Volume required for multi-markets can create weeks of electricity capacity; may require dedicated wind and solar With switch to electrolysis from excess (low cost) wind and solar, H₂ becomes a more effective storage technology
Hydrogen (H₂), biomethanation	<ul style="list-style-type: none"> Electrolysis produces H₂, which is "fed" to archaea microorganisms that consume H₂ and carbon dioxide (CO₂), producing methane (CH₄) 	<ul style="list-style-type: none"> Will be able to use existing gas pipelines and power plants, multi-market Archaea self-replicates through production Dormant at room temperature, catalytic at 60°C 	<ul style="list-style-type: none"> Emerging technology—continued R&D and prototype testing High cost Electrolysis with renewables is becoming increasingly cost effective 	<ul style="list-style-type: none"> Investment required for cost reduction and scaling; infrastructure for transport and delivery already exists Volume required for multi-markets will create weeks of electricity capacity Can serve transport market for methane-powered cars
Ammonia (NH₃)	<ul style="list-style-type: none"> Ammonia is an energy carrier with higher volumetric energy density than hydrogen 	<ul style="list-style-type: none"> No carbon emissions from combustion Transport fuel for fuel cell vehicles Long life Feedstock for green fertilizer Industrial energy source 	<ul style="list-style-type: none"> It is toxic, but widely used Primarily obtained by methane reformation Electrolysis with renewables is becoming increasingly cost effective 	<ul style="list-style-type: none"> Investment required for cost reduction and scaling; infrastructure for transport and delivery already exists Volume required for multi-markets can create weeks of electricity capacity Can serve transport market for methane-powered cars
Flow batteries (vanadium-based, zinc-bromine-based, sodium-based, liquid metal)	<ul style="list-style-type: none"> Small-scale deployments to date 4–12 hour typical duration Combined power capacity: 4 MW Combined energy capacity: 16 MWh 	<ul style="list-style-type: none"> Modular, can add more readily Rechargeable by adding more electrolyte High cycle life (10,000 charge cycles) Operates at ambient temperature 	<ul style="list-style-type: none"> Low energy density, low power density Medium efficiency (60–85%) High cost Relatively few deployments 	<ul style="list-style-type: none"> Extremely large tanks or reservoirs needed at scale Duration is a function of volume Locational flexibility

TABLE A1

TECHNOLOGIES WITH POTENTIAL TO BE GAME-CHANGERS FOR LONG-DURATION STORAGE (CONT'D)

Technology	General Configuration	Beneficial Characteristics	Challenges	Potential for Long-Duration Storage, Days to Weeks
Sodium Sulfur (NaS)	<ul style="list-style-type: none"> Small-scale deployments to date 4–8 hour typical duration Combined power capacity: 9 MW 	<ul style="list-style-type: none"> Medium cycle life (4,000–5,000 charge cycles) 10–15-year life Medium efficiency: 75–85% 	<ul style="list-style-type: none"> Low power density Operates at high temperature; at scale needs effective use of waste heat Single manufacturer to date 	<ul style="list-style-type: none"> Needs industry competition for innovation Needs longer duration development Needs scaling
Ocean-based pumped hydro storage	<ul style="list-style-type: none"> Ocean-based lower reservoir paired with offshore wind as hybrid 8–12 hours typical duration 	<ul style="list-style-type: none"> Large lower reservoir in place West Coast, Alaska, Hawaii have many potential sites 	<ul style="list-style-type: none"> Environmental permitting (land and ocean) Needs elevation gain adjacent to shoreline Very corrosive water Much of East and Gulf Coasts not well-suited 	<ul style="list-style-type: none"> Existing turbine and pump technologies need upgrades for ocean water

Notes: FCEV: fuel cell electric vehicle; °C: degrees Celsius; R&D: research and development; MW: megawatt; MWh: megawatt-hours
Source: Mongird et al. 2019; Descant 2019; Hicks 2017; University of Strathclyde 2020.

TABLE A2

WORKABLE TECHNOLOGY THOUGH PROBABLY NOT FOR LONG-DURATION STORAGE

Technology	General Configuration	Beneficial Characteristics	Challenges	Potential for Long-Duration Storage, Days to Weeks
Li-ion	<ul style="list-style-type: none"> Multiple lithium chemistries: nickel manganese cobalt, cobalt aluminum, iron phosphate, titanate 	<ul style="list-style-type: none"> Most chemistries are mature, lithium air is still developing Costs expected to continue to decline, albeit at lower rates 	<ul style="list-style-type: none"> Raw material supply, competition with electric vehicle market Requires thermal management to prevent overheating 	<ul style="list-style-type: none"> Energy performance not well-matched with scaling or duration of LDS requirements—requires excessive stacking of BESS
Lithium metal	<ul style="list-style-type: none"> Still in early-stage development, with improvements using polymer electrolytes 	<ul style="list-style-type: none"> Promise of higher energy density than Li-ion 	<ul style="list-style-type: none"> Currently lower power density than Li-ion Currently lower efficiency than Li-ion 	<ul style="list-style-type: none"> Has potential for improved costs and performance over Li-ion though duration has not yet been a research focus
Zinc air or other metal air batteries	<ul style="list-style-type: none"> 14 MW contract in United States 	<ul style="list-style-type: none"> High energy density Low-cost materials 3,000–4,000 charge cycles 	<ul style="list-style-type: none"> Largely still in development state Few deployments Few manufacturers Low power and energy delivery 	<ul style="list-style-type: none"> Potential low cost and high energy density make it worth continued R&D, though duration has not yet been research focus
Aggregate EV batteries	<ul style="list-style-type: none"> U.S. EV fleet expected to grow rapidly in late 2020s and continue creating millions of available BESS 	<ul style="list-style-type: none"> By 2040–2050 there should be ample supply of EV batteries connected to grid throughout the day 	<ul style="list-style-type: none"> Grid charging patterns may shorten cycle or physical life, cause performance degradation, or void warranty 	<ul style="list-style-type: none"> Better suited to daily charge/discharge cycle

TABLE A2

WORKABLE TECHNOLOGY THOUGH PROBABLY NOT FOR LONG-DURATION STORAGE (CONT'D)

Technology	General Configuration	Beneficial Characteristics	Challenges	Potential for Long-Duration Storage, Days to Weeks
Advanced lead acid, flooded	<ul style="list-style-type: none"> Improved characteristics from car battery stage 	<ul style="list-style-type: none"> Low cost High efficiency (70–90%) High reliability Mature technology Improved recyclability 	<ul style="list-style-type: none"> Low cycle life Low energy density Off-gassing requires ventilation Requires thermal management Requires periodic watering 	<ul style="list-style-type: none"> Energy performance not well-matched with scaling or duration of LDS requirements—requires excessive stacking of BESS
Advanced lead acid, valve-regulated	<ul style="list-style-type: none"> Sealed battery requires no watering 	<ul style="list-style-type: none"> High efficiency 15–20 year life Low depth of discharge Mature recyclability No ventilation requirement 	<ul style="list-style-type: none"> Requires thermal management 	<ul style="list-style-type: none"> Energy performance is not well-matched with duration of LDS
Gravity-based crane and block^a	<ul style="list-style-type: none"> Manufacturer claims: 4–8 MW power capacity 20–80 MWh energy capacity 8–16 hours duration^b 	<ul style="list-style-type: none"> Can provide duration and ancillary services Siting best at wind farms, could potentially add on to existing permits Ease of siting 	<ul style="list-style-type: none"> Claims of performance have not been backed up by calculations, data, or case studies to date Energy potential decreases with discharge (shorter distance above ground) 	<ul style="list-style-type: none"> Stated energy performance is not well-matched with duration of LDS Scaling to weeks/months may be cost or material prohibitive^b
Gravity-based weighted train^b	<ul style="list-style-type: none"> Manufacturer claims: 2–3 GW power capacity 16–24 GWh energy capacity 8–12 hours duration 	<ul style="list-style-type: none"> Can provide duration and ancillary services No self-discharge 	<ul style="list-style-type: none"> Claims of performance have not been backed up by calculations, data, or case studies to date Requires sloped land with railroad track 	<ul style="list-style-type: none"> Stated energy performance is not well-matched with duration of LDS Scaling to weeks/months may be cost or material prohibitive
Thermal storage, mid-high temperature	<ul style="list-style-type: none"> Store heat in water, concrete to provide building heating loads 	<ul style="list-style-type: none"> Provides heating, thereby avoiding use of fossil fuels (decarbonization) or electricity 	<ul style="list-style-type: none"> Does not deliver electricity Upfront costs 	<ul style="list-style-type: none"> Potential for long-duration effectiveness in offsetting need for fossil fuel or electricity for heating Potential for much expanded use
Thermal storage, low temperature	<ul style="list-style-type: none"> Store "cold" in chilled water, ice, or concrete to provide building cooling load 	<ul style="list-style-type: none"> Provides cooling, thereby avoiding need for electricity Mature technology with ongoing improvement 	<ul style="list-style-type: none"> Does not deliver electricity Upfront costs 	<ul style="list-style-type: none"> Has potential for long-duration effectiveness in offsetting need for electricity for cooling Potential for much expanded use

Note: Information taken from manufacturers' websites, not independently verified or peer-reviewed papers. GW: gigawatt; GWh: gigawatt-hours; MW: megawatt; MWh: megawatt-hours; EV: electric vehicle; LDS: long-duration storage; BESS: battery energy storage system.

Source:

a. Energy Vault, <https://energyvault.com/>.

b. ARES, <https://www.aresnorthamerica.com/>.

ENDNOTES

1. PJM is the regional transmission organization that coordinates the movement of electricity through all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.
2. Section 2.2 provides more detail on the roles storage can play.
3. Definitions vary, but net-zero carbon generally means that carbon emissions are balanced by absorbing an equivalent amount from the atmosphere.
4. Although there are small differences between the definitions of RTOs and independent system operators (ISOs), the terms are often used interchangeably, and we refer to both types of organizations as RTOs throughout this paper for simplicity.
5. Throughout this issue brief, we refer to the “mid-term” without defining a specific timeframe. Many factors can impact specific timeframes, and the grid will develop at different paces across U.S. regions. The mid-term can be thought of as the period over which decarbonization involving 60–80 percent renewable energy penetration is achieved.
6. The appendix provides more detail on the operating and performance characteristics of selected storage technologies.
7. PJM is the regional transmission organization that coordinates the movement of electricity through all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.
8. Batteries represented over 80 percent of the total energy storage resource contribution to the frequency regulation market, on average (Ott 2019).
9. The studies reviewed were published during 2014–16 and framed greenhouse gas reductions compared with their current levels.

GLOSSARY

aquiferous thermal storage. Use of electricity to cool air to a liquid state for storage and later expand (warm) the air to run a turbine generating electricity.

California Energy Commission (CEC). California's primary energy policy and planning agency.

California Independent System Operator (CAISO). Nonprofit public benefit corporation that operates the majority of California's wholesale power grid.

California Public Utilities Commission (CPUC). Agency that regulates privately owned public utilities in California, including electric power, telecommunications, natural gas, and water companies.

carbon capture and storage (CCS). Technology that can capture up to 90 percent of the carbon dioxide emissions produced from fossil fuels in electricity generation and industrial processes.

carbon capture, utilization, and storage (CCUS). Set of technologies that captures carbon dioxide emissions at source, preventing them from entering the atmosphere, and stores them or turns them into useful products.

carve-out. Government mandate to promote a specific amount (as a percentage of megawatt capacity) and kind of energy source, such as solar or wind energy.

clean peak standard (CPS). A program that requires a percentage of electricity delivered during peak hours to come from eligible clean peak resources.

compressed air energy storage (CAES). Energy storage system that converts electrical energy into high-pressure compressed air that can be released at a later time to drive a turbine generator to produce electricity.

concentrating solar power (CSP). Technology that uses mirrors to reflect and concentrate sunlight onto a receiver that transfers the heat to a heat-transfer fluid, which is used in a conventional steam generator to produce electricity or in industrial heat applications such as water desalination.

concentrating solar power with thermal energy storage (CSP-TES). Technology combination approach that enhances CSP reliability and stability while enabling dispatchable renewable electricity generation for up to 10 hours after the sun has set by adding storage.

cryogenic energy storage. The use of low-temperature liquid (cryogen) such as liquid air or liquid nitrogen as energy storage.

curtailment. The act of reducing or restricting energy delivery, typically from renewable energy sources, from a generator to the electrical grid.

cycle. The process of taking a rechargeable battery at full charge through full discharge and back to full charge again. An important metric for comparing batteries is the number of cycles (cycle life) they are designed to deliver.

electric vehicle (EV). A vehicle that derives all or part of its power from electricity.

Federal Energy Regulatory Commission (FERC). The U.S. government agency that regulates the interstate transmission of electricity, natural gas, and oil.

flexible nuclear. Nuclear plants that can modulate output in response to changing demand or prices instead of operating at only maximum output.

fuel cell electric vehicle (FCEV). An electric vehicle that is powered with fuel cells that use hydrogen gas to power the motor.

integrated resource planning (IRP). Utility plan for meeting forecasted annual peak and energy demand, plus some established reserve margin, through a combination of supply-side and demand-side resources over a specified future period.

investment tax credit (ITC). Federal tax credit that allows residential and commercial customers to deduct a portion, currently 26 percent, of the cost of installing a solar energy system from federal taxes.

Also known as the solar investment tax credit.

investor-owned utility (IOU). A privately owned electric utility that is subject to state regulation and financed by a combination of shareholder equity and bondholder debt that operates for profit.

levelized cost of energy (LCOE). Measure of the average net present cost of electricity generation for a generating plant over its lifetime.

levelized cost of storage (LCOS). Measure of the average net present cost of electricity capacity (dollars per kilowatt-hour) and energy basis (dollars per megawatt-hour) for electricity storage systems over expected life.

line loss. The amount of electricity lost as heat when transmitting electric power over distance on transmission lines.

New York Power Authority (NYPA). New York's public power organization, with 16 generating facilities and more than 1,400 circuit-miles of transmission lines.

nickel-cadmium (NiCd) battery. A type of rechargeable battery suitable for a larger operating temperature range (-20–70 degrees Celsius) than other battery systems. It requires periodic full discharge to maintain full discharge capacity.

nickel-metal hydride (NiMH) battery. A type of rechargeable battery that is environmentally friendly, though it has a limited service life, a complex recharge algorithm, and relatively low efficiency.

parabolic trough. A form of concentrating solar power technology where parabolic-shaped reflectors direct sunlight to a central receiver pipe which carries the heat-transfer fluid.

phase change material (PCM). Substances that absorb and release thermal energy during the process of changing phase from solid to liquid or vice versa.

polysulfide-bromide (PSB) battery. Type of regenerative fuel cell involving a reversible electrochemical reaction between two salt-solution electrolytes: sodium bromide and sodium polysulfide.

power to gas to power (P2G2P). Technology that involves using excess electricity to produce hydrogen to be stored in the gas network.

power tower. A form of concentrating solar power technology where a field of reflectors directs and concentrates solar energy to a receiver atop a tower before being used to generate electricity.

public utilities commission (PUC). Governing body that regulates the rates and services of a public utility, such as an electric utility. Also known as a utilities commission, utility regulatory commission, or public service commission.

pumped storage hydropower (PSH). Type of hydroelectric energy storage. It consists of two water reservoirs at different elevations that can generate power (discharge) as water flows down through a turbine; the system recharges as it pumps water back up to the upper reservoir.

regional transmission organization (RTO). Independent, membership-based, not-for-profit organizations that ensure reliability and optimize supply and demand bids for wholesale electric power. Areas within RTOs are considered to be organized wholesale markets.

RTOs and Independent System Operators are often used interchangeably though there are small differences between them.

renewable portfolio standard (RPS). State legislated mandate that requires utilities to generate or supply a certain percentage of their retail electricity sales—or a certain amount of generating capacity—from renewable energy sources according to a specified renewable energy adoption schedule. Renewable portfolio goals are similar to RPS policies, but are not legally binding.

request for proposals (RFP). In this context, a solicitation process, often through competitive bidding, to obtain supplier proposals with the intent to contract for procurement.

sodium-nickel chloride (NaNiCl) battery. Energy storage technology that has a high performance and durability level with low sensitivity to ambient temperature, though it requires a high operating temperature (270–350 degrees Celsius).

sodium-sulfur (NaS) battery. A high-energy-density and -efficiency type of molten-salt battery constructed from liquid sodium (Na) and sulfur (S) that operates at a high temperature (300–350 degrees Celsius).

superconducting magnetic energy storage (SMES). Technology that stores electricity from the grid within the magnetic field of a coil composed of a superconducting wire with near-zero loss of energy.

thermal energy storage (TES). Storage of heat energy during utility off-peak times for use during times of high demand or high electric rates.

uninterruptible power supply (UPS). Electrical apparatus that provides emergency power to a load during a grid outage.

vanadium redox flow battery (VRB). Type of rechargeable flow battery that employs vanadium ions in different oxidation states to store chemical potential energy.

variable renewable energy (VRE). Renewable energy source, such as wind and solar power, that is not dispatchable due to its fluctuating nature.

zinc-bromine (ZBR) battery. A hybrid redox flow battery, where much of the energy is stored by plating zinc metal as a solid onto the anode plates in the electrochemical stack during charge.

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Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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