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A companion report to the *USAID Energy Storage Decision Guide for Policymakers*

Prepared by

NREL

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List of Acronyms

A-CAES	adiabatic compressed air energy storage
CAES	compressed air energy storage
CHP	combined heat and power
CSP	concentrated solar power
D-CAES	diabatic compressed air energy storage
FESS	flywheel energy storage systems
GES	gravity energy storage
GMP	Green Mountain Power
LAES	liquid air energy storage
LADWP	Los Angeles Department of Water and Power
PCM	phase change material
PSH	pumped storage hydropower
R&D	research and development
RFB	redox flow battery
SMES	superconducting magnetic energy storage
TES	thermal energy storage
VRE	variable renewable energy

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1 Introduction

Power systems worldwide are experiencing higher levels of variable renewable energy (VRE) as wind and solar power plants connect to the grid. This trend is expected to continue as costs for VRE resources decline and jurisdictions pursue more ambitious power sector transformation strategies with increased VRE penetrations.[1] Higher penetrations of VRE can drive additional need for power system flexibility in both short-term essential grid services and longer-term energy shifting and peaking capacity services (Chernyakhovskiy et al. 2019). Energy storage is one of several sources of power system flexibility that has gained the attention of power utilities, regulators, policymakers, and the media.[2] Falling costs of storage technologies, particularly lithium-ion battery energy storage, and improved performance and safety characteristics have made energy storage a compelling and increasingly cost-effective alternative to conventional flexibility options such as retrofitting thermal power plants or transmission network upgrades.

This primer is intended to provide regulators and policymakers with an overview of current and emerging energy storage technologies for grid-scale electricity sector applications. Transportation sector and other energy storage applications (e.g., mini- and micro-grids, electric vehicles, distribution network applications) are not covered in this primer; however, the authors do recognize that these sectors strongly interact with one another, influencing the costs of energy storage as manufacturing capacity scales up as well as impacting electricity demand. The storage technologies covered in this primer range from well-established and commercialized technologies such as pumped storage hydropower (PSH) and lithium-ion battery energy storage to more novel technologies under research and development (R&D). These technologies vary considerably in their operational characteristics and technology maturity, which will have an important impact on the roles they play in the grid. Figure 1 provides an overview of energy storage technologies and the services they can provide to the power system.

Several key operational characteristics and additional terms for understanding energy storage technologies and their role on the power system are defined in the Glossary. Table 1 provides several high-level comparisons between these technologies. Many of these characteristics are expected to change as R&D for the technologies progresses. Some technology categories, such as lithium-ion or lead-acid batteries, comprise multiple subtypes that each feature unique operational characteristics; comparisons of subtypes within technologies are considered in their respective sections.

This report serves as a companion piece to the *USAID Energy Storage Decision Guide for Policymakers*, which outlines important considerations for policymakers and electric sector regulators when comparing energy storage against other means for power system objectives.

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[1] By power sector transformation, the authors refer to "a process of creating policy, market and regulatory environments, and establishing operational and planning practices that accelerate investment, innovation and the use of smart, efficient, resilient and environmentally sound technology options" (IEA 2019). For more information on such power sector transformations, see Cox et al. (2020).

[2] Power system flexibility is defined here as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply" (IEA 2018). For information on and sources of power system flexibility, see IEA (2018) and IEA (2019).

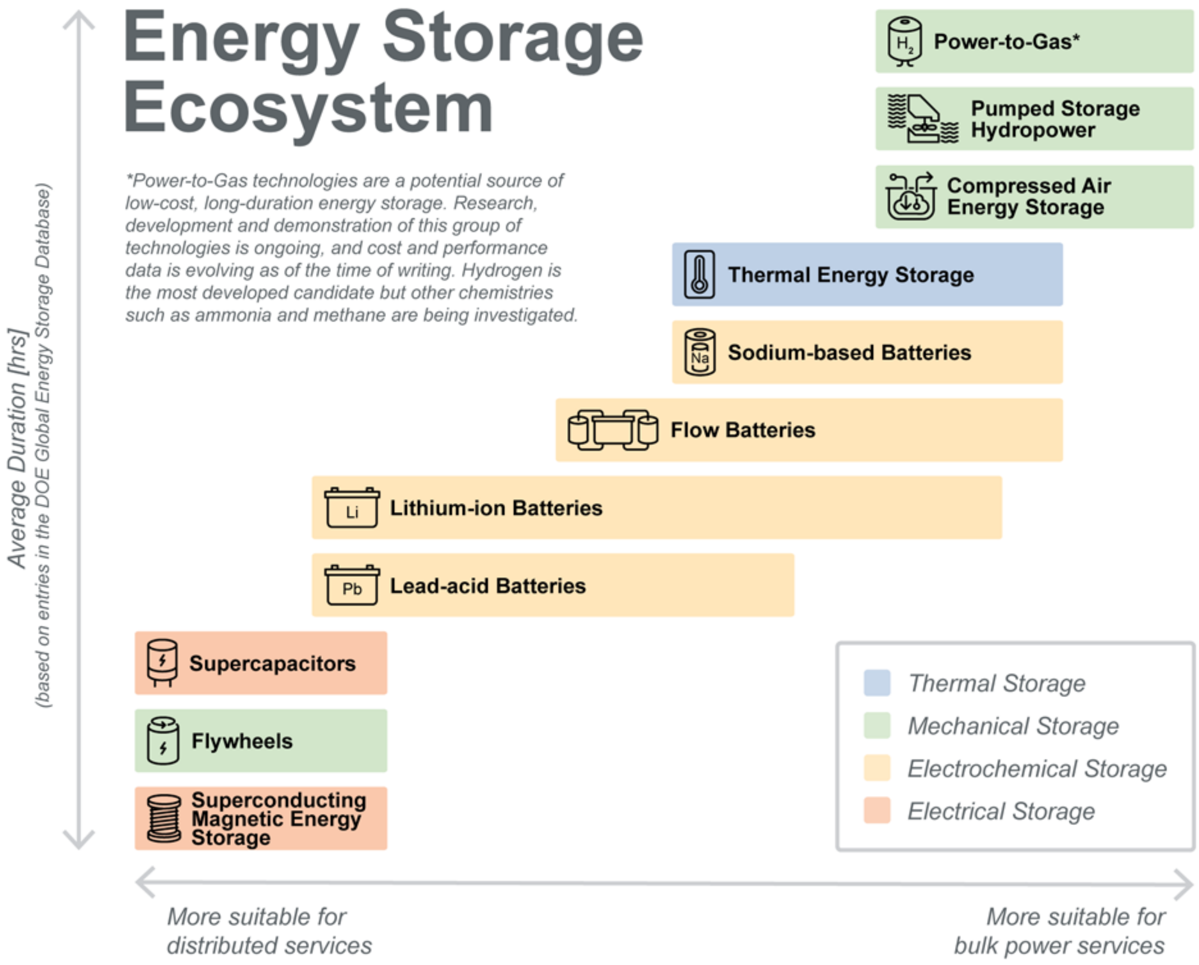

Figure 1. Ecosystem of energy storage technologies and services

Table 1. Qualitative Comparison of Energy Storage Technologies

Source: (Chen et al. 2009; Mongird et al. 2019a; Mongird et al. 2020)

Category	Technology	Development Stage for Utility-Scale Grid Applications	Cost Range	Typical Duration of Discharge at Max Power Capacity	Reaction Time	Round-Trip Efficiency[3]	Lifetime
Electro-Chemical Batteries	Lithium-ion	Widely commercialized	1,408-1,947 ($/kW) 352-487 ($/kWh)†	Minutes to a few hours	Subsecond to seconds	86-88%	10 years
	Flow	Initial commercialization	1,995-2,438 ($/kW) 499-609 ($/kWh)†	Several hours	Subsecond to seconds	65%–70%	15 years
	Lead-acid	Widely commercialized	1,520-1,792 ($/kW) 380-448 ($/kWh)†	Minutes to a few hours	Seconds	79-85%	12 years
	Sodium-sulfur	Initial commercialization	2,394–5,170 ($/kW) 599–1,293 ($/kWh)††	Several hours	Subsecond	77%–83%	15 years
Mechanical	PSH	Widely commercialized	1,504-2,422 ($/kW) 150-242 ($/kWh)†††	Several hours to days	Several Seconds to Minutes (depends on technology choice)	80$^+$%*	40 years
	Compressed air energy storage (CAES)	Initial commercialization	973-1,259 ($/kW) 97-126 ($/kWh)†††	Several hours to days	Several Minutes	52%**	30 years
	Flywheels	Widely commercialized	1,080-2,880 ($/kW) 4,320-11,520 ($/kWh)††	Seconds to a few minutes	Subsecond	86%–96%	20 years
	Gravity	R&D stage	Insufficient data	Several hours	Several Minutes	Insufficient data	Insufficient data
Chemical	Hydrogen production and fuel cells	Pilot stage	2,793-3,488 ($/kW) 279-349 ($/kWh)††††	Several hours to months	Subsecond	35%	30 years
Thermal	Thermal energy storage	Initial commercialization	1,700-1,800 ($/kW) 20-60 ($/kWh)	Several hours	Several Minutes	90$^+$%	30 years

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[3] As some energy storage technologies rely on converting energy from electricity into another medium, such as heat in thermal energy storage systems or chemical energy in hydrogen, we use efficiency here to refer to the round-trip efficiency of storing and releasing electricity (electrons-to-electrons), as opposed to the efficiency of using electricity to produce heat for heating needs or hydrogen for transportation fuel needs.

Electrical	Super-capacitors	R&D Stage	930 ($/kW) 74,480 ($/kWh) [††]	Seconds to a few minutes	Subsecond	92%	10–15 years
	Superconducting magnetic energy storage (SMES)	Initial commercialization	200–300 ($/kW) 1,000–10,000 ($/kWh)	Seconds	Subsecond	~97%	20 years

*: This refers to newer PSH installations and older PSH systems may have efficiencies closer to the 60-75% range.

**: As CAES relies on both electricity to compress air and a fuel (typically natural gas) to expand the air, its efficiency cannot be readily compared to other storage technologies. The value used in this report represents the ratio of the output of electrical energy to the combined input of electrical energy for the compressor and the natural gas input for expansion, using the heating value of natural gas to convert its energy to how much electricity it could have produced (Mongird et al. 2019).

[†] This range refers to a 10 MW 4-hour battery in 2020 costs. For lithium-ion, this refers to the NMC chemistry (see Section 2.1 for additional information on lithium-ion chemistries). See Mongird et. al. (2020) for additional energy storage sizes and durations and estimates for future years.

[††]: This range refers to 2018 costs. See Mongird et. al. (2019) for future years.

[†††] This range refers to 1000 MW 10-hour systems. See Mongird et. al. (2020) for additional energy storage sizes and durations and estimates for future years.

[††††] This range refers to 100 MW 10-hour systems. See Mongird et. al. (2020) for additional energy storage sizes and durations and estimates for future years.

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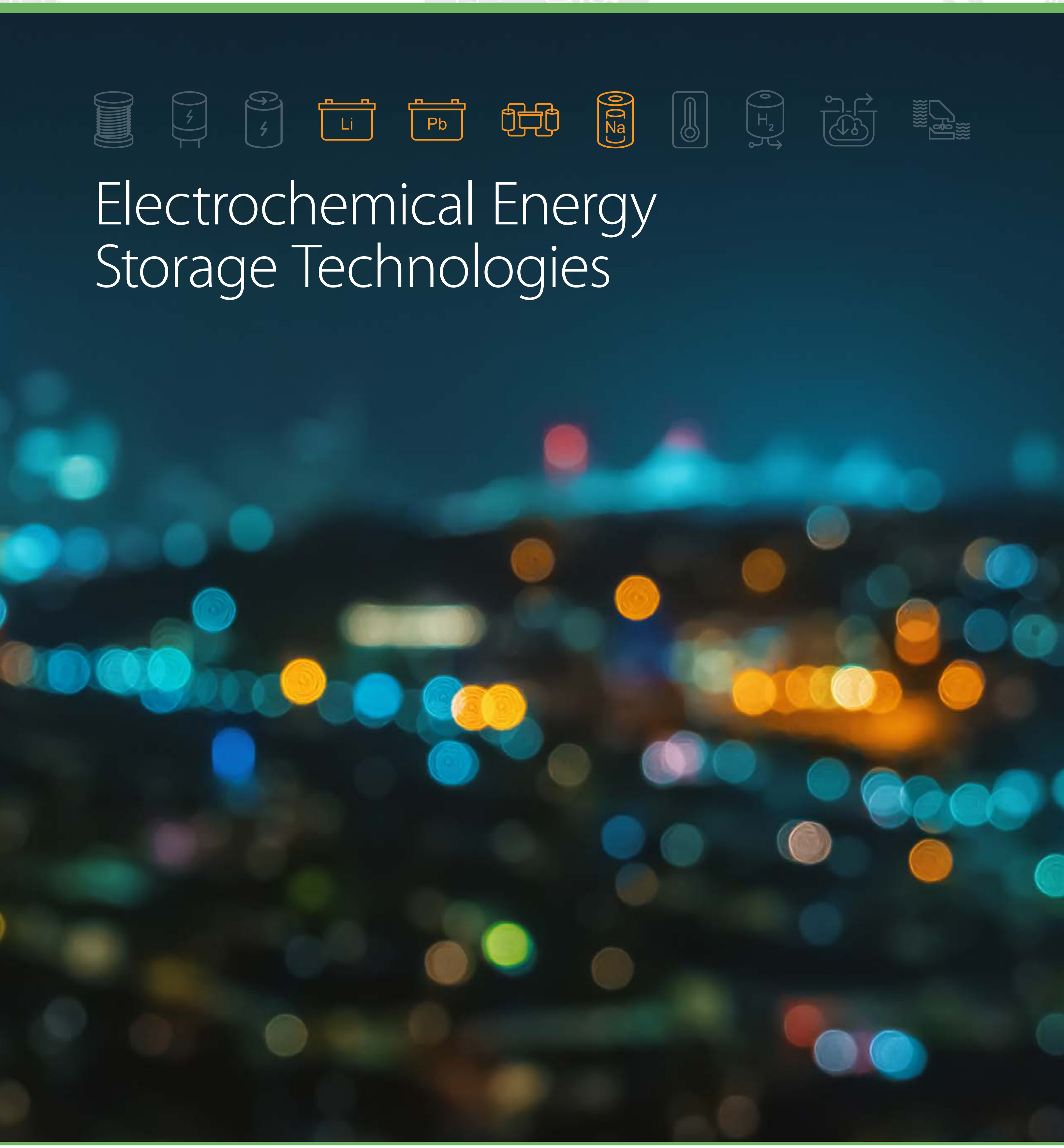

Electrochemical Energy Storage Technologies

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2 Electrochemical Energy Storage Technologies

Electrochemical storage systems use a series of reversible chemical reactions to store electricity in the form of chemical energy. Batteries are the most common form of electrochemical storage and have been deployed in power systems in both front-of-the-meter and behind-the-meter applications, as well as in electronics and transportation applications. Broadly speaking, batteries tend to have durations lasting up to several hours and can change output in the subsecond to several minutes range.

Table 2. Comparison of Electrochemical Storage Technologies

Source: (Fan et al. 2020; DNV GL 2016; Kintner-Meyer et al. 2010; Diaz de la Rubia et al. 2015; Mongird et al. 2020)

Technology	Reaction Time	Round-Trip Efficiency	Energy Density (Wh/kg)	Power Density (W/kg)	Operating Temperature (°C)	Cycle Life (Cycles)**
Lithium-Ion	Subsecond to seconds	86-88%	210–325*	4,000–6,500*	-20–65	1,000–2,000*
Flow	Subsecond	65%–70%	10–50	0.5–2	5–45	12,000–14,000
Lead-Acid	Seconds	79-85%%	30–50	30-50	18–45	500–1,000
Sodium-Sulfur	Subsecond	77%–83%	150–240	120–160	300–350	~4,500

*Values may vary across different cell designs, chemistries, and power electronics configurations. For operational characteristics broken down into common lithium-ion chemistries, see Table 5.
**It should be noted that cycle life is intrinsically related to the behavior and environment of the storage system (e.g., some use cases can lead to lower cycle life as it stresses the storage system, and many electrochemical storage technologies perform worse or suffer shorter cycle life outside their normal operating temperature range).

Table 3. Advantages and Disadvantages of Select Electrochemical Battery Chemistries

Adapted from (Fan et al. 2020)

Storage Type	**Advantages**	**Disadvantages**
Lithium-Ion	• Relatively high energy and power density • Lower maintenance costs • Rapid charge capability • Many chemistries offer design flexibility • Established technology with strong potential for project bankability.	• High upfront cost ($/kWh) relative to lead-acid (potentially offset by longer lifetimes) • Poor high-temperature performance • Safety considerations, which can increase costs to mitigate • Currently complex to recycle • Reliance on scarce materials.
Flow (Vanadium-Redox)	• Long cycle life • High intrinsic safety • Capable of deep discharges.	• Relatively low energy and power density.
Lead-Acid	• Low cost • Many different available sizes and designs • High recyclability.	• Limited energy density • Relatively short cycle life • Cannot be kept in a discharged state for long without permanent impact on performance • Deep cycling can impact cycle life • Poor performance in high temperature environments. • Toxicity of components
Sodium-Sulfur	• Relatively high energy density • Relatively long cycle life • Low self-discharge.	• High operating temperature necessary • High costs.

2.1 Lithium-ion Battery Energy Storage

Technology Summary for Policymakers

Lithium-ion is a mature energy storage technology with established global manufacturing capacity driven in part by its use in electric vehicle applications. The overlap between the transportation and power system sectors have enabled steep price declines in technology costs for lithium-ion batteries, driving higher deployments. In utility-scale power sector applications, lithium-ion has been used predominantly for short-duration, high-cycling services such as frequency regulation, although it is increasingly used to provide peaking capacity and energy arbitrage services in certain jurisdictions. Lithium-ion has a typical duration in the 2- to 4-hour range, with price competitiveness decreasing at longer durations. One major technical issue with lithium-ion is fire safety, as the chemistry can suffer thermal runaway leading to fire concerns. Recent battery pack technology and software innovations are addressing safety concerns related to thermal runaway.

Lithium-ion battery storage currently dominates the landscape for new, utility-scale installations for electrochemical stationary storage applications and is only surpassed by pumped hydro storage for cumulative capacity. Since 2010 in the United States, over 90% of annual additions of utility-scale stationary battery storage in the power sector has been lithium-ion (Figure 2). This trend is driven by several factors, including robust manufacturing capabilities, well-developed supply chains, increasing demand in the transportation sector, and a precipitous drop in lithium-ion battery pack prices over the past several years: lithium-ion battery pack prices declined 89% from 2010 to 2020 (Frith 2020).[4]

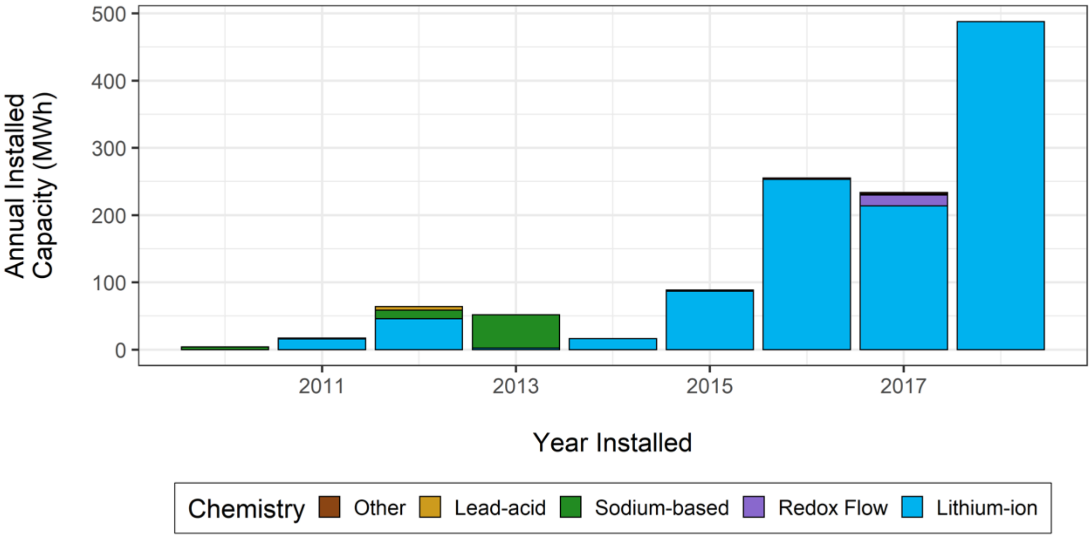

Figure 2. U.S. annual new installations of electrochemical energy storage by chemistry

Source: (EIA 2019)

As with all battery energy storage technologies, lithium-ion batteries convert chemical energy contained in its active materials directly into electrical energy through an electrochemical oxidation-reduction reaction (Warner 2015). Lithium-ion batteries, however, have significantly higher energy densities relative to other electrochemical storage technologies such as lead-acid and flow batteries, which allows

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[4] Note that this price decline refers only to battery pack prices, which reflect lithium-ion battery pack hardware costs and do not include additional hardware components or soft costs that would accumulate when constructing a project.

the same energy needs to be met with smaller and lighter batteries. Lithium-ion batteries are also able to charge and discharge thousands of times before reaching the end of the battery pack life.

The primary safety concern surrounding lithium-ion batteries is fire-risks caused by "thermal runaway." Thermal runaway refers to a point at which the temperature inside the battery cells becomes hot enough to cause self-sustaining heat generation, which can quickly lead to battery failure or even fires (Warner 2015). Even though thermal runaway is not unique to lithium-ion, lithium tends to have a lower runaway temperature, which means thermal management and fire suppression are important factors to consider when operating lithium-ion batteries, even though they may increase overall project costs.[5]

Lithium-ion batteries can consist of various chemistry configurations and each chemistry exhibits slightly different operating parameters. Table 4 compares the key operating metrics for a few of the common lithium-ion chemistries (Warner 2015). Although Lithium Nickel Manganese Cobalt (NMC) is currently the dominate chemistry, competing chemistries Lithium Nickel Cobalt Aluminum (NCA) and Lithium Iron Phosphate (LFP) are expected to grow in popularity over the next several decades (Figure 3).

Table 4. Operating Characteristics of Select Lithium-Ion Chemistries

Source: (Warner 2019; DNV GL 2016; Mongird et al. 2020)

Technology	Energy Density (Wh/L)	Power Density (W/L)	Operating Temperature (°C)	Cycle Life	Self-Discharge (%/month)
Lithium Iron Phosphate	220–250	4,500	-20 to +60	~2,000	<1%
Lithium Nickel Cobalt Aluminum	210–600	4,000–5,000	-20 to +60	>1,000	2%–10%
Lithium Nickel Manganese Cobalt	325	6,500	-20 to +55	~1,200	1%

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[5] Battery cell degradation that can lead to thermal runaway can begin at temperatures as low as 80°C. At 80°C, lithium ions begin to react with chemicals in the electrolyte, decomposing layers around the anode in a heat-generating reaction (exothermic) (Warner 2019).

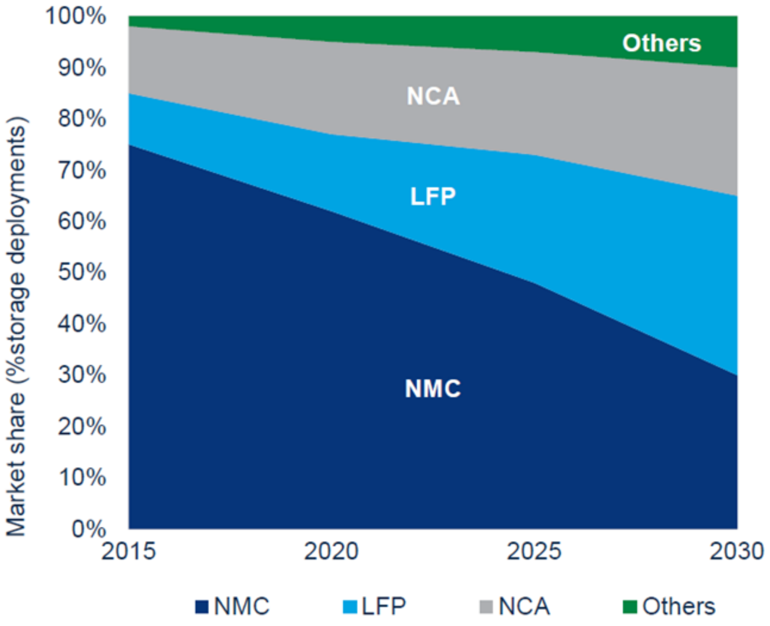

Figure 3: Lithium-ion battery chemistry market share forecast, 2015 – 2030

Source: (Wood Mackenzie 2020)

2.1.1 Current Applications

In addition to widespread electric mobility applications and consumer electronics, lithium-ion battery storage is increasingly used for stationary energy storage applications, both in utility-scale and behind-the-meter applications. Lithium-ion's quick response time, long cycle life, and limited duration lend itself well to shorter-term applications that may require frequent and deep cycling.[6] Currently, lithium-ion is used in frequency response and other essential grid reliability services that help system operators maintain balance between load and demand at short timescales (up to a few hours) (Bowen et al. 2019). Lithium-ion batteries have also seen deployment for providing peaking capacity, charging during times of energy surplus, and discharging during times of higher demand to help utilities meet peak demand. Due to its limited duration, lithium-ion's contribution to system peak demand strongly depends on the shape of the demand curve (Denholm and Margolis 2018). Similarly, lithium-ion can also be used to reduce grid congestion and defer transmission and distribution system upgrades by storing energy during times of excess generation and meeting load locally during times of high demand.

2.1.2 Emerging Applications and R&D Efforts

Future improvements in lithium-ion batteries are primarily focused on increasing energy density, increasing the power output of lithium-ion cells, making the batteries safer to operate, reducing overall costs, and reducing reliance on scarce minerals. Two novel configurations currently being explored are

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[6] "Deep" and "shallow" cycling are used to qualitatively refer to the depth of discharge an energy storage system experiences during operation. The depth of discharge refers to the share of the storage system's capacity that has been discharged and is inversely related to its state of charge. Although there is no set definition, deep cycling may refer to operations when the storage system discharges the majority of its stored energy (such as while providing prolonged peaking capacity) whereas shallow cycling refers to operations when the storage system alternates between charging and discharging such that its state of charge remains relatively high (such as providing frequency regulation). The depth of discharge can have significant effects on the lifetime of the storage system, and technologies vary in their sensitivity to the depth of discharge they experience.

solid-state lithium-ion batteries, which use solid electrolytes and have improved energy densities and lower safety risks compared to liquid-electrolyte lithium-ion batteries, and *lithium-air batteries*, which have improved energy densities and have the potential to be very low cost and could reduce reliance on scarce minerals (Warner 2019).

2.1.3 Example Deployment

Lithium-ion has seen extensive global deployment in the energy sector. One prominent existing project is the Hornsdale Power Reserve, a 100-MW/129-MWh lithium-ion battery in South Australia completed in 2017 for frequency regulation and transmission congestion relief. The South Australia power system is relatively isolated and can disconnect from the larger Australian power system if the point of interconnection is overloaded. One of the battery's additional functions is to provide injections of power to prevent the interconnection from disconnecting. On at least two occasions, during events when large coal plants tripped offline, the Hornsdale Power Reserve responded within milliseconds to immediately inject large amounts of power into the grid over a few minutes to support the grid frequency until other power plants could increase their output, arresting the fall in frequency and potentially avoiding power reliability issues and disconnection from the larger grid (AEMO 2018).

In 2018, the electric cooperative, United Power, completed the installation of a 4-MW/16-MWh (4-hour duration) lithium-ion battery in Firestone, Colorado. The cooperative aims to store excess energy overnight when demand is low and use it to meet peak demand during the day, reducing operating costs for the utility. The local utility expects to be able to save $1 million per year in avoided wholesale capacity charges (United Power 2018).

2.2 Flow Battery Energy Storage

Technology Summary for Policymakers

Flow batteries are in the initial stages of commercialization. The technology is marked by long durations, the ability to deeply discharge its stored energy without damaging the storage system, and exceedingly long life cycles. Flow batteries may be uniquely situated for longer duration services such as load following or peaking capacity. While flow batteries have higher upfront costs than lithium-ion, their longer life cycle can lead to significantly lower lifetime costs. Flow batteries are also typically safer and are less reliant on rare materials, depending on the specific chemistry. Given flow batteries' low energy and power density, these systems tend to be larger than other equivalent storage technologies.

Flow battery energy storage is a form of electrochemical energy storage that converts the chemical energy in electro-active materials, typically stored in liquid-based electrolyte solutions, directly into electrical energy (Nguyen and Savinell 2010). There are various forms of established flow battery energy storage technologies, including redox flow batteries (RFBs) and hybrid flow batteries. RFBs, which include vanadium redox flow and polysulphide bromide flow batteries, have the electro-active material dissolved in a liquid electrolyte that is stored external to the battery. The battery charges and discharges based on redox reactions, which are chemical reactions between two electrolyte solutions at different oxidation states. The electrolytes are typically liquid-based, separated by a membrane, and stored in large tanks. Hybrid flow batteries, which include zinc-bromine and zinc-cerium flow batteries, have one of their electro-active components deposited on a solid surface, as opposed to being dissolved in a liquid electrolyte (Alotto, Guarnieri, and Moro 2014; Nguyen and Savinell 2010).

The global flow battery market is dominated by vanadium RFBs, which is the most studied and commercialized flow battery type (Minke and Turek 2018; Weber et al. 2018). Zinc-bromine (Zn-Br) and polysulphide bromide flow batteries have also been widely studied with some initial commercialization but face technical and economic barriers that have stalled their commercialization. Zn-Br batteries are relatively low cost and exhibit high energy density, high design flexibility, rapid charge, and high depth of discharge capabilities, but suffer from low cycle-life, low energy efficiency, and dendrite formation, which impacts performance.[7] Polysulphide bromides have rapid responses but suffer from expensive material requirements, limited energy density, relatively low efficiencies (~60%–75%), and cross-contamination concerns during long-term battery operation. These challenges currently make Zinc-bromine and polysulphide bromide more expensive and inefficient than the more established vanadium RFBs (Fan et al. 2020).

In principle, flow batteries have several advantages over other electrochemical storage technologies. As the active electrolytic material is separated from the reactive electrodes in the battery, RFBs have a much higher level of safety relative to other electrochemical energy storage technologies. This separation also means that the energy and power capacity of RFBs are independently scalable and modular, with power capacity dictated by the surface area of the electrodes and the energy capacity dictated by the size of the tanks storing the electrolytic material. This flexibility in design means that RFBs can be readily configured for specific needs and applications. RFBs also have stable and durable performance, as the battery electrodes do not undergo any physical or chemical change during operation (Nguyen and Savinell

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[7] Dendrite formation refers to the accumulation of crystals within or on the surface of battery components, which can impact the operation, reliability, and safety of the overall energy storage system.

2010). Additional advantages include long cycle life, low fire risk due to low flammability of battery and electrolyte materials, and easy maintenance relative to other energy storage technologies (Alotto, Guarnieri, and Moro 2014; Fan et al. 2020). RFBs also exhibit a depth-of-discharge capability of nearly 100%, meaning the battery can discharge almost all of its stored energy without impacting system performance or damaging the battery.

Relative to other electrochemical energy storage options, RFBs have lower energy and power densities, and typically involve more space-intensive system infrastructure, which may limit them to large-scale, stationary applications. RFBs also tend to have lower round-trip efficiencies compared to lithium-ion batteries (Alotto, Guarnieri, and Moro 2014). The largest impediment to widespread adoption of RFB, however, is currently its higher costs due in part to a lack of large-scale manufacturing capacity and the need for pumps, sensors and other power and flow management systems (Nguyen and Savinell 2010).

2.2.1 Current Applications

Flow batteries are primarily deployed in utility-scale applications to provide a range of power quality and energy management services, including support for grid integration of solar and wind, although total deployment to date is minimal compared to pumped hydro and lithium-ion battery storage (Alotto, Guarnieri, and Moro 2014). Vanadium RFBs have been used in a range of applications, including provision of peak power and end-of-line voltage support, deferral of conventional transmission and distribution upgrades, and load leveling at substations (Lotspeich 2002; Fan et al. 2020).

2.2.2 Emerging Applications and R&D Efforts

Ongoing R&D for RFBs aims to provide cost-effective longer duration storage for energy shifting, peak shaving, and backup power applications. Ongoing research is mainly focused on:

- **Lowering the costs of existing battery chemistries.** For instance, Primus Power aims to reduce the complexity and balance-of-system costs of zinc-bromine flow batteries by eliminating the need for a membrane separator and separate electrolyte tanks (Primus Power and ARPA-E 2018).
- **Developing newer battery chemistries with fewer raw materials and storage costs**. For example, United Technologies Research Center is currently researching how to develop high-performance flow batteries using inexpensive reactants such as manganese (United Technologies Research Center and ARPA-E 2018). Harvard University has also begun developing pilot RFB storage projects using inexpensive, abundant, precious-metal-free organic materials with the aims of lowering RFB costs while improving performance (Harvard University and ARPA-E 2016).

2.2.3 Example Deployment or Pilot Project

In California, the utility San Diego Gas & Electric developed a 2-MW/8-MWh vanadium RFB, which will participate in California's wholesale power markets as part of a 4-year pilot project. The focus of the pilot is to test and evaluate the most profitable value streams for flow batteries in the commercial wholesale market, and its role in grid integration (CAISO 2019). Researchers at NREL are analyzing this battery's potential value streams using data from performance in distribution support services and have found significant potential savings in grid operational costs from peak shaving (due to transformer upgrade deferral) and energy arbitrage (due to time-shifting energy purchases in the spot market) (Nagarajan et al. 2018).[8]

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[8] The ability for energy storage to provide multiple services across different timescales, at different times and to different stakeholders is known as "value-stacking" and can allow energy storage to maximize its economic potential. In California, regulators helped enable value-stacking by providing rules to utilities seeking to procure services from energy storage (Bowen et al. 2019; CPUC 2018).

2.3 Lead-Acid Battery Energy Storage

Technology Summary for Policymakers

Lead-acid energy storage is a mature, widely commercialized technology driven by its applications in transportation. Lead-acid is marked by low upfront costs relative to newer technologies, including lithium-ion; however, several characteristics, such as its short cycle life and its inability to remain uncharged for long periods or to be deeply discharged without permanent damage, have limited its applications in utility-scale power system applications. Ancillary services that require frequent, shallow charging and discharging like frequency regulation may be better suited for lead-acid, compared to less frequent, deeper discharge applications like peak demand reduction. Despite these limitations, lead-acid is still used in off-grid applications such as in isolated microgrids, particularly where upfront costs can be a barrier.

Lead-acid battery storage serves both stationary and transportation needs and is widely used in micro-grid applications (Lockhart et al. 2019). The basic components of a typical rechargeable lead-acid battery system include a lead dioxide (PbO2) positive electrode, a spongy lead (Pb) negative electrode, an electrolyte solution made of higher concentration of aqueous sulfuric acid solution (H2SO4(aq)) and water. There are several subtypes of lead-acid batteries, each with unique advantages and challenges, including: vented lead-acid, valve-regulated lead-acid, absorbent glass mat, and hybrid systems such as the “Ultrabattery®.”

Lead-acid technologies have a relatively low upfront capital cost compared to other battery technologies such as lithium-ion; however, this technology has a comparably low energy density of around 30–50 Wh/kg and a relatively short life span of about 3–6 years (ADB 2018).

2.3.1 Current Applications

As of 2018, 75 MW of lead-acid batteries for grid-connected applications had been deployed worldwide, which accounts for 2% of energy storage deployment when excluding pumped hydro (Mongird et al. 2019b). Although lead-acid batteries for medium- and large-scale energy storage applications have been commercially available for decades, the low energy density and short cycle life currently limit the use of this technology in widespread grid applications. Historically, utility-scale lead-acid batteries have been used in peak shaving, frequency control, spinning reserve, voltage regulation, and standby power (Parker 2001). Currently, however, most of these grid-scale applications have been overtaken by lithium-ion.

Lead is a toxic metal and exposure can be dangerous for human health. To mitigate this risk, control measures are required during lead-acid battery production, transportation, operation, and recycling processes (WHO 2017). For example, the Commission of Environmental Cooperation of North America has developed technical guidelines on environmentally sound management practices for the recycling of spent lead-acid batteries (CEC 2016).

2.3.2 Emerging Applications and R&D Efforts

In recent decades, research efforts have focused on improving lead-acid battery performance. Two developments that have been proposed to increase life cycle are hybrid systems and carbon-modified system designs (Enos 2015). In general, R&D efforts and funding for lead-acid batteries have historically been limited due to the technology’s maturity and the storage industry’s focus on new, emerging battery chemistries; however, with new grid-scale applications available and increasing competition from alternative chemistries such as lithium-ion, research efforts have increased in recent years. For instance, researchers at the University of California, Los Angeles have begun investigating new acid-based chemistries to extend the lifetimes of traditional lead-acid batteries. Although this research is specifically focused on transportation applications, such fundamental research could potentially be applied to grid-scale applications as well (University of California, Los Angeles and ARPA-E 2017).

2.3.3 Example Deployment or Pilot Project

In 2012, East Penn Manufacturing developed a 3-MW Ultrabattery® lead-acid-supercapacitor hybrid system that can provide frequency regulation and demand management services to the PJM Interconnection, a wholesale market operator in the United States. When not supplying ancillary services to the wholesale market, the storage system can provide customer-facing services such as demand management to the local distribution utility, Met-Ed. The energy storage installation consists of several containerized units that can be modulated or relocated should local power system conditions change. During its initial 3 years of operation, the storage system was able to provide ancillary services in the regulation market 53% of the time and had an average round-trip AC-AC efficiency of 81% (Seasholtz 2015).

In 2015, the Vermont utility Green Mountain Power (GMP) commissioned a 4-MW/3.4-MWh energy storage system to provide ancillary services in the wholesale market and help integrate a 2.5-MW solar PV installation. The storage system consists of a 2-MW lithium-ion battery and a 2-MW lead-acid battery. The storage system is interconnected at the distribution system, and, when not selling services into the wholesale market, it helps GMP reduce demand charges from the wholesale market by meeting load locally. The storage system can also help a portion of GMP's territory "island", providing backup power for a nearby designated emergency center. The lithium-ion component is typically used for providing frequency regulation and smoothing the solar PV system's output, given its higher efficiency and cycle life, while both the lead-acid and lithium-ion components are used for peak shaving, with lead-acid more suitable for longer discharging periods. The project has been able to successfully provide all planned services with an estimated payback time of 8–10 years; however, GMP has stated that future projects will likely consist only of lithium-ion batteries (Schoenung et al. 2017).

2.4 Sodium-Sulfur Battery

Technology Summary for Policymakers

Sodium-sulfur is an energy storage technology in the initial commercialization phase, marked by high energy density, low levels of self-discharge (which correspond to higher efficiencies), and relatively long cycle life. These storage systems rely on common, abundant, and cheap materials, which may help drive down costs relative to storage systems reliant on scare minerals. Despite these advantages, sodium-sulfur has seen relatively little deployment due to its high operating temperature requirements (300°–350°C). Given its long duration capability, on the scale of several hours, and its high cycle life, sodium-sulfur may be well suited for longer duration services such as peaking capacity and energy arbitrage.

Sodium-sulfur batteries are a type of high-temperature battery that relies on a reversible redox reaction between molten sodium and sulfur to charge and discharge electricity. This high-temperature battery utilizes a solid electrolyte operating at 300°C to manage reactions between liquid electrodes and has a fast response time of around 1 millisecond (Tewari 2015). Sodium-sulfur battery systems are typically designed to discharge energy at maximum power capacity in the 6–8 hours range. These systems also have high energy densities, which can make them advantageous for areas with space constraints. In addition, sodium-sulfur batteries have high reliability and can be easily installed, relocated, and maintained; however, these batteries operate at high temperatures, which presents certain safety issues that could limit applications. Several notable safety failures of deployed sodium-sulfur systems, which caused fires, combined with declining lithium-ion costs, have led to declining deployments.

2.4.1 Current Applications

About 190 MW of sodium-sulfur battery capacity was deployed globally in 2018. Sodium-sulfur battery's high energy density make it a desirable technology for long-duration applications such as providing firm capacity, energy arbitrage, and transmission system upgrade deferral. However, the high operating temperatures of these systems typically makes them unsuitable for small-scale and behind-the-meter applications.

2.4.2 Emerging Applications and R&D Efforts

Current R&D efforts focus on reducing the operating temperature of these systems and reducing corrosion in the battery, which can lead to higher self-discharge rates. Reducing the operating temperature could lead to a reduction in overall system costs. The intermediate temperature sodium-sulfur battery, an advanced version of this technology, can be operated between 100°–200°C (Nikiforidis 2019; Lu et al. 2013). Recently, researchers with the University of Wollongong developed nanomaterials for improved performance of room-temperature sodium-sulfur batteries (Long 2019).

2.4.3 Example Deployment or Pilot Project

In 2015, the Chugoku Electric Power Company installed a hybrid battery system as part of a demonstration project in the Oki islands in Japan (Energia Economic & Technical Research Institute and Chogoku Electric Power Company 2016). This project used a 2-MW/0.7-MWh lithium-ion battery in combination with a 4.2-MW/25.2-MWh sodium-sulfur battery to address fluctuations in energy output from a large, planned increase in renewable energy capacity in the island system. The hybrid system used the lithium-ion system to address short-term fluctuations in VRE output and the sodium-sulfur system to address longer term changes in the VRE output. The addition of the lithium-ion component also helped reduce auxiliary (heating) and installed costs relative to a stand-alone sodium-sulfur battery system.

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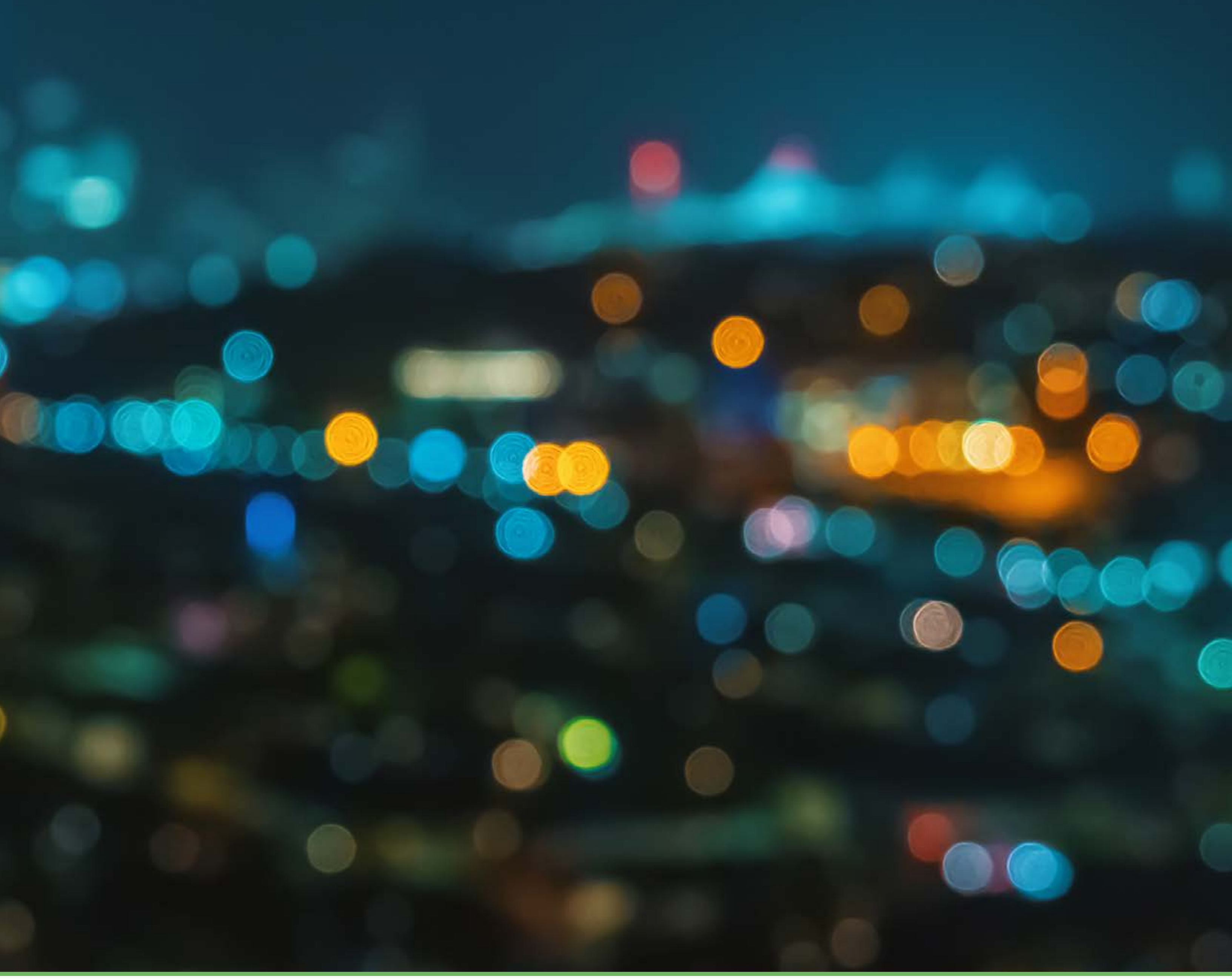
Mechanical Energy Storage Technologies



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3 Mechanical Energy Storage Technologies

Mechanical energy storage systems, which include PSH, compressed air energy storage (CAES), flywheels, and gravity have historically been the most common category of energy storage around the world, in particular PSH. These systems either store energy in the kinetic energy of a spinning mass (flywheels) or by forcing a mass or volume against a potential (e.g., by pumping water uphill in the case of PSH, or pressurizing a gas in the case of CAES). These systems generate electricity by converting the kinetic energy back into electricity or by allowing the mass or volume to work in the direction of the potential (allowing water to flow downhill or gas to expand). Table 5 compares a few of these mechanical systems along with key operating characteristics.

Table 5. Comparison of Mechanical Storage Technologies

Technology	**Duration**	**Reaction Time**	**Round-Trip Efficiency**	**Unique Geographic Requirements**
PSH	Several hours to days	Several seconds to minutes (depends on technology choice)	80^{+}%	Separate reservoirs with adequate differences in elevation
CAES	Several hours to days	Several minutes	52%*	Typically requires unique impermeable underground caverns
Flywheels	Seconds to a few minutes	Subsecond	93%–96% (high)	None
Gravity Energy Storage (GES)	Several hours	Several minutes	Insufficient data	None

*: As CAES relies on both electricity to compress air and a fuel (typically natural gas) to expand the air, its efficiency cannot be readily compared to other storage technologies. The value used in this report represents the ratio of the output of electrical energy to the combined input of electrical energy for the compressor and the natural gas input for expansion, using the heating value of natural gas to convert its energy to how much electricity it could have produced (Mongird et al. 2019).

3.1 Pumped Storage Hydropower (PSH)

Technology Summary for Policymakers

PSH is the most developed and widely commercialized energy storage technology for power sector applications globally. PSH is marked by large capacities and long durations that make it well-suited for services such as load following or energy arbitrage, charging during times of cheap power and meeting demand during system peaks. Despite its well-developed status, PSH is limited by its geographic requirements and high upfront capital cost, which may be a strong barrier to its continued deployment in certain contexts.

PSH facilities are typically large-scale facilities that use water resources at different elevations to store energy for electricity generation. The basic components of a PSH unit include an upper reservoir, a lower water reservoir, a penstock or tunnel, a pump/turbine, and a motor/generator. The motor/generator and pump/turbine are located in a powerhouse that is connected to a local electrical substation.

PSH facilities can have *open-loop* or *closed-loop* water systems. An *open-loop* PSH facility has at least one reservoir that is continuously connected and replenished with a naturally flowing water source. In contrast, a *closed-loop* PSH facility uses two artificially constructed lower reservoirs, and the system must be periodically replenished with water. In both configurations, the upper reservoir is replenished with water pumped through the penstock from the lower reservoir. Electricity is generated when water is released from the upper reservoir, traveling down through the penstock into the powerhouse where the increased water pressure drives the turbine that powers the generator. Many new proposals tend to use closed-loop designs because the regulatory oversight and development time is anticipated to be shorter when not impacting existing natural waterbodies. Regardless, pumped hydropower requires locations suitable to host these facilities, which may be difficult to find close to where the energy storage is needed and electrical interconnection is available.

There is about 131 GW of PSH capacity currently in operation worldwide, representing about 97% of global energy storage capacity. Furthermore, in many jurisdictions, there is already significant hydropower resources, which could be operated as a flexible resource to reduce the need for other sources of energy storage or which could potentially be converted or retrofitted to provide PSH capabilities. Modern PSH facilities have long operational lives of 50–60 years and, while older systems typically had efficiencies in the range of 60%–75%, newer installations can exceed 80% round trip efficiencies.

Over 70% of PSH plants currently installed in the United States were designed to provide daily energy shifting with a duration in the range of 4 to 8 hours. One advantage of PSH compared to other storage technologies is that increasing storage duration (i.e., higher energy capacity) is relatively inexpensive, assuming favorable topology for the upper reservoir. During periods with low electricity demand and high energy availability, electricity can be used to pump water to the upper reservoir. When demand for electricity is highest, water can be released from the upper reservoir to generate electricity.[9] This daily operational cycle helps reduce the need for peaking generation from more costly and potentially polluting

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[9] The presence of low cost variable renewable energy can play an important role in how energy storage systems, including PSH are operated by changing the residual or net load that must be met by system operators. For instance, high penetrations of solar PV may shift low demand periods from the night to the middle of the day. Denholm and Margolis (2018) show that as solar PV penetration increases in California, shorter duration energy storage can help meet peak demand. Increasing penetrations of solar PV have already begun affecting the pumping patterns of PSH in California, with increasing pumping occurring in the day as more solar PV has been added (Somani et al. 2021).

peaking resources. PSH plants can also serve as backup capacity in the case of generator and/or transmission network outages elsewhere on the grid.

3.1.1 Emerging Applications and R&D Efforts

Most PSH facilities installed to date use fixed-speed pump-turbines, meaning that both the pumping and generating units are designed to operate at a fixed rotational speed. Modern advances in fixed-speed technologies can improve PSH response time (i.e., faster change from pumping to generating mode) and operational flexibility, while emerging variable-speed configurations can generate/pump efficiently at much wider ranges of power output, enabling the facility to provide essential grid reliability services (DOE 2016).

Ternary PSH is a state-of-the-art design that provides increased operational flexibility. A ternary-PSH facility combines the motor and generator into a single synchronous unit with the generator, turbine, and pump rotating in the same direction on a single shaft. A torque converter enables simultaneous operation of the pump and turbine and fast switching between pumping and generating modes at an estimated rate of 20–40 MW/second, enabling greater operational flexibility and faster response for reliable grid management (Corbus et al. 2018).

3.1.2 Example Deployment or Pilot Project

On the Spanish island of El Hierro, which has abundant wind resources and enough wind generating capacity to meet 100% of the island's energy needs, a PSH project has been successfully used to store excess renewable energy to meet demand during periods of wind energy shortfall. In 2019, with the help of the PSH system, a total of 54% of the island's annual energy demand was met through renewable energy. Furthermore, the PSH system was able to fully meet the island's energy demand for 25 days in a row, beating its previous 18-day record in 2018. Since its commissioning in 2014, the PSH project has saved nearly 7,500 tons of diesel fuel and offset more than 24,000 tons of greenhouse gases that would have otherwise been burned and emitted to balance electricity supply and demand (Gorona del Viento El Hierro, S.A. 2021).

In the United States, two proposed projects include Goldendale, a 1,200-MW closed-loop project on the Washington/Oregon border, and Banner Mountain, a 400-MW closed-loop project in Wyoming. Both projects are interested in providing multiple services to a wide array of potential customers, making them distinct from previous PSH projects that were owned by, deployed by, and served a single vertically integrated utility. The Goldendale project will use conventional pumps while the Banner Mountain project plans to use ternary pumps (DOE 2018b).

3.2 Flywheel Energy Storage

Technology Summary for Policymakers

Flywheels are an established, widely commercialized energy storage technology, primarily used in smaller-scale applications relative to other mechanical energy storage technologies like PSH or CAES. Flywheels are characterized by rapid charging and discharging capabilities, relatively little maintenance, long lifetimes, and short discharge durations. These systems are practical for maintaining power quality in uninterruptible power supply applications and for short duration services like grid frequency regulation. While costs are comparable to other technologies on a power basis ($/kW), on an energy basis ($/kWh), flywheels are significantly more expensive than comparable alternatives like batteries, which has limited their deployment outside specific applications.

Flywheel technology is a mechanical device that is used to convert electricity to and from rotational kinetic energy. Flywheel energy storage systems (FESS) consist of three main elements: a motor-generator, low-friction bearings, and a rotor (also known as a flywheel). The motor-generator uses electricity to accelerate the rotor to high speeds in a low-friction environment, storing kinetic energy. When needed, the stored kinetic energy is converted back to electricity through deacceleration. Compared to other energy storage mediums such as lithium-ion and lead-acid batteries, flywheels rely significantly less on corrosive or toxic materials. Flywheels exhibit very long lifetimes and require relatively little maintenance compared to other mechanical energy storage technologies. Table 6 describes a few key operational characteristics for three main categories of flywheel storage.

Table 6. Typical Characteristics of Select Flywheel Technologies

Adapted from (Wicki and Hansen 2017)

Characteristics	**Low-Speed Flywheel**	**High-Speed Flywheel**	**Micro High-Speed**
Operating Speed	<10,000 rpm	>10,000 rpm	>10,000 rpm
Rotor Composition	Steel	Carbon fiber composite	Carbon fiber composite
Bearings	Rolling-element/mechanical ball	Magnetic (low friction)	Rolling-element/mechanical ball
Typical Specific Energy	~5 Wh/kg	Up to 100 Wh/kg	~10 Wh/kg
Lifetime	20 years	20 years	20 years

3.2.1 Current Applications

Flywheels can provide a range of grid stability support services, such as frequency regulation, as this technology can provide high power for short durations and quick responses during charge-discharge cycles (Wicki and Hansen 2017; Amiryar and Pullen 2017). Flywheels can also be used for maintaining power quality by quickly absorbing or injecting power to maintain nominal voltage and frequency levels (Arani, Zaker, and Gharehpetian 2017). At smaller scales, FESS has been used in uninterruptible power supply applications in sensitive industries like health care, semiconductor manufacturing, and data centers. The FESS rapidly responds to loss of power from the grid until slower, longer lasting resources like diesel generators can come online.

3.2.2 Emerging Applications and R&D Efforts

Flywheels are a mature technology and as such have seen few recent R&D efforts relative to newer technologies. Outside the power sector, there is interest in flywheels for applications in the public transportation sector for capturing energy that is wasted during deacceleration (Gee and Dunn 2015).

3.2.3 Example Deployment or Pilot Project

Beacon Power developed a 20-MW flywheel energy storage plant in Pennsylvania to explore applications of flywheels in the regional electricity market's fast response regulation market. This project builds on a previous FESS project in Pennsylvania that successfully demonstrated the deployment of fast response flywheel-based frequency regulation. Beacon Power began operation in September 2013 at 4 MW with full commercial operation commencing in July 2014, and the plant can charge and discharge at full rated power without restriction. The system functions year-round with over 98% availability (NETL 2015).

A demonstration project by California's Emerging Technology Coordinating Council assessed the potential value of FESS to the grid, including load shifting and ancillary services needed for grid stabilization. The financial analysis study found a proposed flywheel (6.25 kW/25 kWh) to be cost-effective on a 4-hour discharge duration demonstrating the efficiency of this flywheel to improve grid stabilization through load shifting and ancillary services (Amber Kinetics, Inc. 2015).

3.3 Compressed Air Energy Storage

Technology Summary for Policymakers

Traditional CAES (diabatic compressed air energy storage [D-CAES]) is a mature technology, although it has seen relatively little deployment to date, but new variations of CAES (e.g., adiabatic compressed air energy storage [A-CAES] and liquid air energy storage [LAES]) are currently immature and in pilot-testing phases. CAES is characterized by high energy capacity and can have exceedingly long duration times on the scale of several hours to days. CAES has slower response times than other storage technologies like flywheels or batteries and may be more suitable for applications like providing peak capacity, secondary and tertiary operating reserves, and energy arbitrage. As CAES relies on spinning turbines to generate and store electricity, it can also provide system inertia, which is critical to arresting rapid changes in frequency (Denholm et al. 2020). Traditional CAES deployment is limited by unique geological requirements, which may be avoided in new variations. CAES costs on a power basis are comparable to other technologies; however, on an energy basis, CAES is significantly cheaper than most alternatives.

CAES is a form of mechanical energy storage that uses electricity to compress and store ambient air for later use. The air has historically been stored underground in salt caverns but it could be stored in any other suitable geologic formation such as hard and porous rock formation (Succar and Williams 2008; Luo et al. 2015). When needed, this compressed air is withdrawn from the storage medium, expanded, and passed through a turbine to generate electricity (Succar and Williams 2008; Luo et al. 2015). CAES operation is very similar to that of a conventional gas turbine, except its gas compression and expansion phases occur independently at different times determined by whether the system is charging or discharging energy (Succar and Williams 2008).

In general, there are three configurations of CAES systems based on the how the heat produced during compression is used and stored: D-CAES, A-CAES, and isothermal CAES. Today's CAES systems are D-CAES, which do not recover the heat generated during gas compression. These systems can be classified as hybrid, in that they require an external heat source (typically fossil fuel) during gas expansion. A-CAES stores compression heat at a higher temperature for later use and in some cases adds additional heat during the expansion stage to generate more power. Isothermal systems aim to minimize or even prevent the formation of compression heat (Venkataramani, Ramalingam, and Viswanathan 2018; Luo et al. 2015; Wang et al. 2017).

D-CAES technology has been the only commercialized design for several decades, but a 1.75-MW/10-MWh A-CAES system plant was recently completed by Hydrostor in Canada and has been contracted to provide the local system operator with peaking capacity and ancillary services (Globe Newswire 2019). The same company has also recently announced a 5-MW/10-MWh A-CAES system expected to be online in 2020-21 in South Australia and contracted to provide load leveling, frequency regulation, and system inertia (Hydrostor 2020). Although D-CAES is the primary type of CAES currently deployed, project development for D-CAES has been restricted by the unique geologic formations required for gas storage, which must be large and impermeable and have storage capacity ranging from several hours to over 24 hours.

Compared to other storage technologies, CAES typically has lower energy capacity costs, as it uses off-the-shelf components from more established technologies like compressors. Given the proper geologic formations, CAES can also have significantly longer durations than most energy storage technologies. The main disadvantage of CAES is that development is constrained by availability of suitable storage mediums. As CAES must switch between compression and expansion phases when charging and discharging, it is also possible that the response time for CAES plants may be slower than other technologies, which may make them less suitable for services that require rapid changes in output (Succar and Williams 2008).

Luo et al. (2015) suggests that one additional barrier to CAES is its relatively low round-trip efficiency compared to alternatives such as PSH and battery technologies; however, directly comparing the efficiencies of CAES versus alternative storage technologies can be quite difficult, as CAES designs rely on two different energy inputs, electricity for the compressor when compressing/charging and fossil fuels for heating the air when expanding/discharging. Efforts have been made, however, to determine a suitable metric for CAES efficiency by attempting to convert the quantities of electricity required by the compressor, the amount of gas or other fossil fuel needed to heat the gas, and the electricity output by the system into equivalent terms (Succar and Williams 2008).

3.3.1 Current Applications

CAES systems were initially developed to meet black start and peak capacity needs by storing cheap nuclear and fossil fuel-generated electricity for use during peak demand periods. Large-scale CAES could also be used in grid applications for load shifting, peak shaving, and frequency and voltage control, as well as addressing imbalances in VRE supply (Succar and Williams 2008).

3.3.2 Emerging Applications and R&D Efforts

Initial research efforts in CAES partly focused on D-CAES development because it was perceived as the more commercialization-ready CAES technology, but there is a wide range of ongoing research. This includes developing aboveground and smaller-scale CAES systems, identifying other suitable geologies for air storage, developing hybrid and integrated CAES systems, and improving the overall efficiency of D-CAES systems.

Other related systems designs include LAES and supercritical CAES. LAES may be classified as either a thermal energy storage system or as a CAES technology based on its expansion phase (Luo et al. 2015; Wang et. al 2017). In LAES, air is compressed and liquefied and stored in low-temperature tanks and discharged for expansion, during which time it becomes a high-pressure gas (Wang et al. 2017; Sciacovelli, Vecchi, and Ding 2017). Unlike D-CAES, LAES does not have geographic constraints and could also provide higher modularity because the component parts are independently scalable (Lin et al. 2019). There is a growing body of work on the technical performance of LAES, but more needs to be understood on its potential market value, especially in comparison to CAES and other storage technologies (Lin et al. 2019). Supercritical CAES systems integrate A-CAES and LAES designs by compressing the air to its supercritical state, using a heat exchanger to collect the compression heat with the liquefied air reheated by the heat exchanger for power generation (Luo et al. 2015; Wang et al. 2017).

Other ongoing research includes identifying the suitability of geologies such as hard rock and porous rock structures for gas storage, developing hybrid and integrated CAES systems, and improving the round-trip efficiency of CAES (Luo et al. 2015; Wang et al. 2017). Utilizing such geologies could increase the technical potential for CAES in many contexts, but these geologies typically have a much higher development cost, making them uneconomical compared to other storage mediums (Succar and Williams 2008; Luo et al. 2015). There is also ongoing research into integrating thermal energy storage with CAES systems, which could improve round-trip efficiency and the economic feasibility of CAES systems (Luo et al. 2015; Sciacovelli, Vecchi, and Ding 2017).

3.3.3 Example Deployment or Pilot Project

There are two operating commercial CAES plants (both diabatic) worldwide—a 290-MW plant in Huntorf, Germany commissioned in 1978, and a 110-MW plant in McIntosh, Alabama, commissioned in 1991. The Huntorf plant was initially developed to provide fast response services—specifically, black start capabilities for nearby nuclear plants, as well as storing cheap off-peak power from these nuclear plants and discharging during peak periods. Its daily storage capacity was expanded from 2 to 3 hours to allow for a broader range of grid support. It currently provides peak shaving in the evening, grid balancing for wind power in northern Germany, and frequency response services (van der Linden 2006; Crotogino, Mohmeyer, and Scharf 2001; Succar and Williams 2008).

The McIntosh plant has a larger storage capacity and can operate continuously for up to 26 hours. It also uses a recuperator, which reuses exhaust heat, reducing overall fuel consumption and improving cycle efficiency (Luo et al. 2015; van der Linden 2006).

Ongoing pilot and demonstration projects include a Hydrostor A-CAES facility in Canada and a LAES demonstration project in Vermont. Hydrostor has developed an emissions-free, water-compensated A-CAES system where water is used to maintain constant air pressure. Hydrostatic pressure then forces the compressed air to the surface, which is expanded together with the stored heat for electricity generation (Hydrostor 2020; Venkataramani, Ramalingam, and Viswanathan 2018). Hydrostor recently commissioned a first-of-its kind 2.2-MW/10-MWh A-CAES plant in Ontario, Canada (Globe Newswire 2019).

A 50-MW/400-MWh LAES demonstration project in Vermont is currently planned to provide transmission network upgrade deferral services and is intended to provide more than 8 hours of storage capacity. The system will be designed to clean and compress air during off-peak periods, liquefying the compressed gas and storing it in cold tanks at ~-196°C, allowing the compressed air to evaporate and expand turns turbines that can be used to generate power (Highview Power 2019; Lin et al. 2019).

3.4 Gravity Energy Storage

Technology Summary for Policymakers

GES is an immature technology with the potential to provide long-term energy storage similar to CAES or PSH. These systems could potentially be used to provide slower, longer-duration services such as peaking capacity, load following, and energy arbitrage.

GES uses established mechanical bulk storage principles, using the potential energy of a mass at a given height. PSH can be categorized as a GES technology that uses water as the energy storage medium. Different materials and methods for GES have been proposed (Fyke 2019). Emerging GES technologies typically use a low-cost and abundant medium such as sand, concrete, gravel, or rock. The general concept involves lifting the storage medium from the ground (or from underground in places with abandoned mine shafts) to a higher elevation. The kinetic energy of the heavy weight held at high elevation can be extracted using an electric induction generator, similar to the concept that enables regenerative braking in electric vehicles.

To date, no GES technology has demonstrated commercial viability at scale; however, there are several startups that have either developed pilot projects or are working toward beginning construction on larger projects. Startup Energy Vault has developed a demonstration project in Switzerland that uses cranes to lift and lower large blocks of concrete to store and generate electricity. Likewise, the California-based Advanced Rail Energy Storage startup is currently developing a pilot project that stores and releases electricity by moving a mass on a rail line up and down an incline.

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Additional Energy Storage Technologies: Chemical, Thermal and Electrical

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4 Additional Energy Storage Technologies

Chemical energy storage relies on utilizing thermal or electrical energy to drive chemical or physical reactions. These reactions yield stable chemicals that can store energy for long periods of time given the proper storage conditions. These chemicals can then be burned or subjected to additional chemical reactions to convert the latent energy in the chemical to electricity. Due to its relatively stable composition, chemical energy storage has the potential to store large amounts of energy for long timescales and may potentially be used to address long-term seasonal imbalances in energy supply and demand. These technologies are often referred to as **power-to-gas** as the chemicals used to store energy occur in gaseous forms (although in some cases they may be cooled to a liquid state or embedded on the surface of or within solids). Common chemicals investigated for their potential to store energy for the power sector include: hydrogen, methane, and ammonia. This paper focuses on hydrogen for power-to-gas chemical energy storage technologies as it is the most prominent choice for chemical energy storage and is currently receiving the most investment.

Thermal energy storage (TES) refers to technologies that can store heat for later use. Some TES technologies use electricity to generate heat and store the heat until it is converted back to electricity, while other TES store and release heat directly without converting to and from electricity. This primer focuses on the former. In some applications, such as with concentrated solar power, TES is used to store heat directly and that heat is later used to power steam turbines that generate electricity.

Electrical energy storage systems typically refer to supercapacitors and superconducting magnetic energy storage. Both of these technologies are marked by exceedingly fast response times and high power capacities with relatively low energy capacities.

4.1 Hydrogen Energy Storage Systems

Technology Summary for Policymakers

The large-scale production of hydrogen from electricity and its efficient conversion back to electricity is still in the pilot-phase of development, although a few large-scale projects have been completed around the world, with more planned. Although technically capable of providing short-term services like frequency regulation, hydrogen is currently unable to compete with electrochemical energy storage like lithium-ion batteries for shorter duration services on a cost-basis; however, hydrogen energy storage is uniquely suited to provide services on very long timescales, such as shifting surpluses of renewable energy in the spring to deficits in the winter or summer. While costs are currently high for producing hydrogen and subsequent generation of power, its potential applications in the transportation sector and industrial processes could help accelerate cost declines.

Hydrogen energy storage systems for electricity (electrons-to-electrons) rely on the production, storage, and eventual reconversion of the hydrogen into electricity (either through the combustion of hydrogen gas, or the direct conversion of hydrogen and oxygen in a fuel cell). Large-scale hydrogen production to store electricity will rely on both water and electricity inputs. There are many potential ways to convert water into hydrogen gas, however, the most mature method is based on electrolysis, in which electricity is used to split the water molecule into hydrogen and oxygen gas.[10] Electrolysis is an efficient process (72%–82%) over a wide range of power levels, which makes the production of hydrogen from electricity a flexible process that could help balance fluctuations in supply and demand and absorb surpluses of renewable electricity.[11] Because electrolysis relies on low voltage direct current electrical input, solar photovoltaic or wind power plants could potentially serve as a direct power source for this water-splitting process. Figure 3 shows an overview of several methods that are currently used, or could be used, to produce hydrogen feedstock and their end uses. Table 7 discusses some of the processes available to produce hydrogen in more detail.

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[10] This is opposed to producing hydrogen from natural gas through a process known as steam reforming, which currently accounts for approximately 95% of hydrogen production in the United States (U.S. DRIVE 2017). For an in-depth review of the various methods to produce hydrogen gas, either from water or hydrocarbons such as natural gas, see Basile and Iulianelli (2014), Zhang et al. (2014) or U.S. DRIVE (2017).

[11] When discussing the efficiency of producing hydrogen through electrolysis, the standard format is to represent the ratio of the energy required to produce a set amount of hydrogen and the chemical energy in the hydrogen produced. This metric does not capture losses from using the hydrogen to later produce electricity and is thus not a round-trip efficiency.

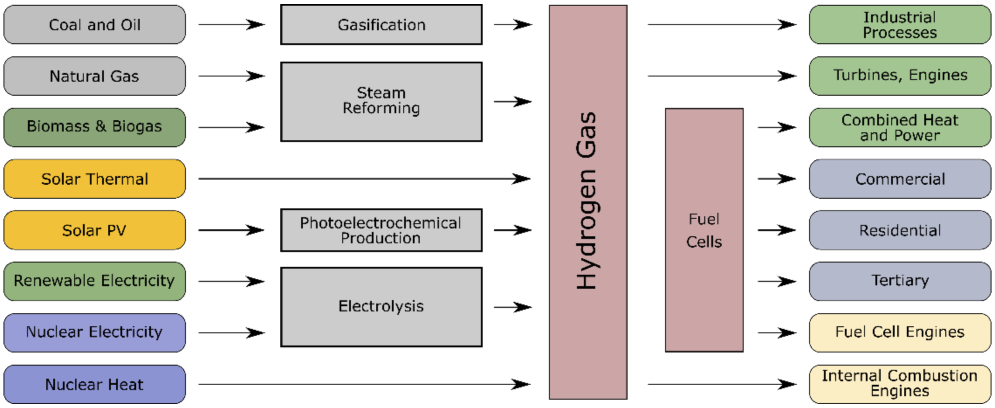

Figure 4. Pathways in the hydrogen economy from feedstock to end application

Source: Basile and Iulianelli (2014)

Table 7. Methods for Producing Hydrogen

Method	Status	Feedstock	Description
Gasification	Mature	Coal or biomass	Air (or pure oxygen) and steam are used to initiate chemical reactions with the feedstock to create 'syngas,' a mixture of carbon monoxide and hydrogen and slag mineral residue. This syngas can be further refined through additional steam and catalysts to yield pure hydrogen. This process also yields several greenhouse gases such as CO_2 and CO.
Steam (Methane) Reforming	Mature	Natural gas or biogas	The gas feedstock is heated to over 700°C in the presence of a catalyst producing syngas (carbon monoxide and hydrogen), which can be further refined to yield pure hydrogen gas. This process also yields several greenhouse gases such as CO_2 and CO.
Electrolysis			
Proton-Exchange Membrane	Pilot for at-scale production	Electricity plus water	A proton-exchange membrane is used to split water in the presence of electricity. This process occurs at relatively low temperatures (70°–90°C).
Alkaline	Mature at scale		A liquid alkaline solution of sodium or potassium hydroxide is used as the solution to generate hydrogen in the presence of electricity. This process occurs at relatively low temperatures (100°–150°C).
Solid Oxide	R&D		A solid ceramic material is used as the electrolyte. This process must occur at relatively high temperatures (700°–800°C) but operates at a higher electrical efficiency.
Photoelectrochemical Splitting	R&D	Solar energy plus water	This process uses semiconductor materials (similar to those found in solar photovoltaic panels) to directly harness the energy from light to split water molecules. This process can occur in a panel-based reactor, in which the semiconductor material is submerged in water and generates electricity when exposed to light, which is used to generate hydrogen. Alternatively, semiconductor photocatalyst particles can be dispersed throughout a volume of water, which will generate hydrogen gas when exposed to sunlight.
Thermochemical Splitting	R&D	High heat plus water	This process uses high temperatures, either from nuclear waste heat or concentrated solar power (CSP), to drive chemical reactions in a closed loop to split water into hydrogen and oxygen. This process can be either direct (only using temperatures ~2,000°C) or hybrid (using lower temperatures, ~500°C, and electricity).

Once produced, hydrogen can be stored and used later for electricity generation. Hydrogen can be stored as either a gas, liquid, or on the porous surfaces of nanostructures of certain materials. When stored as a gas, due to hydrogen's low density, it must be stored in large, pressurized containers or at very low temperatures, which can complicate transportation and increase associated storage costs. Similar to natural gas and CAES, large underground caverns, such as retired salt mines, could be used to store high volumes of hydrogen gas. When stored as a liquid, the overall storage volume required decreases but storage costs may increase and efficiency may decrease. Finally, hydrogen atoms can be stored within the spaces inside metal or alloy lattices or on the surface of carbon structures (such as carbon nanotubes) (Sherif et al. 2014). The benefit of storing the hydrogen on the surface of or within other materials is that the hydrogen requires an energy input to release the hydrogen, providing some safety advantages to gaseous or liquid hydrogen.

When electricity is needed, hydrogen can either be combusted with oxygen (from the air) to generate steam or electrochemically combined in fuel cells to produce water and electricity. The combustion process can create exceedingly high temperatures (above 3,000°C), but these temperatures can be lowered through the use of catalysts, which can reduce the temperatures involved to below 500°C (Sherif et al. 2014). The combustion of hydrogen and oxygen produces only water vapor as a byproduct, and, at higher temperatures, some nitrogen oxides. Combining hydrogen and oxygen in fuel cells generates water and electricity through an electrochemical reaction (the reverse of electrolysis). While some forms of hydrogen production can see efficiencies as high as 80^{+}%, the round-trip electrons-to-electrons efficiency of hydrogen energy storage is relatively low, in the 40%–50% range.

4.1.1 Current Applications

Current applications and R&D efforts for hydrogen storage are still in their initial phases and focus primarily in the transportation sector as fuel cell electric vehicles. Other applications, including transportation purposes or for stationary energy storage, are still in testing/piloting phases. Challenges in storing and transporting hydrogen economically are limiting factors that currently impede development of larger-scale hydrogen energy storage adoption. Some turbine manufacturers have experimented with burning mixtures of natural gas and hydrogen as a means of partially decarbonizing the production of electricity from natural gas. For example, the Los Angeles Department of Water and Power's (LADWP's) Intermountain Power Project in California plans to transition a natural gas plant in its territory to burn 100% hydrogen by 2045 (LADWP 2019).[12]

4.1.2 Emerging Applications and R&D Efforts

In addition to potential applications in the transportation sector, hydrogen has the possibility to provide a wide range of grid services for the power sector. Electrolyzers, which convert water into hydrogen and oxygen through electrolysis, have been shown to be able to respond fast enough to participate in electricity and ancillary service markets, including markets for services such as contingency reserves, load-following, and frequency regulation (Melaina and Eichman 2015). In these applications, hydrogen can be stored when there is excess electricity and can either be used as an input for transportation applications or in electricity generation at a later time. Furthermore, due to the ability to store hydrogen for long periods of time (relative to battery energy storage which loses stored energy over time due to self-discharge), hydrogen may be able to address seasonal imbalances in energy supply and demand in high-VRE power systems. Hydrogen also has many applications in the industrial sector from supplying heat to creating ammonia and purifying raw metallic ore (Zhang et al. 2014).[13] Currently, storing electricity with hydrogen is more expensive relative to more mature technologies such as lithium-ion or lead-acid; however, hydrogen prices could eventually benefit from economies of scale due to multisectoral applications in transportation and industry.

4.1.3 Example Deployment or Pilot Project

In 2015, the municipal utility of Mainz, Germany, in collaboration with several industrial, university, and government partners developed a 6-MW photon-exchange membrane-electrolyzer hydrogen production facility that will be able to produce 89.8 kg of hydrogen gas per hour.[14] The electrolyzer is connected to

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[12] Although the plant will only be required to generate with pure hydrogen by 2045, the plant will be capable of using a mixture of up to 30% hydrogen once operation begins in 2025. The facility intends on using the abundance of renewable energy in the immediate area of the repurposed gas plants to generate hydrogen and store the hydrogen in a large salt cavern near the plants (LADWP 2019).

[13] Purifying the metallic ore of tungsten and molybdenum is already common, but this could be expanded to other metallic ores such as iron, copper, and aluminum, which currently use carbon and carbon monoxide (Zhang et al. 2014).

[14] The electric capacity of the electrolyzer (6 MW) refers to the peak capacity of electricity the system can produce when converting hydrogen gas and oxygen back to water and electricity through reverse electrolysis.

an adjacent 8-MW wind power plant and seeks to store excess renewable energy as well as supply ancillary services to the wholesale market (Kopp et al. 2017).

In Linz, Austria, the world's largest hydrogen production facility powered solely with renewable energy commenced operation in late 2019 (Collins 2019). This 6-MW capacity pilot plant will use clean energy from renewable energy resources to create 'green hydrogen' that will be used at a neighboring steel manufacturer. The pilot project will also investigate the opportunity to use the variable demand of the hydrogen plant to provide grid services and compensate for variable clean energy supply, turning up hydrogen production to absorb excess clean electricity and turning down operations during times of low VRE output.

4.2 Thermal Energy Storage (TES)

Technology Summary for Policymakers

TES is an established technology that relies on storing energy as heat and extracting the heat at a later period, either to meet heating demands directly or to generate electricity. TES is marked by long durations of several hours and is therefore a good fit for peaking capacity needs. While not subject to geologic constraints such as PSH or CAES, TES is often combined with CSP, which needs high levels of direct solar radiation that can only be found in select geographies. In a CSP plant, TES is used to shift energy generated during high solar hours to evening or nighttime periods. In district heating applications, thermal energy storage enables flexible operations of combined heat and power (CHP) plants.

TES stores excess thermal energy to be used at a later time in heating/cooling and power generation applications (IRENA 2013). There are three types of TES systems: sensible heat storage, latent heat storage, and thermochemical storage systems. A *sensible heat storage* system uses temperature changes within a solid or liquid storage medium to store thermal energy. A *latent heat storage* system stores thermal energy by using phase change materials (PCMs) such as polymers and compounds like water, salt hydrates and fatty acids. PCMs can absorb and release thermal energy during phase change, typically through melting and freezing.[15] When the temperature rises, the PCM melts (solid to liquid phase change) and stores the heat. As the temperature drops, the PCM releases heat as it solidifies. A *thermochemical storage* system is a form of thermal energy storage that releases or stores energy as a byproduct of chemical reactions.

4.2.1 Current Applications

TES can be applied in centralized district heating systems, in bulk power system applications, as well as for building heating and cooling needs. In district heating systems, TES is used to store thermal energy from CHP plants that provide both electricity generation and heat output. Because the timing of demand for heating does not perfectly coincide with demand for electricity, TES enables the CHP plants to decouple the timing of electricity generation from heat supply. Decoupling electricity supply from heat supply enables CHP plants to provide flexible supply for the power system, increasing or decreasing electricity production when needed.

TES is also a key component of CSP plants. The TES system in a CSP plant stores thermal energy, which is converted into electricity using a steam-driven turbine generator. The TES component of a CSP plant can generate electricity when sunlight is not available, thus providing a dispatchable source of renewable energy. Currently, CSP plants primarily use molten salt as the liquid sensible heat storage medium. As of 2018, 5.5 GW of CSP plants are in operation, and global CSP-TES capacity has reached 16.6 GWh (REN21 2019).

TES is also marked by slower reaction times than other storage mediums, such as electrochemical storage systems and may be poorly suited for applications that require rapid adjustments in output. On the other hand, TES may also have difficulties maintaining its charge for long periods of time, such as in seasonal storage applications, due to thermal losses as heat is dissipated from the storage medium to the environment (Enescu et al. 2020). TES may be currently best suited for shifting energy over shorter time periods, providing load following and intra-day energy arbitrage services.

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[15] Solid-solid PCMs also exist and can be utilized to store energy.

Although outside the focus of this guide, TES has also been applied to buildings to meet heating and cooling needs. These have been used primarily to shift heating and cooling demands by adding additional thermal mass to a building, such as adding tanks of PCMs to a cold-storage warehouse to allow the building to reduce cooling needs during periods of high electricity prices.

4.2.2 Emerging Applications and R&D Efforts

Two of the main challenges facing TES projects are high costs and relatively lower efficiencies for charging and discharging. Advanced CSP-TES technology is focusing on developing more cost-effective and reliable materials that allow operation at higher temperatures, which in turn can improve the efficiency of the TES system. For example, in 2018, the U.S. Department of Energy announced the Generation 3 CSP funding program to enhance CSP's competitiveness by supporting materials science research into alternative materials for CSP plant operation at 700°C (DOE 2020).

Although sensible heat storage technology has relatively low cost and is the most developed, other TES subtypes are attracting considerable interest. For example, PCM technologies have a higher storage density and a narrower operating temperature range, so melting and solidification temperatures are easier to adjust within a shorter period (Dileep Singh and Yu 2019).

4.2.3 Example Deployment or Pilot Project

Most CSP-TES plants are in Spain, the United States, Morocco, and China. In 2013, a 280-MW parabolic trough CSP with 6-hour TES system project was constructed in Arizona. The first large-scale commercialized power tower CSP (110 MW paired with 10-hour TES) in the United States, built in Nevada, has been in operation since 2015 (NREL 2015).

4.3 Supercapacitors

Technology Summary for Policymakers

A supercapacitor, also known as an ultracapacitor, is a device that stores energy by static charge. These systems have high power and low energy capacities. Supercapacitors are useful for power quality applications, as they can frequently charge and discharge at high currents for short durations. Supercapacitors are not used for long-term energy storage but rather sustain power gaps for up to 60 seconds with quick recharging capabilities. When paired with electrochemical devices, they have been shown to improve the efficiency and lifetime of the battery components.

Supercapacitors are devices with exceedingly high capacitance values, meaning they can hold a very high charge at a relatively low voltage, or that they can hold more energy with less work required to charge the storage system relative to a system with a lower capacitance. These storage systems are marked by high power capacity, able to discharge significant power over relatively short timeframes. Relative to electrochemical storage systems like lithium-ion, supercapacitors have much longer cycle lives and can charge and discharge much more rapidly, as well as exhibiting higher round-trip efficiencies.

4.3.1 Current Applications

According to the U.S. Department of Energy Global Energy Storage Database, there are more than 35 supercapacitor-based and hybrid battery projects using supercapacitors in operation as of winter 2018 (DOE 2018a). Hybrid battery projects use supercapacitors to absorb pulse power, helping to reduce degradation and extend the lifetime of battery systems. Extremely fast charge and discharge rates also make supercapacitors suitable for regenerative braking applications, absorbing braking energy and providing propulsion support in transportation systems (Maxwell Technologies 2018).

4.3.2 Emerging Applications and R&D Efforts

Within the power system, supercapacitors could be well-suited for applications that require rapid absorption or discharge of power over shorter time spans. These can include helping to buffer fluctuations in currents and harmonic frequencies caused by electric vehicle charging. Without remediation, these issues could lead to considerable voltage fluctuations throughout the power system. Supercapacitors can be used to “buffer” these fluctuations to improve power quality and ensure the impacts of unique loads do not propagate issues throughout the rest of the power system (Mangaraj, Panda, and Penthia 2016). Similarly, supercapacitors also have applications unique to renewable energy generation, where they can be used to buffer rapid changes in supply caused by cloud cover or gusts of wind changing VRE generation output. Finally, supercapacitors can be used to consume reactive power along transmission or distribution lines, improving the power factor and increasing overall power system efficiency (Kularatna and Fernando 2009). Research efforts to improve supercapacitor storage systems include increasing energy density, which can help in transportation applications (Jayaramulu et al. 2020).

4.3.3 Example Deployment

In 2012, East Penn Manufacturing developed a 3-MW Ultrabattery® lead-acid–supercapacitor hybrid system, which can provide frequency regulation and demand management services to the PJM Interconnection, a wholesale market operator in the United States. When not supplying ancillary services to the wholesale market, the storage system can provide customer-facing services such as demand management to local distribution utility, Met-Ed (Seasholtz 2015). The supercapacitor component of the energy storage system allows for more efficient and rapid charging, and drastically extends the life cycle of the system relative to a stand-alone lead-acid battery (Ferreira et al. 2012).

4.4 Superconducting Magnetic Energy Storage (SMES)

Technology Summary for Policymakers

SMES systems store energy in the electrical charge of a coil of superconducting material, which exhibits zero resistance below certain temperatures. These devices require external cooling infrastructure to maintain extremely low temperatures. SMES devices have been used for several decades in applications that require near-instantaneous absorption or injection of high levels of power over short time frames, such as in power quality applications. SMES systems are marked by high power densities, low energy densities, very fast reaction times, and long cycle lives.

A SMES device stores energy by passing an electrical charge through a coil of superconducting material, producing a strong magnetic field. The material used in SMES devices are metal alloys that must be cooled to extremely cold temperatures to achieve zero electrical resistance. An SMES device charges by drawing electrical current from the grid into the superconducting coil. As long as the necessary temperature is maintained inside the device, electrical energy will be stored without losses until it is drawn from the coil. Round-trip AC-AC efficiency is relatively high at 90%, with most of the losses occurring in the conversion of AC to DC power and DC to AC power during charging and discharging. Storage efficiency is also impacted by the energy required to maintain the extremely low temperature of the superconducting coil (Luo et al. 2015; Breeze 2018).

In addition to cooling needs, SMES structures require significant physical reinforcement to stabilize the storage system under the magnetic forces generated during operation. As such, most successful SMES projects to date have been of limited overall size (Breeze 2018). Despite these size and cooling limitations, SMES is a very stable form of energy storage as there are no moving parts. SMES are marked by exceedingly high power densities and very low energy densities, and can almost instantaneously discharge their energy, making them suitable for short duration, high power applications such as power quality and responding to sudden changes in load or generation.

4.4.1 Current and Emerging Applications

SMES have been used in power systems primarily in stabilizing applications due to their ability to absorb or inject large amounts of real and reactive power in relatively short timeframes. These applications can occur at the bulk power system to help ensure that voltage, current or frequency fluctuations do not propagate through the power system, or at specific customer locations to ensure power quality for sensitive applications.

4.4.2 Emerging Applications and R&D Efforts

While high-temperature superconducting materials are available, which would lower the associated costs of cooling the SMES system, these materials typically display poorer operating characteristics relative to traditional superconducting materials. Furthermore, these materials (primarily ceramic) are quite brittle, making them difficult to apply in power system applications. Improved performance, stability, and reliability from these high-temperature superconducting materials is being explored and would help make SMES more economically attractive to power system applications (Breeze 2018). Additional research efforts have been made to both reduce the overall costs of SMES systems, as well as economically scale the systems for larger bulk power system applications (Luo et al. 2015).

4.4.3 Example Deployment

In one application, portable SMES storage systems were connected to a portion of a transmission system in Wisconsin that was experiencing regular voltage excursions. The SMES systems were able to increase transmission stability until an additional transmission line was installed as a longer-term solution. In another smaller-scale application, SMES was used by an industrial plant in Japan to compensate for small voltage dips in the power delivered from the grid, which would impact the sensitive process of manufacturing liquid crystals (Tixador 2008).

Glossary

C-rate: The rate of discharge relative to the capacity of the storage system, typically electrochemical used for batteries. For instance, a 1-C battery would take 1 hour to fully discharge, while a 2-C battery would take 30 minutes, and a 0.5-C battery would take 2 hours to fully discharge.

Cycle life: The amount of time or cycles a battery storage system can provide regular charging and discharging before failure or significant degradation. Higher cycle life is associated with lower lifetime annualized costs, as the system can earn revenues for a longer period before needing to be replaced.

Depth of discharge: The share of the storage system's capacity, expressed as a percentage, that has already been discharged to provide services. The depth of discharge influences a system's ability to provide services to the grid at any given time and can impact the system's lifetime. Some technologies are sensitive to the depth of discharge, with deeper discharges associated with shorter lifetimes.

Duration: The maximum amount of time (in hours) a storage system can discharge at its maximum power capacity before depleting its energy capacity. While some applications, such as frequency regulation, may only require short bursts of energy, others, such as peaking capacity or shifting excess renewable energy between seasons, may require several hours up to months of duration.

Energy capacity: The maximum amount of stored energy (in kWh or MWh) the system is capable of holding. Some applications, such as helping customers shift their demand away from peak electricity price periods, may require a modest discharge of electricity over longer periods of time.

Energy or power density: The energy or power capacity of the storage system relative to its volume or weight (kWh/kg, kWh/m^3, kW/kg, kW/m^3). Energy and power densities can influence the applications for which a system may be appropriate, with less dense systems requiring more space and weight, making them unsuitable for distributed or transportation applications.

Power capacity: The maximum power (in kW or MW) the system can achieve, or its maximum instantaneous discharge. Some applications, such as arresting the fall in grid frequency after a generator trips offline, may require short bursts of large amounts of power.

Round-trip efficiency: A ratio of the energy charged to the energy discharged from the storage device, as a percentage. It can represent the total DC-DC or AC-AC efficiency of the battery system, including losses from self-discharge and other electric losses.

Self-discharge rate: Self-discharge occurs when the stored charge (or energy) of the storage system is reduced through internal chemical reactions, or without being discharged to perform work for the grid or a customer. Self-discharge, expressed as a percentage of charge lost over a certain period, reduces the amount of energy available for discharge and is an important parameter to consider in storage systems intended for longer-duration applications.

State of charge: The storage system's present level of charge, expressed as a percentage, which can range from completely discharged to fully charged. The state of charge influences a battery's ability to provide energy or ancillary services to the grid at any given time. The state of charge is inversely related to the storage system's depth of discharge.

Thermal runaway: A process caused by degradation or damage by which the temperature in an electrochemical battery system becomes hot enough to cause self-sustaining heat generation, which can lead to fires or explosion if not interrupted.

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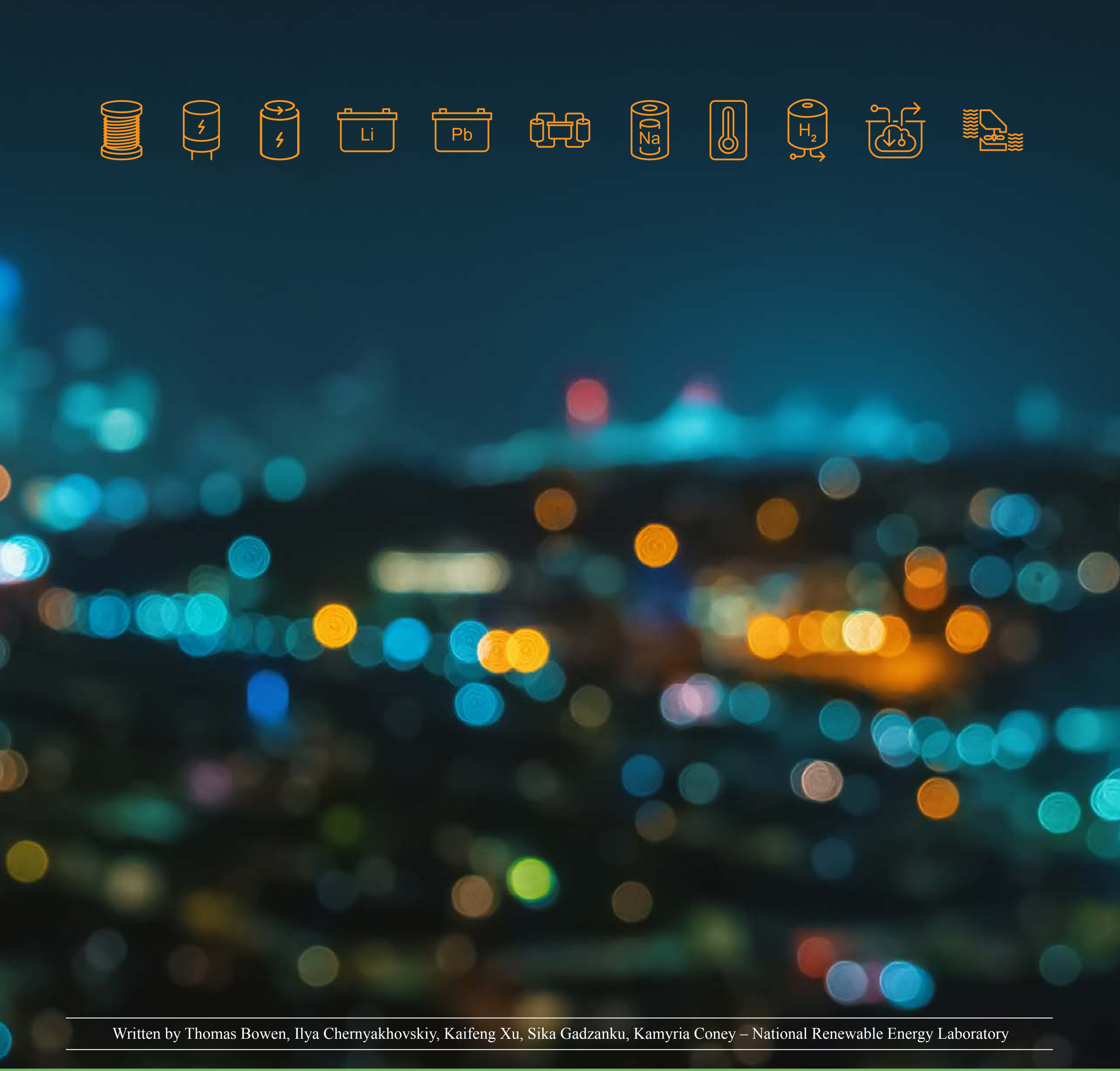

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