Electricity Storage: Applications, Issues, and Technologies

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Electricity Storage: Applications, Issues, and Technologies

SUMMARY

Electricity, as it is currently produced, is largely a commodity resource that is interchangeable with electricity from any other source. Since opportunities for the large-scale storage of electricity are few, it is essentially a just-in-time resource, produced as needed to meet the demand of electricity-consuming customers. Climate change mitigation has increased the focus on the use of renewable electricity. While energy storage is seen as an enabling technology with the potential to reduce the intermittency and variability of wind and solar resources, energy storage resources would have to be charged by low- or zero-emission or renewable sources of electricity to ensure a reduction of greenhouse gases.

Energy storage is being increasingly investigated for its potential to provide significant benefits to the interstate transmission grid, and perhaps to local distribution systems and thus to retail electric customers. The ability to store energy presents an opportunity to add flexibility in how electricity is produced and used, and provides an alternative to address peak loads on the system using renewable electricity stored at low-demand times. In addition to providing power on demand, energy storage technologies have the potential to provide ancillary services to the electricity grid to ensure the reliability and stability of the power system, and better match generation to demand for electricity.

Hydropower pumped storage (HPS), compressed air energy storage, and cryogenic energy storage are examples of technologies that store potential (or kinetic) energy. These are examples of the mostly large, monolithic systems used for energy storage today do not store electricity directly, but provide a means of producing electricity by use of a stored medium (e.g., water or air). According to the Federal Energy Regulatory Commission (FERC), approximately 24 HPS systems are currently operating with a total installed capacity of over 16.5 Gigawatts. HPS is approximately 94% of existing U.S. energy storage capacity. Since the storage of potential energy systems is well established on the grid, this report focuses on the relatively new use of modular batteries for grid level storage.

Modular battery technologies generally store electrical energy in chemical media that can be converted to electricity, and consist of standardized individual cells with relatively small power and voltage capacities that are typically aggregated to serve larger power loads. Lead-acid batteries and lithium ion (Li Ion) cells are the most used modular battery technologies for utility scale (i.e., projects of one megawatt or greater in capacity) applications on the electric grid. Li Ion cells are being used for a variety of applications, due largely to their high energy density and ability to undergo a number of full power charging cycles. However, battery technologies, in general, can provide energy for only a few hours, and vary with regard to the time required to recharge battery systems. Procurement of cobalt for Li Ion batteries has also been controversial due to child labor and safety concerns in many Congolese artisanal mines.

While Li Ion battery systems are currently the most prevalent form of modular storage, and a key technology for electric vehicles, several issues exist with system cost, materials used, and the safety of these systems. Congress may want to direct further research into modular battery system materials and charging technologies to reduce the cost, improve the safety of systems, increase system performance and cycle efficiency, and to assure the sustainable development of modular battery systems. Congress may also want to look at providing guidance for policy regimes or incentives that promote energy storage in a manner that can decrease greenhouse gas emissions.

FERC acknowledged that existing market rules for traditional resources can create barriers to entry for emerging technologies, and energy storage in particular. FERC designed its Order No. 841 to require "each regional grid operator to revise its tariff to establish a participation model for electric storage resources that consist of market rules that properly recognize the physical and operational characteristics of electric storage resources."

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Introduction

As the technological needs of an increasingly mobile society increase, the choices in how and when we use energy are growing. An increase in the power requirements for smaller and smaller devices has resulted in new technologies improving the density of energy storage in these devices. With these improvements has also come a wider array of applications for power storage on the electric grid and in electric vehicles (EVs). Energy storage is being increasingly investigated for its potential to provide significant benefits to the interstate transmission grid, and perhaps to local distribution systems and thus to retail electric customers.

Interest in reducing greenhouse gas (GHG)[1] emissions in the energy sector to mitigate climate change risks has increased the focus on renewable sources of electricity. While energy storage is seen as an enabling technology with the potential to reduce the intermittency and variability of wind and solar resources, energy storage resources would have to be charged by low or zero emission or renewable sources of electricity to ensure a reduction of greenhouse gases.

This report will describe technologies for storing electric power, with an emphasis on battery systems, focusing on the readiness of the technologies for various storage applications for electric power services to the electric grid. Congress has held hearings in the 116th session on a number of topics—including climate change mitigation, electric power system resilience, incorporation of more renewable energy into the grid—all of which have considered the opportunities for increasing energy storage. As of September 2019, more than 40 bills have been introduced in the 116th session addressing various aspects energy storage technologies and research.

Given the many uses for energy storage—both current and projected—this report will discuss some of the main drivers for energy storage. This report will also discuss the challenges for energy storage and potential options for Congress to further explore, if it chooses to advance the technologies to meet societal or other goals.

Why the Need for Grid Electricity Storage

Electricity, as it is currently produced, is largely a commodity resource that is interchangeable with electricity from any other source. Since opportunities for the large-scale storage of electricity are few, and electricity is transmitted almost instantaneously, it is essentially a just-in-time resource, produced as needed to meet the demand of electricity-consuming customers. The electric power system is largely designed to support electric system reliability,[2] and sized to ensure that electricity generation resources will be available to meet the maximum load demand the system is expected to see.

Given that most electric power is produced in bulk, at large power plants located at some distance from where the power is consumed, keeping power generation in balance with demand is an

[1] Greenhouse gases are any gases that absorb infrared radiation in the atmosphere. There are six main greenhouse gases discussed in the context of climate change: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases—sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Carbon dioxide is the most prevalent GHG produced by combustion of fossil fuels. U.S. Environmental Protection Agency, *Greenhouse Gas Emissions—Overview of Greenhouse Gases*, April 11, 2019, https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

[2] John Miller, *How Important Is Baseload Generation Capacity to U.S. Power Grids' Reliability?*, The Energy Collective Group, October 2, 2017, https://www.energycentral.com/c/ec/how-important-baseload-generation-capacity-us-power-grids-reliability.

important function of system managers. Regional balancing authorities[3] seek to ensure electricity supply is in balance with the demand for power. The normal frequency of the U.S. grid is 60 Hertz (i.e., cycles per second), and operational issues can arise with even with a small fluctuation of as little as 1% above or below this parameter.[4] If the supply of power is less than demand (causing the frequency of power transmission to decrease) or if the supply of power is greater than demand (causing the frequency of transmitted power to increase), then damage to equipment or system infrastructure can result.[5]

Some regions of the United States have their maximum demand for electricity in the summer months (driven by air-conditioning loads), and some regions have a maximum demand for electricity in winter months (to meet residential and building heating purposes). Given that this variation in use can lead to some of the larger, less flexible generation resources being underutilized (especially during the night or even seasonally), some observers argue that the electric grid is overbuilt.[6] Additionally, some have suggested that energy storage may be able to help reduce the need for large power generation projects in the future, and provide support for less costly renewable energy systems.[7]

Figure 1 is illustrative of the daily cycle of demand for electricity (i.e., the load), and how generation resources may be used to meet that demand. The figure also illustrates how "frequency regulation," a service currently provided by some generators, is used to reconcile the momentary differences caused by the fluctuations between generation and demand. The thicker gray line in the figure shows a smoother system response after damping of the fluctuations (shown by the undulating yellow line) with frequency regulation.[8]

[3] "The responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a balancing authority Area, and supports Interconnection frequency in real time." North American Electric Reliability Corporation (NERC), *Glossary*, August 12, 2019, https://www.nerc.com/files/glossary_of_terms.pdf.

[4] Frequency is the rate at which the alternating current in the grid changes direction per second, and is influenced by load from customer demand to power generated. U.S. Energy Information Administration, *Electricity Explained—How Electricity Is Delivered to Consumers*, August 31, 2018, https://www.eia.gov/energyexplained/index.php?page=electricity_delivery.

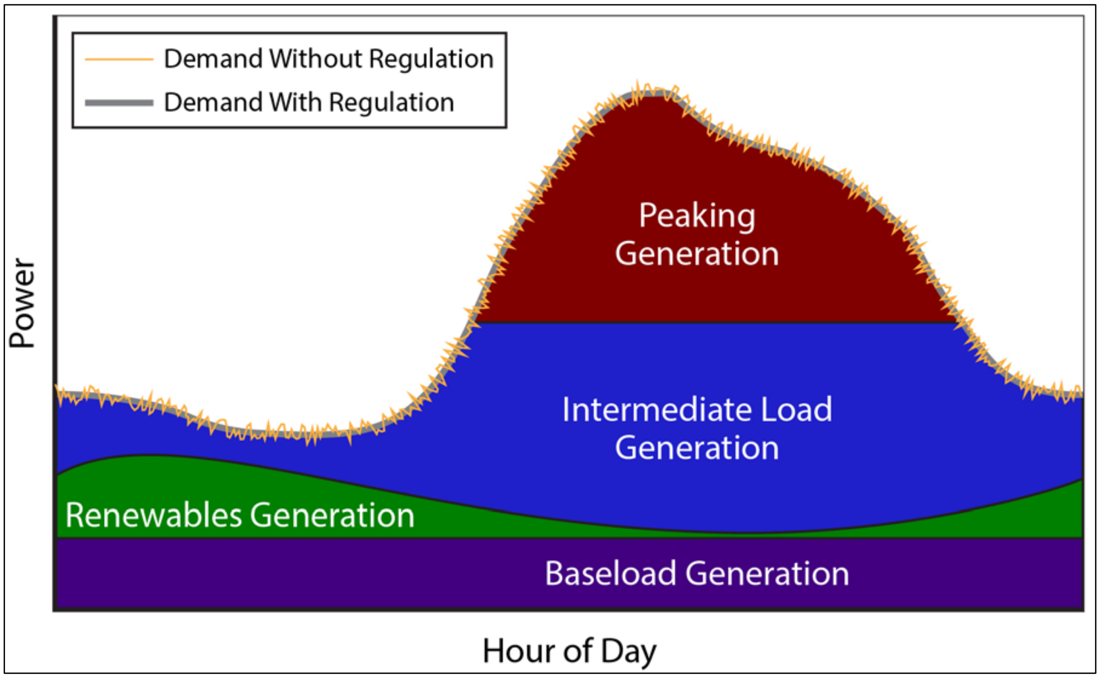
[5] B.J. Kirby, J. Dyer, and R. Shouresi, et al., *Frequency Control Concerns in the North American Electric Power System*, Oak Ridge National Laboratory, ORNL/TM-2003/41, December 2002, https://info.ornl.gov/sites/publications/Files/Pub57419.pdf.

[6] David Roberts, *Using Electricity at Different Times of Day Could Save Us Billions of Dollars*, August 7, 2019, https://www.vox.com/energy-and-environment/2019/8/7/20754430/renewable-energy-clean-electricity-grid-load-flexibility.

[7] David Timmons, *Opinion: We Now Have the Technology to Create a Grid of Cheap Fully Renewable Electricity*, Market Watch, August 27, 2019, https://www.marketwatch.com/story/we-now-have-the-technology-to-create-a-grid-of-cheap-fully-renewable-electricity-2019-08-22.

[8] Sandia National Laboratory, *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA*, SAND2013-5131, July 2013, https://www.energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf (Hereinafter, DOE/EPRI).

Figure 1. Conceptual Example of a System Load Without and With Regulation



Source: Sandia National Laboratories, DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA, July 2013, https://www.energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf.

Notes: DOE—U.S. Department of Energy; EPRI—Electric Power Research Institute; NRECA—National Rural Electric Cooperative Association.

Peaking generation is power generation normally operated only during the hours of highest daily, weekly, or seasonal loads. Intermediate load generation is normally operated on a daily cycle to serve on-peak loads during the day but not off-peak loads during nights and weekends. Baseload generation serves the minimum level of electric power demand of a utility, region, or utility customer delivered or required over a given period of time at a steady rate. Renewables generation (in this instance) represents variable electric generation primarily from intermittent wind or solar photovoltaic sources whose peak generation does not necessarily coincide with electricity system periods of peak demand.

Energy storage is one way to decrease the need for power generation on the grid at peak demand periods. But storage is not the only means of meeting these goals. Other means of potentially reducing the generation of electricity from large, central station power plants include:

- End-use efficiency (also called energy conservation) requires the reduction of consumption through improved efficiency. However, upgrading the technologies used by electric power customers to utilize equipment and appliances that are more efficient may be required to achieve end-use efficiency goals.
- End-user demand reduction (or demand response) is a process by which customers respond to a price signal from a utility or other power provider in return for incentive payments. While most demand response programs are focused on large industrial users with the flexibility to reduce or move consumption to other times of lower demand, commercial, apartment and other

residential customers may be signed to aggregation agreements to gain the scale needed for participation in such programs.[9]

- Distributed generation utilizing renewable sources such as wind, and tidal energy can potentially accomplish similar goals. Smaller gas turbines, if there are no local air quality or other environmental concerns, can also be used to meet peak demand.[10]

The capacity for storing large amounts of energy on the electric grid is presently limited. In one study, curtailing excess energy was reportedly seen as a possibly cost-effective alternative to deploying expensive energy storage options (at higher levels of solar photovoltaic (PV) penetration).[11] However, with improvements in energy storage technologies, and regulatory regimes encouraging economic deployment of energy storage, the applications and opportunities to use storage on the grid are growing.

Energy Storage and the Arbitrage Opportunity

The ability to store energy presents an opportunity to add flexibility in how electricity is produced and used, and provides an alternative to address peak loads on the system using renewable electricity stored at low-demand times. An arbitrage opportunity also exists under some circumstances to take advantage of power storage in regulatory regimes that attach value to such opportunities.

Under such a scenario, electricity can be purchased from the grid and stored during times of lower demand. An energy storage system can be charged at this time so that the stored energy can be used or sold at another time when the price or costs are higher. Alternatively, energy storage can provide the opportunity to store excess energy production that may otherwise be curtailed from renewable sources such as wind or solar PV. However, the number opportunities for the storage system to perform efficiently in an arbitrage role can be limited by the technology.[12] Additionally, opportunities for arbitrage may be limited by the number of storage participants potentially providing the service thus possibly reducing the sell-back price.

Energy Storage and Electricity Storage

Energy storage can take many forms, and can involve the storage of electricity directly or as potential (or kinetic) energy that can be used to generate electricity when it is needed. Electricity can also be stored in the chemical systems of batteries, both in bulk scale and in modular forms as

[9] See Energy Information Administration, *Glossary*, "Demand Response," 2019, https://www.eia.gov/tools/glossary/index.php.

[10] According to a report from the U.S. Department of Energy (DOE), distributed generation (DG) is any customer-sited electric power and thermal energy system. While many earlier installations were in the industrial sector, DG includes emergency power for use by hospitals and telecommunications centers during outages. DG also includes renewable electric generation such as solar panels installed on homes, biogas using the waste from farm animals to generate electricity, and cogeneration uses (i.e., recycling the waste heat from power generation). U.S. Department of Energy, *The Potential Benefits of Distributed Generation and Rate-Related Issues That May Impede Their Expansion*, A Study Pursuant to Section 1817of the Energy Policy Act of 2005, February 2007, https://www.ferc.gov/legal/fed-sta/exp-study.pdf.

[11] Peter Maloney, "Minnesota Study Finds It Cheaper to Curtail Solar Than to Add Storage," *Utility Dive*, January 22, 2019, https://www.utilitydive.com/news/minnesota-study-finds-it-cheaper-to-curtail-solar-than-to-add-storage/546467/.

[12] Daniel V. Crotzer, *Energy Storage Myths: #1 Arbitrage*, Fractal Energy Storage Consultants, June 17, 2016, https://www.energystorageconsultants.com/energy-storage-arbitrage/.

summarized below. Storage systems generally replenish their energy using electricity generated at low-demand (off-peak) times. Storage of energy is measured both in terms of the maximum rated power capacity (for storage charge/discharge) measured in megawatts (MW) or in terms of energy storage capacity over time, measured in megawatt-hours (MWh).

Hydropower pumped storage (HPS), compressed air energy storage (CAES), and cryogenic energy storage are examples of technologies that store potential (or kinetic) energy. These examples of the mostly large, monolithic systems used for energy storage today do not store electricity directly, but provide a means of producing electricity by use of a stored medium (e.g., water or air). The gradual release of the stored medium physically turns the shaft of a turbine connected to an electric generator, converting potential energy from the stored medium to electricity. Other opportunities for energy storage from the production of hydrogen gas are being explored, but are not a focus of this report.[13]

Batteries are chemical systems that produce electricity when the component parts and chemicals combine to create a flow of electrons, thus creating an electrical current. The potential to produce an electrical charge can be stored directly in large chemical systems (e.g. flow batteries) or in modular battery systems composed of smaller cells (such as lead-acid or lithium ion batteries). The smaller cells of modular battery systems do not store large amounts of electricity individually, but can be aggregated in battery systems to provide larger amounts of power.

The major potential energy and battery storage technologies for energy storage discussed in this report are summarized below:

- **Hydropower pumped storage**: Water stored in an upper reservoir is released to a lower reservoir through a turbine to generate electricity. Water is pumped in reverse at times of low demand to store energy. HPS is the most widely-used technology for storing energy on the electric grid.
- **Compressed air energy storage**: Compressed air is heated and expanded in a turbine to generate electricity. Compressing air causes it to cool, and it is stored in a tank or cavern using off-peak electricity to store energy.
- **Liquid air (cryogenic) energy storage**: Ambient air cooled to a liquid state is re-gasified and injected into a turbine when used to generate electricity. Ambient air is cooled and compressed to a liquid state to restore the system, and is stored in insulated tanks.
- **Flywheels**: A cylinder rotating around a core in a vacuum at high speeds stores kinetic energy. Slowing the cylinder releases energy to turn a generator to produce electricity, and speeding up the cylinder stores energy.
- **Flow Batteries**: Liquid electrolytes[14] with positive and negative charges are stored in large, separate tanks. Electric charge is drawn from the electrolytes by electrodes as they

[13] "Another option is to store the energy by converting it into hydrogen fuel. Devices called electrolyzers do this by using electricity—ideally from solar and wind power—to split water into oxygen and hydrogen gas, a carbon-free fuel. A second set of devices called fuel cells can then convert that hydrogen back to electricity to power cars, trucks, and buses, or to feed it to the grid." Robert F. Service, "New Fuel Cell Could Help Fix the Renewable Energy Storage Problem," *Science*, March 12, 2019, https://www.sciencemag.org/news/2019/03/new-fuel-cell-could-help-fix-renewable-energy-storage-problem.

[14] "The electrolyte is a chemical medium that allows the flow of electrical charge between the cathode [the positive electrode] and anode [the negative electrode]. When a device is connected to a battery—a light bulb or an electric circuit—chemical reactions occur on the electrodes that create a flow of electrical energy to the device." Mary Bates, *How Does a Battery Work?*, Massachusetts Institute of Technology—School of Engineering, May 1, 2012, https://engineering.mit.edu/engage/ask-an-engineer/how-does-a-battery-work/.

are pumped through a central tank where the liquids are separated by a membrane based on charge, and the spent liquids returned to separate tanks.

- **Lead-acid batteries**: One of the oldest and most used methods of energy storage uses connected compartments (cells) made of a lead alloy and lead, immersed in a water-sulfuric acid electrolyte, which combine to generate an electric charge.
- **Lithium ion (Li Ion) batteries**: Movement of lithium ions from the positive electrode (cathode) to the negative electrode (anode) through an electrolyte (commonly a lithium salt solution) creates an electric charge. Li Ion batteries have a cathode made of lithium-cobalt oxide, and an anode made of carbon. When batteries are recharged, the lithium ions move in reverse.
- **Nickel Cadmium (NiCad), Nickel-metal Hydride (NiMH), Sodium Sulfur (NaS), Sodium-Nickel Chloride ($NaNiCl_2$) batteries**: Different chemical systems can be used for battery storage. Commonly, the movement of charged particles from cathode to anode through an electrolyte generates an electric current.

These technologies are described in more detail in **Appendix A** of this report.

Summary of Grid Energy Storage Opportunities

Energy storage can help maintain the balance between supply and demand on an electricity system, and assist with system reliability by providing back-up power (for several hours at a time) during electricity outages. Since the storage of potential energy in larger, monolithic systems (e.g., HPS) is well established on the grid, this report focuses on the relatively new use of modular batteries for grid level storage. Battery storage technologies can also supply energy to the grid, and can also provide many of the ancillary services[15] necessary to ensure the grid's stability. These services are described in more detail in **Appendix B** of this report. Currently, however, the best value of grid energy storage for energy storage project developers is likely to come from supplying energy to the grid, and additionally providing the ancillary services best-suited to the storage technology, when available (as the storage resource cannot do both simultaneously).

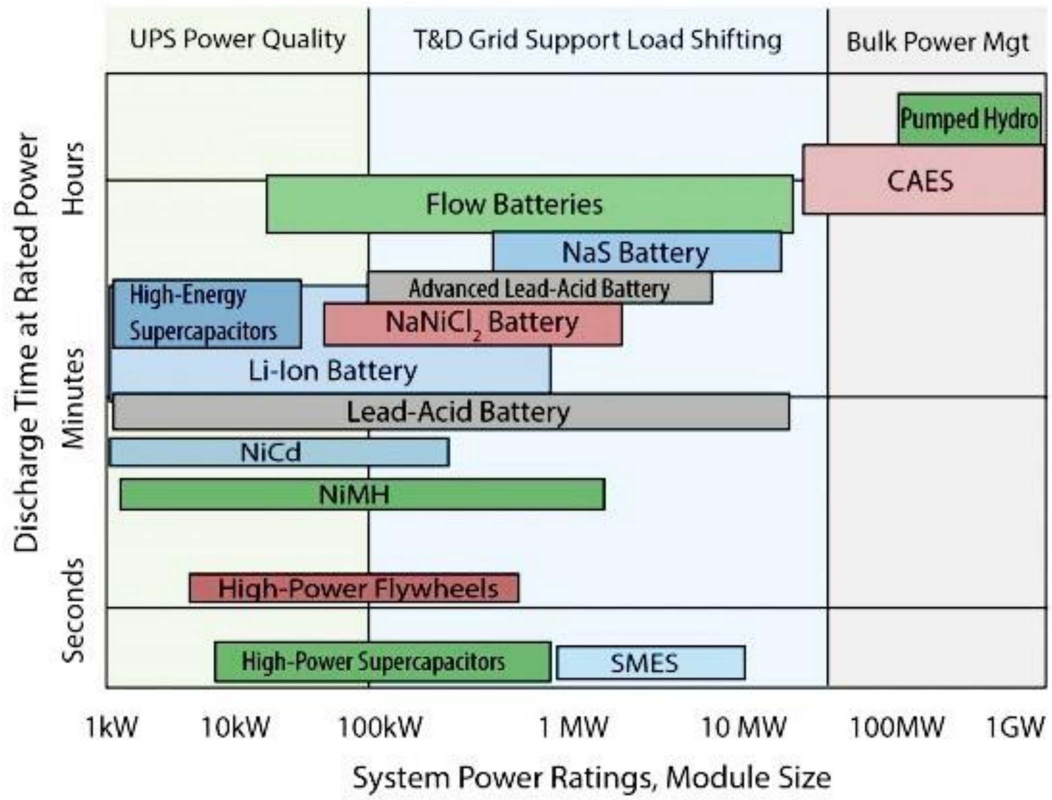
Once stored energy is sent to the grid, how quickly the energy storage technology can recharge may influence when and how often recharging of the system is accomplished. When recharging, the energy storage system is a load on the grid, and is not a generation resource. The timing of the charging and recharging cycle during a day can affect the value proposition of storage, since it is unlikely that recharging would be scheduled at times of peak demand. The ability of an energy storage system to provide several services to the grid may also bear on the economics of a system.

Figure 2 presents a current view of the opportunities for energy storage technologies to provide capacity and energy for the grid and various ancillary services. It provides a general summary and comparison of energy storage technologies for applications over various timescales for electric grid services.[16]

[15] Ancillary Services are "[t]hose services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system." Federal Energy Regulatory Commission, *Guide to Market Oversight—Glossary*, March 15, 2016, https://www.ferc.gov/market-oversight/guide/glossary.asp.

[16] DOE/EPRI, p. 29.

Figure 2. Positioning of Energy Storage Technologies for Grid Services



Source: Sandia National Laboratories, DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA, July 2013, https://www.energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf.

Notes: T&D—Transmission and Distribution; UPS—Uninterruptible Power Supply; CAES—Compressed Air Energy Storage; NaS—Sodium Sulfur; NaNiCl - Sodium-nickel chloride; NiCd—Nickel Cadmium; NiMH—Nickel Metal Hydride; SMES—Superconducting Magnetic Energy Storage.

Larger, more monolithic bulk power energy storage projects (such as HPS or CAES) can supply electric power in a discharge time over tens of hours.[17]

Battery systems and flywheel energy storage are sometimes used for uninterruptible power supply (UPS) in backup power applications. UPS applications solely for energy storage typically have enough energy to operate for up to several minutes. UPS systems may also incorporate generation (e.g., diesel generation) which can provide power over an extended period.[18]

Energy storage can also provide a power quality service by storing power and quickly discharging energy to smooth out variations in voltage supply or frequency, or service interruptions from a fraction of a second to several minutes, which could negatively affect a customer's manufacturing process or operations.[19]

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[17] Ibid.

[18] DOE/EPRI, p. 163.

[19] DOE/EPRI, pp. 21-22.

Energy storage for transmission and distribution (T&D) systems can support the grid in several ways. For example, a T&D upgrade project can be deferred by using modular storage to provide electric energy to customers until a permanent upgrade can be made. Another example may allow a utility to "avoid making a potentially unneeded investment in more T&D capacity by using transportable, modular storage to serve peak demand for one or two years until there is more certainty."[20] Energy storage can also potentially help to alleviate the bottlenecks of transmission congestion by providing a non-transmission alternative, and thus provide power locally at times of high demand.

By using energy stored in off-peak hours, customers of utilities can potentially shift their energy use from one time period to another. Alternatively, utilities or energy storage providers can store energy in periods of low demand to serve loads in times of higher demand.[21]

Supercapacitors may be used in energy storage applications undergoing frequent charge and discharge cycles at high current and a very short duration.[22] Similarly, superconducting magnetic energy storage (SMES) has rapid discharge capabilities that have been implemented in some instances for industrial pulsed-power,[23] and system-stability applications on electric power systems. However, the components for SMES limit its uses, as the cost of high-temperature superconducting wires would make grid-scale SMES systems prohibitively expensive."[24]

SMES has long been pursued as a large-scale technology because it offers instantaneous energy discharge and a theoretically infinite number of recharge cycles.

Energy Storage Considerations

Matching an energy storage technology to the opportunity is key, and considerations will include:

- **The application**. For example, ancillary services in electricity markets provide an opportunity for storage by providing "services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system."[25]
- **The duration of the application**. For example, the duration may be relatively short (e.g., 30 minutes) requiring the quick provision of a large amount of

[20] Energy Storage Association, *T&D Upgrade Deferral*, 2019, http://energystorage.org/energy-storage/technology-applications/td-upgrade-deferral.

[21] Energy Storage Association, *Electricity Supply Benefits and Uses*, 2019, http://energystorage.org/energy-storage/energy-storage-benefits/benefit-categories.

[22] "Supercapacitors … are able to quickly accommodate large amounts of energy (smaller than in the case of batteries—lower energy density from weight and volume point of view) and their charging response is slower than in the case of ceramic capacitors." Jiri Libich, Josef Maca, and Jiri Mondrak, et al., "Supercapacitors: Properties and Applications," *Journal of Energy Storage*, vol. 17, June 2018, pp. 224-227, https://www.sciencedirect.com/science/article/abs/pii/S2352152X18301634.

[23] Industrial applications of pulsed power generators include food processing, medical treatment, water treatment, exhaust gas treatment, ozone generation, engine ignition, ion implantation and others. H. Akiyama, Takashi Sakugawa, and Naoyuki Shimomura, et al., *Industrial Applications of Pulsed Power Technology*, Institute of Electricial and Electronics Engineers, 2007, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4339465&tag=1.

[24] Phil McKenna, "Superconducting Magnets for Grid-Scale Storage," *MIT Technology Review*, March 8, 2011, https://www.technologyreview.com/s/423227/superconducting-magnets-for-grid-scale-storage/.

[25] Federal Energy Regulatory Commission, *Guide to Market Oversight—Glossary*, March 15, 2016, https://www.ferc.gov/market-oversight/guide/glossary.asp.

power[26] in applications such as frequency regulation.[27] Alternatively, the duration may be relatively long (perhaps two hours or more) requiring energy[28] to be provided such as for peak load shaving.[29]

- **The rates of charge**. Storage resources used to provide power must be recharged. For potential energy resources, the resource used must be restored so it can be used again to provide electric power.

Structure of Modular Batteries

All rechargeable batteries have a similar physical structure that allows for the flow of electricity from an outside source to recharge the chemical system once depleted. As shown in **Figure 4**, the cathode is the positive terminal, and the anode is the negative terminal. The anode of a device is the side where current flows in, while the cathode is where current flows out.

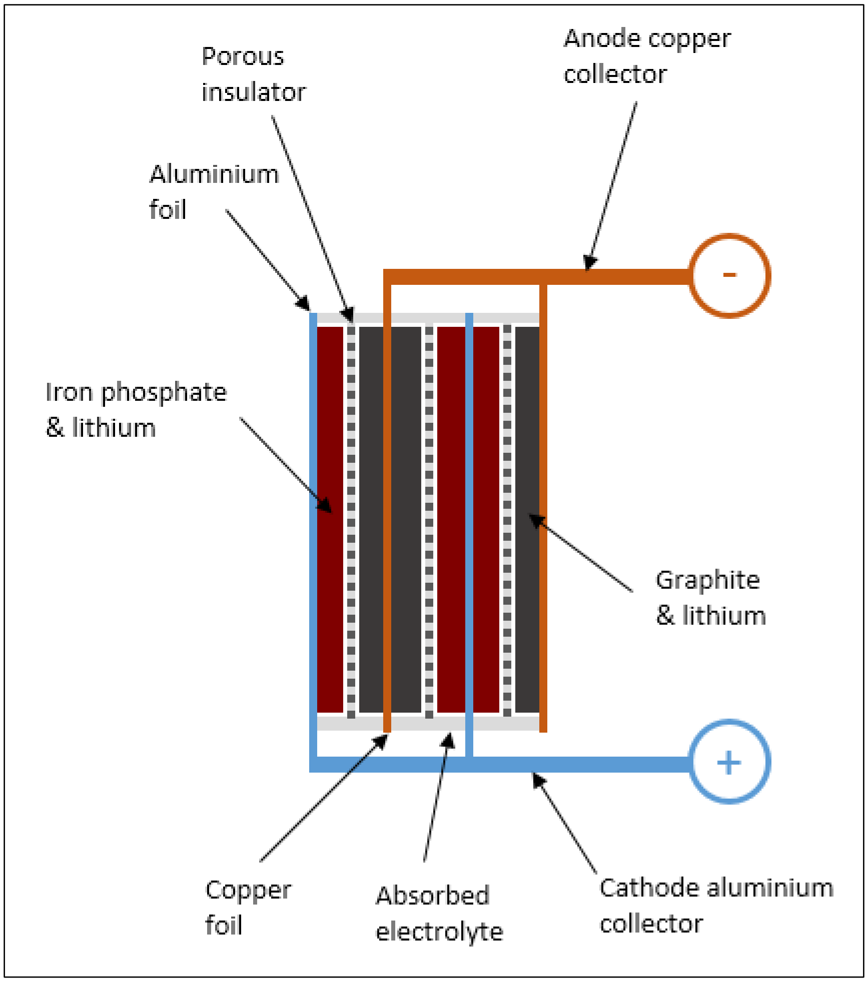
[26] Power is determined by the voltage, current and the resistance inherent in the circuit. "The rate of producing, transferring, or using energy, most commonly associated with electricity. Power is measured in watts and often expressed in kilowatts (kW) or megawatts (MW)." EIA, *Glossary*, 2019, https://www.eia.gov/tools/glossary/index.php?id=P.

[27] Frequency regulation is mainly provided by ramping (up and/or down) of generation assets. This typically takes minutes rather than seconds.

[28] Energy is measured with respect to the time it is provided. "The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatthours, while heat energy is usually measured in British thermal units (Btu)." EIA, *Glossary*, p. 2019, https://www.eia.gov/tools/glossary/index.php.

[29] Peak load shaving is the process of reducing power during times of high demand typically for a prolonged period.

Figure 3. Lithium Iron Phosphate Battery Cell



Source: Lithium Battery Banks—Fundamentals, at http://nordkyndesign.com/lithium-battery-banks-fundamentals/#lithium-safety.

A conductive electrolyte allows the flow of electrons between the anode and the cathode. When a battery is discharged, electrons are released from the negative end and captured by the positive end. Cells can be built by stacking parallel plates (i.e., prismatic or box-shaped cells) or from single long strips rolled onto themselves into a cylinder or flattened cylinder (i.e., cylindrical or wound cells). They have the same chemistry with the main difference residing in their construction and ability to dissipate internally generated heat. [30]

> Wound cells, and small cylindrical cells in particular, are cheaper to manufacture than the larger prismatic ones for a given capacity. They also have a higher volumetric energy density, but their round cross-section prevents from packing them together without gaps and this advantage does not extend to the assembled battery. The gaps between the cells can present an advantage for cooling when thermal management is necessary due to very high currents.... Mechanically, cylindrical cells are very robust and very resilient to mechanical damage from shocks and vibrations, which is good in electric vehicles.[31]

[30] Nordkyn Design, *Lithium Battery Banks—Fundamentals*, 2019, http://nordkyndesign.com/lithium-battery-banks-fundamentals/#lithium-safety.

[31] Ibid.

Battery Characteristics

The evaluation of the performance and suitability of modular batteries for an application is typically based on several key characteristics, including:

Specific Energy—the capacity a battery can hold (defined in terms of Watt-hours per kilogram (Wh/kg)). For example, specific energy can determine the battery weight required to achieve range of a vehicle given its energy consumption.

Specific Power—the ability to deliver power (defined in terms of Watts per kilogram (W/kg)). For example, specific power can determine the battery weight required to achieve a given performance target for an engine.

Energy Density—the battery energy per unit volume (defined in terms of Watt-hours per liter (Wh/L).

The three characteristics listed above are functions of the battery chemistry and its packaging, with the controlling characteristic being dependent on the particular application.

> For photovoltaic systems, the key technical considerations are that the battery experience a long lifetime under nearly full discharge conditions. Common rechargeable battery applications do not experience both deep cycling and being left at low states of charge for extended periods of time. For example, in batteries for starting cars or other engines, the battery experiences a large, short current drain, but is at full charge for most of its life. Similarly, batteries in uninterruptible power supplies are kept at full charge for most of their life. For batteries in consumer electronics, the weight or size is often the most important consideration.[32]

Utility-Scale Battery Storage

According to the U.S. Energy Information Administration (EIA), energy storage projects can be used in a variety of electricity production applications.

> Electricity storage can be deployed throughout an electric power system—functioning as generation, transmission, distribution, or end-use assets—an advantage when it comes to providing local solutions to a variety of issues. Sometimes placing the right storage technology at a key location can alleviate a supply shortage situation, relieve congestion, defer transmission additions or substation upgrades, or postpone the need for new capacity.[33]

Utility scale battery storage consists of projects of one MW or greater in capacity.[34] Utility-scale battery storage operating in the United States has reportedly quadrupled from a total of 214 MW at the end of 2014 to 899 MW (through March 2019). EIA expects U.S. utility-scale battery storage capacity to grow to perhaps 2,500 MW by 2023 "assuming currently planned additions are completed and no current operating capacity is retired." As of March 2019, the two largest U.S. operating utility-scale battery storage projects each provide 40 MW of power capacity, and there were another 16 operating battery storage sites with a power capacity rated at 20 MW or

[32] Christiana Honsberg and Stuart Bowden, "Battery Characteristics," PV Education, 2019, https://www.pveducation.org/pvcdrom/batteries/battery-characteristics.

[33] EIA, *Electricity Storage: Location, Location, Location … and Cost*, June 29, 2012, https://www.eia.gov/todayinenergy/detail.php?id=6910.

[34] Patricia Hutchins, *U.S. Utility-Scale Battery Storage Power Capacity to Grow Substantially by 2023*, Energy Information Administration, July 10, 2019, https://www.eia.gov/todayinenergy/detail.php?id=40072.

greater.[35] For comparison, there is approximately 16,500 MW of HPS capacity deployed in the United States.[36]

Balance of Plant Costs

Grid-connected battery storage projects commonly require a power management system to protect the battery and prevent uses that would damage or destroy the system. Of these systems for battery storage, balance of plant (BOP) costs are the most significant. BOP includes basic infrastructure (such as a building foundation and security fencing), and on-site electrical systems comprised of any equipment required to interconnect a battery storage system to the electric utility transmission or distribution grid.[37]

A 2018 study by the National Renewable Energy Laboratory (NREL) estimated the costs of Li Ion battery storage systems, both as standalone projects (e.g., with storage connected to the grid only), and projects connected to solar PV projects and the grid. A project capacity of 60 MW was used for the estimates. For standalone systems, a battery price of $209 per kilowatt-hour (KWh) was assumed, with total system costs varying from $380 per kWh (e.g., for a four hour duration system) to $895 per kWh (e.g., for a 0.5-hour duration system). The battery cost in these estimates accounted for 55% of total system cost in the 4-hour system, as compared to 23% in the 0.5-hour system. According to NREL, "the per-energy-unit battery cost remains constant at $209/kWh, the total battery cost—and the proportion of the cost attributed to the battery—decrease as system duration decreases." [38] The report also stated that co-locating the solar PV and storage subsystems produces cost savings by "reducing costs related to site preparation, land acquisition, permitting, interconnection, installation labor, hardware (via sharing of hardware such as switchgears, transformers, and controls), overhead, and profit."[39]

For comparison, a 2019 report from the Energy Information Administration estimates the overnight capital cost[40] of a new natural gas-fired combined cycle powerplant (with a capacity of 1,100 MW) at approximately $794 per Kwh, and the overnight cost of a new onshore wind powerplant (with a capacity of 100 MW) at $1,624 per Kwh (before application of the investment tax credit).[41] A solar PV powerplant with a capacity of 150 MW had an estimated overnight cost of $1,783 per Kwh. The report also estimated an overnight capital cost for a 30 MW capacity

[35] Ibid.

[36] FERC, *Pumped Storage Projects*, September 24, 2018, https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp.

[37] "Depending on the size of the system, the Point of Interconnection (POI) to the electric utility may be a new transmission substation, a distribution line, or a spare terminal at an existing substation. Systems under 10 MW will likely connect to the distribution system, while systems greater than 20MW will connect to the transmission system. Systems from 10 MW to 20 MW could connect to either depending local conditions on the electric utility grid."

[38] Ran Fu, Timothy Remo, and Robert Margolis, *2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark*, National Renewable Energy Laboratory, NREL/TP-6A20-71714, November 2018, https://www.nrel.gov/docs/fy19osti/71714.pdf.

[39] Ibid.

[40] "Overnight cost is the cost of a construction project if no interest was incurred during construction, as if the project was completed "overnight." The overnight cost is frequently used when describing power plants. The unit of measure typically used when citing the overnight cost of a power plant is $/kW." U.S. Energy Information Administration, *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2019*, January 2019, https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.

[41] Ibid.

battery storage project at $1,950 per Kwh (but with no specific battery technology or length of storage duration identified).

Energy Storage and Grid Resilience

Most power outages occur in electric distribution systems where wind or other weather cause vegetation (e.g., trees and tree limbs or branches) to contact power lines and cause damage to the line or associated equipment. Power outages can also result from equipment failure, vehicle accidents knocking down distribution poles, and even animal incursions into equipment. Outages caused by these factors typically last in the range from minutes to a few hours. Most of the longer-lived power outages (i.e., lasting from hours to days or longer) are due to weather-related events causing extensive damage to power lines and associated equipment.[42]

More extreme events (i.e., those affecting a larger part of the electric power grid) can result in a widespread shutdown of generating plants/units and the de-energization of the transmission and distribution system.[43] In 2007, DOE stated that since weather is the primary reason for reliability problems, and conclude that there is a need for resilient systems to ensure that when power outages occur "they are short-lived and affect the fewest number of customers as possible."[44]

In the wake of recent major weather events[45] in the United States (e.g., Superstorm Sandy), there has been an increased focus by federal and state officials on electric reliability and the need for investments in the grid. A recent study examined the statistical relationship between annual changes reported by U.S. distribution utilities in electricity reliability over a period of 13 years, and a broad set of variables (including various measures of weather and utility characteristics), and concluded that severe weather is causing longer, more severe power outages:

> We find statistically significant correlations between the average number of power interruptions experienced annually by a customer and a number of explanatory variables including wind speed, precipitation, lightning strikes, and the number of customers per line mile…. In addition, we find a statistically significant trend in the duration of power interruptions over time—especially when major events are included. This finding suggests that increased severity of major events over time has been the principal contributor to the observed trend.[46]

FERC recently proposed defining resilience as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."[47]

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42 CRS Report R42696, *Weather-Related Power Outages and Electric System Resiliency*, by Richard J. Campbell.

43 "Some jurisdictions, both in the United States and internationally, consider storm-related outages as 'extreme' events, and thus are not included in power outage statistics. Additionally, what is considered as unusual weather in one region may not be counted as unusual in another region." Ibid.

44 U.S. Department of Energy, *The Potential Benefits of Distributed Generation and Rate-Related Issues That May Impede Their Expansion*, p. 42, February 2007, https://www.ferc.gov/legal/fed-sta/exp-study.pdf.

45 "Major events refer to times during the year when the utility is subjected to significant, yet generally infrequent stresses, often due to severe weather." Peter H. Larsen, Kristina H. LaCommare, and Joseph H. Eto, et al., *Assessing Changes in the Reliability of the U.S. Electric Power System*, Ernest Orlando Lawrence Berkeley National Laboratory, August 2015, https://emp.lbl.gov/sites/all/files/lbnl-188741.pdf.

46 Ibid.

47 FERC did not further define the term "disruptive." See Federal Energy Regulatory Commission, "Notice of Inquiry Regarding the Commission's Electric Transmission Incentives Policy," 84 *Federal Register* 11759-11768, March 28, 2019.

Energy storage could conceivably help reduce the impact of power outages in these instances. However, storage would have to be energized and available, which underscores the source of the electricity used to charge the batteries (or other storage media). Wind power is variable, and often the winds are strongest at night, while solar photovoltaic storage only charges in the daytime. The discharge characteristics would also determine the usefulness of battery storage, as power form these sources may only last for several hours.

The type of event causing a power outage would also be key, as a severe weather event could stress or potentially take down power lines over a wide, possibly multistate region. Power can only reach electricity customers if the electrical wires (particularly the distribution lines) are still serviceable and connected.

Electric Vehicles and Grid Storage

The plug-in hybrid and battery electric share of the U.S. light vehicle market in 2018 was 2.1%.[48] Nearly all automakers offer electric vehicles for sale: 42 different models were sold in 2018, with Tesla and Toyota recording the largest number of vehicle sales.[49] A recent study from NREL assumed that EVs would be an increasing part of an electrified U.S. transportation sector, estimating that "electric vehicles would account for up to 76% of vehicle miles traveled in 2050," and could result in an increased demand for electricity to charge them.[50]

Some utilities have been considering whether EVs will be a longer-term avenue for increasing electricity demand, providing opportunities for vehicle-to-grid (V2G) energy storage and related services. Under V2G, EV batteries could eventually be used as storage of off-peak energy for the grid, and help provide demand response when the vehicles are not in use. A report from the Smart Power Electric Alliance observed that "utilities do not want to just serve this new load—they want to take advantage of EVs as a distributed energy resource (DER) with the ability to modulate charge (i.e., managed charging), or even dispatch energy back into the grid (i.e., vehicle-to-grid)."[51]

However, while the V2G concept has been discussed for well over a decade in the United States, some have expressed doubts about its adoption.

> The idea is attractive because of the growing amount of lithium-ion battery capacity tied up in electric vehicles, and the fact that this capacity is not being used for around 95 percent of the time. Ten new Nissan Leafs can store as much energy as a thousand homes typically

[48] CRS calculation based on Oak Ridge National Laboratory data: Oak Ridge National Laboratory, *Transportation Energy Data Book*, Table 6.2, April 2019, at https://tedb.ornl.gov/wp-content/uploads/2019/03/TEDB_37-2.pdf#page=178. For further information on vehicle electrification, see CRS Report R45747, *Vehicle Electrification: Federal and State Issues Affecting Deployment*, by Bill Canis, Corrie E. Clark, and Molly F. Sherlock.

[49] CRS analysis shows that of the 42 models sold domestically, 10 were produced at seven U.S. plants, with the remainder imported.

[50] "The adoption of electric technologies in the Medium and High scenarios results in much greater electricity consumption growth than in the Reference [e.g., business as usual] scenario. In the Medium scenario, annual electricity demand grows by 1.2% per year and reaches 5,656 [TeraWatt-hours (TWh), where 1 TW is 1×10^{12} watts] by 2050 with Moderate technology advancements. Electricity consumption in 2050 spans a wider range—5,520 TWh (1.1% per yr from 2016 to 2050) to 5,871 TWh (1.3% per yr)—when the full set of technology advancement projections is considered." National Renewable Energy Laboratory, *Electrification Futures Study*, p. 61, July 9, 2018, https://www.nrel.gov/news/program/2018/analysis-demand-side-electrification-futures.html.

[51] Smart Electric Power Alliance, *Utilities and Electric Vehicles: Evolving to Unlock Grid Value*, March 2018, https://sepapower.org/resource/utilities-electric-vehicles-evolving-unlock-grid-value/.

> consume in an hour.... However, despite numerous pilot studies over the last decade, V2G has yet to become a commercial reality.[52]

Among the major concerns expressed about V2G is the effect on the vehicle's batteries. V2G allows a utility to draw on energy storage from stationary vehicles, which could increase the stress on the batteries, one of the most expensive parts of the vehicle. As at least one observer has noted, it is unclear who would cover the cost of this usage or battery replacements under a V2G regime, or how vehicle owners might be otherwise compensated for taking part in V2G programs.[53]

A potential driver for further EV adoption (and perhaps V2G itself) could be GHG reduction in the transportation sector. Electrification of the transportation sector can conceivably reduce GHG emissions—depending on the electricity generation source, among other factors[54]—seen as a contributor to potential climate change. According to projections by the U.S. Energy Information Administration, new sales of battery electric vehicles may increase by a factor of seven by the year 2025, over model year 2018, under a reference case scenario.[55] Other studies project the possibility for an almost complete transition of U.S. automobiles from internal combustion engines to EVs by 2050, should that be a policy goal.[56] The potential for a large scale GHG reduction from such a transition would depend, in part, on the electricity generation sources used across the life cycle of the vehicles assuming that U.S. policy is focused on almost exclusive use of low or zero-carbon fuels and sources.

Batteries charged from renewable electricity sources may reduce climate change concerns, and aid renewable energy growth goals. However, fuel cell vehicles[57] could present a competitive or alternative pathway to a potential transportation future dominated by battery-powered EVs.

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[52] Jason Deign, Greentech Media, *Why Is Vehicle-to-Grid Taking So Long to Happen?*, March 19, 2018, https://www.greentechmedia.com/articles/read/why-is-vehicle-to-grid-taking-so-long-to-happen.

[53] Ibid.

[54] The life cycle environmental effects of EVs, and their advantages or disadvantages relative to internal combustion engine vehicles (ICEVs), are influenced by a range of key variables associated with vehicle design, vehicle choice and use patterns, vehicle end-of-life options, and the electricity generation mix and other energy inputs employed during the production and use of the vehicles. Given this range of parameters, the findings presented in the published life cycle literature on this topic offer a range of results, both positive and negative. Broadly speaking, reviews of the published literature have found that in most cases EVs have lower life cycle greenhouse gas emission profiles than ICEVs when based on current vehicle design and use inputs (see, as examples, Dunn, J. B., Gaines, L., Kelly, J. C., James, C., and Gallagher, K. G., "The Significance of Li-Ion Batteries in Electric Vehicle Life-Cycle Energy and Emissions and Recycling's Role in Its Reduction," *Energy and Environmental Science*, 2015, vol. 8, pp. 158-168; Nordelöf, A., Messagie, M., Tillman, A., Söderman, M.L., Van Mierlo, J., "Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment?" *International Journal of Life Cycle Assessment*, 2014, vol. 19, pp. 1866-1890; and Hawkins, T., Singh, B., Majeau Bettez, G., Stromman, A., "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles," *Journal of Industrial Ecology*, 2012, vol. 17, pp. 53-64).

[55] EIA, *Annual Energy Outlook 2019 with Projections to 2050*, January 24, 2019, pp. 126-128. https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[56] Sustainable Development Solutions Network and Institute for Sustainable Development and International Relations, *Pathways to Deep Decarbonization*, United Nations, July 8, 2014, http://unsdsn.org/wp-content/uploads/2014/07/DDPP_interim_2014_report.pdf.

[57] "Fuel cell vehicles use hydrogen gas to power an electric motor. Unlike conventional vehicles which run on gasoline or diesel, fuel cell cars and trucks combine hydrogen and oxygen to produce electricity, which runs a motor. Since they're powered entirely by electricity, fuel cell vehicles are considered electric vehicles ("EVs")—but unlike other EVs, their range and refueling processes are comparable to conventional cars and trucks." Union of Concerned Scientists, *How Do Hydrogen Fuel Cell Vehicles Work?*, March 14, 2018, https://www.ucsusa.org/clean-vehicles/electric-vehicles/how-do-hydrogen-fuel-cells-work.

A California Case Study

A team of researchers from Lawrence Berkeley National Laboratory (LBL) examined EV charging in California as a case study.[58] The team suggested that controlling when EV charging happened could help accomplish California's goals for renewable electricity integration less expensively than its 2010 mandate for deploying grid energy storage.[59]

The LBL case study discussed California's growing system-wide balancing problems forecast out to 2025, as more renewables (especially solar PV) are deployed. This has been epitomized as the "California Duck Curve" issue.[60] By implementing a policy regime to charge EVs in the middle of the day (when renewable solar generation is greatest, instead of the evening or overnight), EVs could use excess renewable electricity available at this time and help balance the grid, thus avoiding the cost of ramping up and down other electric generation. This regime is referred to as V1G, representing the "one-way" charging of EVs. According to the LBL researchers, the technology for a one-way charging regime largely exists (i.e., grid to vehicle charging) and could possibly be implemented for about $150 million in California.[61]

In addition, implementing a regime to also allow a V2G two-way flow of power from EVs could potentially allow the benefits of EV batteries to become even more pronounced.

> In the V1G only case, down-ramping and up-ramping are both mitigated by more than 2 GW/h by 2025. In the case with a mix of V1G and V2G vehicles, however, substantially larger gains are seen … both down-ramping and up-ramping are substantially mitigated, by almost 7GW/h, equivalent to avoiding construction of 35 natural gas 600 MW plants for ramping mitigation.[62]

The LBL researchers estimated that such a proposal could save California the equivalent of $12.8 billion to $15.4 billion in stationary storage investment.[63]

Grid Reuse of EV Batteries

While up to 98% of lead-acid battery component materials may be recycled at the end of a battery's useful life,[64] estimates are that Li Ion battery recycling is less than 5% in the United

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[58] Jonathan Coignard, Samveg Saxena, and Jeffery Greenblatt, et al., "Clean Vehicles as an Enabler for a Clean Electricity Grid," IOP Publishing, *Environment Research Letters*, May 16, 2018, https://iopscience.iop.org/article/10.1088/1748-9326/aabe97/pdf. (Hereinafter, LBL Study).

[59] The state of California enacted Assembly Bill 2514 in 2010 requiring the California Public Utilities Commission to direct California investor-owned utilities to procure a combined 1,325 MW of energy storage (excluding large scale pumped hydro storage) by 2020.

[60] So named because of the characteristic shape of the electricity dispatch curve. For more information, see CRS Report R43742, *Customer Choice and the Power Industry of the Future*, by Richard J. Campbell.

[61] "From pricing of today's commercially available charging stations on the cost of V1G [i.e., one-way charging] over uncontrolled charging … we estimate this 1.0 GW of equivalent storage from V1G is available with an added investment of less than $150 million—substantially less than the cost of equivalent stationary storage." LBL Study, pp. 5-6.

[62] LBL Study, p.4.

[63] LBL Study, p.6.

[64] Battery Solutions, *How Are Batteries Recycled?*, 2019, https://www.batterysolutions.com/recycling-information/how-are-batteries-recycled/.

States.[65] This may become a growing concern as transportation electrification is expected to increase the use of Li Ion battery packs.

Finding ways to increase the recycling and reuse of Li Ion battery components would seem to be an option, given the potential cost and difficulty of obtaining the lithium and cobalt used in battery manufacture. However, since it has been estimated that Li Ion battery packs in EVs may retain about 70% of their storage capacity at the end of the battery's service life to a vehicle, the potential for a second use in home energy storage may exist (especially for solar PV storage systems).[66] Therefore, reuse in electric grid applications may present a larger opportunity.

> Reuse can provide the most value in markets where there is demand for batteries for stationary energy-storage applications that require less-frequent battery cycling (for example, 100 to 300 cycles per year). Based on cycling requirements, three applications are most suitable for second-life EV batteries: providing reserve energy capacity to maintain a utility's power reliability at lower cost by displacing more expensive and less efficient assets (for instance, old combined-cycle gas turbines), deferring transmission and distribution investments, and taking advantage of power-arbitrage opportunities by storing renewable power for use during periods of scarcity, thus providing greater grid flexibility and firming to the grid. In 2025, second-life batteries may be 30 to 70 percent less expensive than new ones in these applications, tying up significantly less capital per cycle.[67]

FERC Authority to Promote Grid Storage

Under the Federal Power Act[68] (FPA), the Federal Energy Regulatory Commission (FERC) has authority over the sale and transmission of wholesale power,[69] the reliability of the bulk power system, utility mergers and acquisitions, and certain utility corporate transactions.[70] FERC is required by the FPA to ensure that wholesale electric power rates are "reasonable, nondiscriminatory, and just to the consumer."[71]

The Energy Policy Act of 1992 (P.L. 102-486; EPACT) opened wholesale electricity markets to competition by allowing wholesale buyers to purchase electricity from any generator, requiring transmission line owners to transport (or "wheel") power for other generators and purchasers of wholesale power at "just and reasonable" rates. The next step was to ensure that these transactions could take place as efficiently as possible, and momentum for allowing access to the

[65] Waste360, *Department of Energy Commits to Ramping Up Lithium-Ion Battery Recycling*, January 23, 2019, https://www.waste360.com/e-waste/department-energy-commits-ramping-lithium-ion-battery-recycling.

[66] Joey Gardiner, "The Rise of Electric Cars Could Leave Us with a Big Battery Waste Problem," *The Guardian*, August 10, 2017, https://www.theguardian.com/sustainable-business/2017/aug/10/electric-cars-big-battery-waste-problem-lithium-recycling.

[67] Hauke Engel, Patrick Hertzke, and Giulia Siccardo, *Second-Life EV Batteries: The Newest Value Pool in Energy Storage*, McKinsey Center for Future Mobility, April 2019, https://www.mckinsey.com/~/media/McKinsey/Industries/Automotive%20and%20Assembly/Our%20Insights/Second%20life%20EV%20batteries%20The%20newest%20value%20pool%20in%20energy%20storage/Second-life-EV-batteries-The-newest-value-pool-in-energy-storage.ashx.

[68] 16 U.S.C. 791 et seq.

[69] Wholesale (or Resale) sales are electricity sold to other electric utilities or to public authorities for sale to an ultimate consumer.

[70] Federal Energy Regulatory Commission, "Overview of FERC," April 9, 2012, http://www.ferc.gov/about/overview.asp.

[71] 16 U.S.C. §§813.

transmission grid for all users was realized with the issuance of FERC Order No. 888 in 1996.[72] FERC oversees the competitive electricity markets served by regional transmission organizations (RTOs) and Independent System Operators (ISOs) established in accord with Order No. 888. The order required electricity transmission owners to allow open, non-discriminatory access to their transmission systems, thus promoting wholesale competition.

In 2018, FERC issued its final version of Order No. 841[73] to remove what it saw as barriers to the participation of electric storage resources in RTO/ISO markets.[74] Each RTO/ISO has until December 3, 2019 to revise and implement the Order No. 841 market rules.

Subsequently, in April 2019, FERC issued Order No. 845,[75] which changed "the definition of "Generating Facility" to explicitly include electric storage resources."[76] Order No. 845 also changed the interconnection rules to allow "interconnection customers to request a level of interconnection service that is lower than their generating facility capacity."[77] This could potentially allow some electric generators to add storage capacity to their facility (i.e., co-location), and use that storage capacity to send energy to the grid. This may provide an opportunity for renewable generators, in particular, to sell power when the renewable capacity is unavailable.

Discussion of FERC Order No. 841

In Order No. 841, FERC recognized that HPS has been operating in the competitive electricity markets that it regulates for years. However, FERC also acknowledged that existing market rules for traditional resources can create barriers to entry for emerging technologies. Order No. 841 defined an energy storage resource as "a resource capable of receiving electric energy from the grid and storing it for later injection of electric energy back to the grid."[78]

FERC designed Order No. 841 to require "each regional grid operator to revise its tariff to establish a participation model for electric storage resources that consist of market rules that properly recognize the physical and operational characteristics of electric storage resources."[79]

The participation model is to:

- ensure that electricity storage resources are eligible to provide all capacity, energy, and ancillary services that they are technically capable of providing in competitive markets;

[72] 75 FERC ¶ 61,080.

[73] FERC Order No. 841 at 162 FERC ¶ 61,127.

[74] FERC further defined the RTO/ISO markets "as the capacity, energy, and ancillary services markets operated by the RTOs and ISOs."

[75] FERC Order No. 845 at 163 FERC ¶ 61,043.

[76] Ibid, p. 5.

[77] Ibid.

[78] FERC Order No. 841, 162 FERC ¶ 61,127, p. 26.

[79] FERC, "FERC Issues Final Rule on Electric Storage Participation in Regional Markets," press release, February 15, 2018, https://www.ferc.gov/media/news-releases/2018/2018-1/02-15-18-E-1.asp#.XVxR-ZCWyUk.

- ensure that electricity storage resources can be dispatched, and can set the wholesale market clearing price as both a wholesale seller and wholesale buyer consistent with existing market rules;
- recognize that markets must account for the physical and operational characteristics of electricity storage resources through bidding parameters or other means; and
- establish a minimum size requirement for participation in the Regional Transmission Organization/Independent System Operator markets that does not exceed 100 kW.

Electric storage resources may be a buyer and a seller of electricity from the markets, since they must charge and discharge their resources. FERC requires that the sale of electric energy from the wholesale electricity market to an electric storage resource (that the resource then resells back to those markets) must be at the wholesale locational marginal price (i.e., the market-clearing price for electricity at the location the energy is delivered or received).[80]

FERC recognized that various energy storage resources had the potential to provide ancillary services (e.g., battery storage can provide frequency regulation, voltage support, and spinning reserves), and provide energy to serve peak demand loads. FERC also recognized that "electric storage resources tend to be capable of faster start-up times and higher ramp rates than traditional … generators and are therefore able to provide ramping, spinning, and regulating reserve services without already being online and running."[81]

Some RTO/ISO Comments on the Order

The compliance filings submitted by the RTO/ISO stakeholders had various degrees of existing energy storage participation. Several compliance responses are discussed in the following summaries.

PJM

The PJM RTO (PJM) submitted its compliance filing to FERC in two submissions. One filing submitted details of PJM's proposed energy storage resource participation model (i.e., the "Markets and Operations Proposal." [82] PJM said that its energy storage resource (ESR) participation model is designed to ensure that "ESRs are eligible to provide services in a manner consistent with other resources providing that service."[83] PJM stated that its capacity, energy and ancillary services markets offer a number of products that participating resources can provide to serve load and to ensure the reliability of the electric grid. However, PJM noted that although ESRs are currently eligible to provide services in each of these markets, the ESR participation model explicitly addresses each available product to ensure that ESRs are eligible to provide all services which they are technically capable of providing. PJM said that its review of its markets

[80] Ibid.

[81] 162 FERC ¶ 61,127, p. 71.

[82] PJM RTO, *Order No. 841 Compliance Filing - ESR Markets and Operations Proposal*, December 3, p. 2018, https://www.pjm.com/directory/etariff/FercDockets/3872/20181203-er19-469-000%20.pdf.

[83] Ibid, p.6.

and operations indicated that "certain changes are needed to fully support the ESR participation model required by Order No. 841," and include:[84]

> **Modal Operation in Energy Markets**: PJM proposes to allow ESRs to participate in the Day-ahead and Real-time Energy Markets under three different modes: (1) Continuous Mode; (2) Charge Mode; and (3) Discharge Mode. This feature provides significant flexibility and allows Market Participants of ESRs to best manage a resource's changing and discharging cycles.[85]
>
> **Reserves**: PJM proposes to allow ESRs to participate in the Synchronized Reserve market without an energy offer. If an ESR is physically disconnected from the grid and capable of providing energy within ten minutes, then the resource's reserve MWs shall be treated as Non-Synchronized Reserve. An ESR wishing to clear in the Day-Ahead Scheduling Reserve market would require an energy schedule and must inform PJM that it would like to be considered.
>
> **Cost-Based Offers**: PJM proposes to continue to apply the same offer development rules applied to all generation resources. PJM proposes to modify the Operating Agreement to clarify that ESR fuel costs include charging costs for later injection to the grid.
>
> **Make-Whole Payments**: PJM proposes to allow ESRs to receive make-whole payments when moved off economic dispatch.
>
> **Billing for ESR Charging**: PJM proposes to adopt several different categories of ESR charging to account for the resource's behavior and later resale of the charging energy. PJM also proposes to modify the Tariff to exempt "Direct Charging Energy" from certain "load" charges related to administrative costs, uplift, and meter/scheduling reconciliation.

PJM was developing a methodology to determine wholesale vs. non-wholesale charges for stored energy, since ESRs can be connected to transmission, distribution, or behind the meter (i.e., storage designed for a specific building or residential use). PJM says that this may be complicated since ESRs that are behind the customer meter (or that otherwise directly serve retail load) may not, in some cases, resell that energy to PJM per its proposed rules.[86] A second response was filed separately by PJM focusing on metering, accounting and market settlement issues (i.e., the "Energy Storage Resource (ESR) Accounting Proposal") to address such issues.[87]

NYISO

While noting that it did not have a single participation model as required by FERC Order No. 841, the New York ISO (NYISO) filed its existing plans for electric storage.[88] NYISO stated that while electric storage can currently participate in its energy, ancillary services, and installed capacity markets under various existing participation models, it also recognized that energy storage be a component of a demand side plan in certain demand response programs. Nevertheless, NYISO proposed to establish a participation model with energy storage resources

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[84] Ibid, pp. 4-5.

[85] For further information on the various markets offered in the competitive RTOs and ISOs under FERC's jurisdiction, see CRS Report R43093, *Electricity Markets—Recent Issues in Market Structure and Energy Trading*, by Richard J. Campbell.

[86] Ibid, pp. 12-16.

[87] PJM RTO, *ESR Accounting Proposal, ER19-462-000*, FERC Order No. 841, December 10, 2018, https://www.pjm.com/-/media/documents/ferc/filings/2018/20181210-er19-462-000.ashx.

[88] FERC, New York Independent System Operator, Inc.; Compliance Filing and Request for Extension of Time of Effective Date; Docket Nos. RM16-23-000, AD16-20-000, FERC Order No. 841, December 3, 2018, https://elibrary-backup.ferc.gov/idmws/File_list.asp?document_id=14725304.

as a subset of generators under its tariffs. Electric storage facilities unable to satisfy a qualification as generators would be able to elect to participate in existing participation models that accommodate their physical and operational characteristics. For example, some storage resources may be able to participate as "energy limited resources," e.g., installed capacity suppliers that are unable to operate continuously on a daily basis but that can provide energy for at least four contiguous hours each day. Alternatively, other energy storage resources may be able to participate as "limited energy storage resources," i.e., generators that are not able to sustain continuous operation at maximum energy withdrawal or maximum energy injection for a minimum period of one hour.[89]

CAISO

The California ISO (CAISO) expressed support for FERC Order No. 841, stating that its rules were already in compliance with Order No. 841, and are not, generally, technology specific.[90] But there were areas on which CAISO requested clarification. These included whether metering would be required for storage resources, and how storage resources should be treated under models of dispatch for energy (i.e., providing spinning reserves) or when acting as a load and consuming energy from the grid.[91]

Compliance Deficiency Letters to RTOs/ISOs

FERC was apparently not satisfied with the RTO/ISO compliance filings for Order no. 841. Requests for more information (as filing deficiency letters) were sent to each of the RTOs/ISOs. As one example of the information requested, FERC asked each grid operator to provide details of various aspects of energy storage market participation models, including size requirements, state of charge management, and how storage resources can participate as both buyers and sellers in wholesale market.[92]

Senate Hearing on Grid Scale Energy Storage

In June 2019, the Senate Energy and Natural Resources Committee held a hearing to examine opportunities for the expanded deployment of grid-scale energy storage in the United States. Among the key statements from witnesses were observations on the developing nature of battery storage systems.[93]

Among the observations from Dr. George Crabtree, the director of the Joint Center for Energy Storage Research and Argonne National Laboratory was a statement on the readiness of battery technologies for long-term grid support:

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[89] Ibid, p. 6.

[90] California Independent System Operator, *Order No. 841 Compliance*, May 1, 2019, http://www.caiso.com/Documents/May1-2019-Response-DeficiencyLetter-Compliance-OrderNo841-ElectricStorageParticipation-ER19-468.pdf.

[91] Ibid.

[92] Gavin Blade, "FERC Asks Grid Operators for More Detail on Storage Participation," *Utility Dive*, April 3, 2019, https://www.utilitydive.com/news/ferc-asks-grid-operators-for-more-detail-on-storage-participation/551924/.

[93] U.S. Congress, Senate Committee on Energy and Natural Resources, *Grid-Scale Energy Storage*, 116th Cong., 1st sess., June 4, 2019, https://www.energy.senate.gov/public/index.cfm/hearings-and-business-meetings?id=83B728AC-6708-40D6-9B96-CC007F5B5906.

> The present cost of lithium-ion battery packs, about $200/kWh, must fall by a factor of two or more to make storage economically appealing across all its uses in the grid. In addition, we must be able to purpose-design batteries for a diversity of applications in the grid spanning generation, transmission, and distribution. An example is long duration storage, needed to fill in for renewable generation when the wind does not blow or the sun is blocked by clouds for as many as seven days in a row. These long, cloudy, or calm periods are common in weather patterns in the Northeast and Midwest. The present generation of lithium-ion batteries can optimally discharge for about four hours, much too short to span many weather-related generation gaps. New battery materials, concepts, and technology are needed to meet the challenges of long-duration-discharge energy storage.[94]

Among other observations, the witness from Xcel Energy, Mr. Ben Fowke noted that Xcel Energy's long-term carbon strategy depends on the deployment of advanced clean technologies. He said that grid-scale storage helps with renewable integration, allowing higher renewable energy levels than would otherwise be possible. Storage can also provide other system benefits, including more reliable grid operations, voltage support and frequency control. At the same time, he pointed out that storage today still has limitations. Two significant challenges for storage were described in his testimony:

> First, storage cannot today solve the problem of the wide seasonal variation in renewable energy generation, which is the chief factor preventing the creation of fully renewable electricity system. Second, while storage can initially help integrate renewables by moving energy from the time it is produced to when it is needed, the value of each additional increment of storage capacity declines as more is added to the system. Finally, although storage can bring multiple services to the grid—power quality and grid support, for example—the value of all of these services are not all additive (or "stackable"). As a general rule, these services are not all available at the same time.[95]

Mr. Fowke also pointed to potential areas for further energy storage research:

> While lithium ion batteries are the dominant technology in the battery storage industry today, a federal research agenda should target those technologies that have the greatest potential to address long-term system needs and reach commercialization. Those technologies include pumped storage, flow batteries, compressed air energy storage, and other forms of mechanical, thermal and ice storage. The federal research agenda should also encourage the development of hydrogen and other power-to-gas technologies that have the potential to link renewables and other sources of clean electricity to the rest of the economy and dramatically increase the amount of energy storage capacity in the nation.[96]

Among other comments, the witness from the PJM RTO, Mr. Andrew Ott, discussed the readiness of ESRs for grid applications. He also discussed the potential for competition between demand response resources, ESRs, and other generation resources.[97]

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[94] George Crabtree, Testimony before the U.S. Senate Energy and Natural Resources Committee, Joint Center for Energy Storage Research and Argonne National Laboratory, Hearing on Grid-Scale Energy Storage, June 4, 2019, p. 3, https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=01D9CF4D-2FED-43B6-ACB8-DC02E0EF8906.

[95] Ben Fowke, *Testimony before the U.S. Senate Energy and Natural Resources Committee*, Xcel Energy, Hearing on Grid-Scale Energy Storage, June 4, 2019, p. 4, https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=CC2444DF-815E-4D67-A2D9-7825304FEF8D.

[96] Ibid, p. 18.

[97] Andrew Ott, *Testimony Before the U.S. Senate Energy and Natural Resources Committee*, PJM RTO, Grid-Scale Energy Storage, June 4, 2019, https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=08C06596-519A-42C9-BAB6-DC45E9166152.

> One issue that has garnered attention is how energy storage resources can participate in PJM's capacity market and therefore displace a coal, nuclear or natural gas unit to be available on call to provide energy when needed in system emergencies. Consistent with FERC's requirements, we have indicated that battery storage resources can be deemed capacity resources and be fully paid to the extent to which they have the duration capability to be available on call when needed. We require the same of a coal, natural gas or nuclear unit, and we require the same of pumped storage hydro or a demand response resource. Our approach is consistent with FERC's directive that the markets need not create undue preferences for energy storage resources but instead must be open to their participation consistent with their "technical capability" of providing the service in question.[98]
>
> Today, in PJM and in other areas of the country, battery duration is generally limited—duration could be anything from 15 minutes to one or two hours (typically never longer than four hours) at their rated capacity before they need to be recharged. However, even with these relatively short durations compared to other resource types on the grid today, we don't exclude these batteries from participating in the capacity market. Instead, short-duration batteries are prorated based on their capability (just as we do with renewable resources) to recognize this limited duration. In short, we are treating batteries comparably to any other resource that seeks to serve as a capacity resource. As capacity resources are integral to ensuring reliability and keeping the lights on, we think it is only fair, as well as consistent with the FERC Order, to pay them comparably to what we would pay a cleared nuclear, coal or natural gas resource when they provide a comparable service.[99]
>
> I would note that the duration requirements for energy storage capacity resources that we submitted to FERC are, in-part, driven by the success that demand response has had in our capacity market. The advent of demand response, in which industrial operations or buildings and other facilities agree to curtail their load during system emergencies, has worked to "flatten" our expected load curve when demand response is called upon. In effect, this has transformed our capacity design requirements from serving what used to be a one-hour "needle" peak demand into a lower, wider but more sustained multi-hour peak demand.[100]

Key Issues for Congress

As the U.S. electric grid is modernized to incorporate new technologies capable of making the system more efficient and responsive to the needs of the future, energy storage is increasingly seen as a key component in that future. Energy storage systems have the potential to provide many essential services to the electric grid that can potentially benefit electricity customers in a number of ways.

Interest in reducing GHG emissions in the energy sector to mitigate climate change risks has increased the focus on renewable sources of electricity. While energy storage is seen as an enabling technology with the potential to reduce the intermittency and variability of wind and solar resources (in particular), energy storage resources would have to be charged by low or zero emission or renewable sources of electricity to ensure a reduction of greenhouse gases. Congress may look at providing guidance for regimes or incentives that promote energy storage in a manner that can ensure a decrease in greenhouse gas emissions.

Energy storage resources can potentially delay the need or avoid the cost of constructing traditional power plants, depending on how, where used, and what type of storage system is used.

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98 Ibid, p. 6.

99 Ibid, p. 6.

100 Ibid, pp. 6-7.

For such a scenario, storage resources must be capable of providing the more than four hours of energy often mentioned as available from current battery storage resources. Congress may consider whether further research and development is needed to develop longer duration, higher capacity energy storage resources capable of a higher number of charging/discharging cycles. DOE and the national laboratories may be able to lead cooperative efforts in basic research to address basic science issues.

As state governments, local communities, and U.S. businesses aim to increase their intake of renewable electricity, energy storage technologies are seen aiding increased renewable energy deployment and integration. While the cost of battery storage technologies is falling, a potential area for Congress to consider is efforts to reduce the cost of the many different items in balance of plant systems that may represent 20% to over 50% of a battery storage project's overall cost.

Further electrification of the economy may be required if reducing emissions seen as contributing to climate change is a driver of federal policy. Electrification of the transportation sector may be a key part of such a strategy. Options for charging electric vehicles sometimes discuss V2G as an option or V1G to promote grid efficiency. Congress may want to define goals for battery storage technologies to support such goals, pathways for the infrastructure needs, a regulatory framework, and/or the interoperability of technologies, if transportation electrification is a policy goal.

Recycling of spent Li Ion batteries and/or their components may be one way to ensure the sustainability of modular batteries systems. Over time however, the efficiency of any such technology for charging and discharging will diminish. Congress may want to investigate ways to promote a more efficient, less resource intensive future for modular battery systems, if electrification of the transportation sector to reduce GHG emissions is a policy goal.

While Li Ion battery systems are currently the most prevalent form of modular storage, and a key technology for EVs, several issues exist with the procurement of materials for battery components, and the safety of Li Ion battery systems. Congress may want to direct further research into modular battery system materials and charging technologies to reduce the cost, improve the safety of systems, increase system performance and cycle efficiency, and to assure the sustainable development of modular battery systems.

Selected Bills in 116th Congress

To-date, over 40 bills have been introduced in the 116th Congress on various topics concerning energy storage. This section summarizes several bills considered representative of the overall goals and directions of the proposed legislative efforts.

In the House

The Advancing Grid Storage Act of 2019 (H.R. 1743), introduced in March 2019, would authorize a research program, loan program, and technical assistance and grant program, among other purposes. DOE would be required to carry out a program for research of energy storage systems, and provide to eligible entities loans for the demonstration of and deployment of energy storage systems. Included in the objectives of the programs improvements to energy storage for microgrids, improved security of emergency response infrastructure, use of energy storage for optimization of transmission and distribution system operation and power quality, and the use of energy storage to meet peak energy demand and make better use of existing grid assets. A public program for technical assistance would be established, and grants would be made available to eligible entities for technical assistance to identify, evaluate, plan, and design energy storage systems. Projects to be prioritized would be those that facilitate the use of renewable energy resources, strengthen reliability and resiliency, improve the feasibility of microgrids in rural areas (including rural areas with relatively high electricity costs), and that minimize environmental impacts and greenhouse gas emissions.

The Promoting Grid Storage Act of 2019 (H.R. 2909), introduced in May 2019, would authorize an energy storage research program, a demonstration program, and a technical assistance and grant program, among other purposes. DOE would be required to establish a cross-cutting national program within the Department of Energy for the research of energy storage systems, components, and materials. DOE would also be required to establish a technical assistance and grant program to disseminate information and provide technical assistance directly to eligible entities so the eligible entities can identify, evaluate, plan, design, and develop processes to procure energy storage systems. DOE would be authorized to make grants to eligible entities so that the eligible entities may contract to obtain technical assistance to identify, evaluate, plan, design, and develop processes to procure energy storage systems. DOE would also administer a competitive grant program for pilot energy storage systems for eligible entities to improve the security of critical infrastructure and emergency response systems. The goal of these demonstrations would be to improve the reliability of the transmission and distribution system, particularly in rural areas, including high energy cost rural areas; and, to optimize transmission or distribution system operation and power quality to defer or avoid costs of replacing or upgrading electric grid infrastructure, including transformers and substations, among other purposes.

In the Senate

The Better Energy Storage Act (S. 1602), introduced in May 2019, would authorize a research, development, and demonstration (RD&D) program for grid-scale energy storage, among other purposes. The bill would amend the U.S. Energy Storage Competitiveness Act of 2007 (42 U.S.C. 17231) to promote RD&D for grid-scale energy storage. DOE would be required to develop goals priorities, and cost targets for the program, and submit a report on a 10-year strategic plan for the program to the Senate Committee on Energy and Natural Resources, and the House Committee on Science, Space and Technology. The focus of the program would be to develop cost-effective energy storage systems able to provide output for 6 hours, over not less than 8,000 cycles at full output, capable of operating 20 years, and systems capable of storing energy over several months to address seasonal variations in supply and demand. Cost targets for the systems are to updated every five years. Not more than five grid-scale projects would be required to be ready by 2023 for DOE to enter agreements for demonstration.

The Joint Long-Term Storage Act of 2019 (S. 2048), introduced in June 2019, would authorize a demonstration initiative focused on the development and commercial viability of long-duration energy storage technologies, including a joint program to be established in consultation with the Secretary of Defense, and for other purposes. The Secretary of Energy, acting through the Director of the Advanced Research Projects Agency-Energy, would be required to establish a demonstration initiative composed of demonstration projects focused on the development of long-duration energy storage technologies. Among the goals of the initiative would be to demonstrate how long-duration energy storage could benefit the resilience of the electricity grid, and improve the efficient use of the grid by peak load reduction and avoiding investment in traditional grid infrastructure.

Appendix A. Energy and Electricity Storage Technologies

Storage of Potential Energy

The large monolithic systems that are used for energy storage today do not store electricity directly, but provide a means of producing electricity by use of a stored medium (e.g., water or air). The gradual release of the stored medium physically turns the shaft of a turbine connected to an electric generator, converting potential energy from the stored medium to electricity. Several technologies storing potential energy for conversion to electricity are described in the next section.

Hydropower Pumped Storage

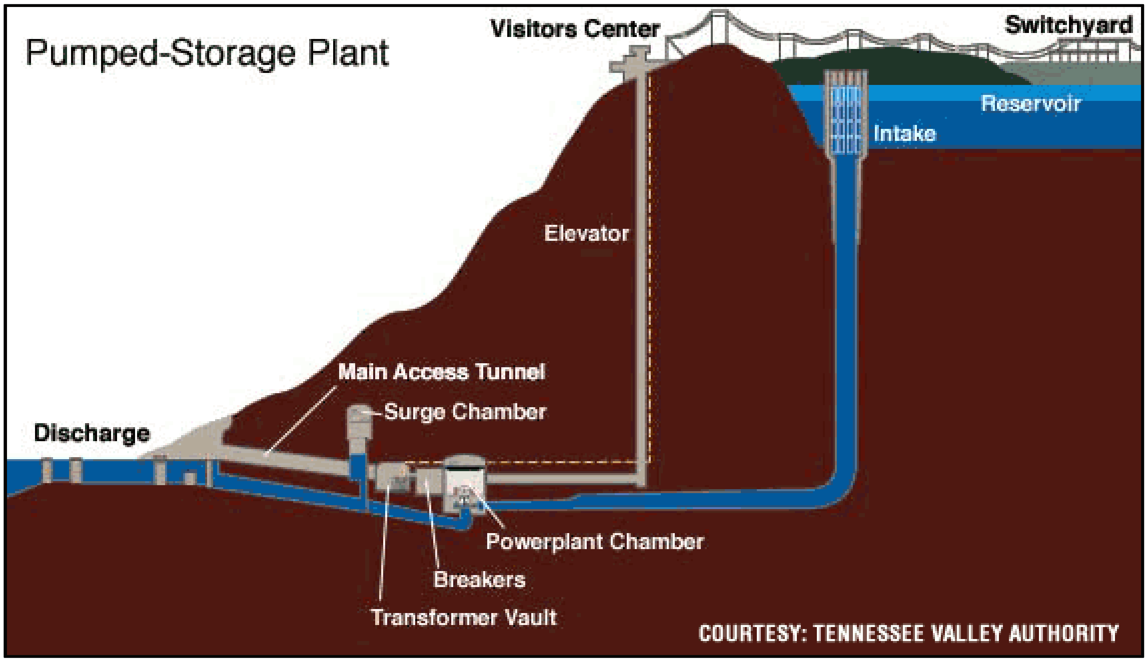
The largest current system and use of energy storage on the electric grid is from hydropower pumped storage (HPS) projects. Approximately 94% of U.S. energy storage capacity is from HPS, representing about 23 GigaWatts (GW - a gigawatt equals 1,000 megawatts) as of 2018.[101] The generation of electricity from falling water takes the potential energy of water held behind an impoundment and coverts it to kinetic energy as it moves the blades of a turbine to generate electricity. A typical HPS design is illustrated in **Figure A-1**. While traditional hydropower relies solely on favorable topography to allow for the gravity-aided flow of water to generate electricity on demand, HPS systems can be developed where the suitable geographic and ecological conditions exist. HPS systems also consider the time-related value of when electric power is needed on a system.

> Pumped storage projects move water between two reservoirs located at different elevations (i.e., an upper and lower reservoir) to store energy and generate electricity. Generally, when electricity demand is low (e.g., at night), excess electric generation capacity is used to pump water from the lower reservoir to the upper reservoir. When electricity demand is high, the stored water is released from the upper reservoir to the lower reservoir through a turbine to generate electricity.[102]

[101] National Hydropower Association, *Pumped Storage*, 2019, https://www.hydro.org/waterpower/pumped-storage/.

[102] Federal Energy Regulatory Commission, *Pumped Storage Projects*, June 25, p. 2019, https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp.

Figure A-1. Diagram of a Pumped Storage Project



Source: Federal Energy Regulatory Commission, *Pumped Storage Projects* at https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp.

Notes: Open-loop systems use a free flowing source of water for either the upper or lower reservoir. For a closed-loop pumped storage hydropower, neither the upper reservoir nor the lower reservoir is located on a dammed stream.

Most HPS projects operating today are "open-loop" systems, which utilize water from free-flowing sources for the upper or lower reservoir. According to the Federal Energy Regulatory Commission (FERC), approximately 24 HPS systems are currently operating with a total installed capacity of over 16.5 GW. However, FERC states that most of these systems were authorized more than 30 years ago.[103] HPS systems are estimated to have an efficiency of conversion for energy to electricity of between 70% and 75%.[104]

A newer technology for HPS utilizes water that is not free-flowing (e.g., possibly from groundwater), and is therefore described as a "closed-loop" system. FERC states that it has issued three licenses since 2014 for closed-loop HPS with a total capacity of 2.1 GW.[105] One of these projects will have an estimated 400 MW generation capacity and be able to provide an estimated annual energy generation of 1,300 GWh, and may see construction begin in 2020.[106] With closed-loop pumped HPS systems, neither the upper reservoir nor the lower reservoir is located on a dammed stream.

[103] Federal Energy Regulatory Commission, *Pumped Storage Projects*, June 25, 2019, https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp.

[104] The Economist, *Energy Storage: Packing Some Power*, May 3, 2012, https://www.economist.com/technology-quarterly/2012/03/03/packing-some-power?frsc=dg%7Ca.

[105] Email from Woohee Choi, FERC, Environmental Engineer, July 8, 2019.

[106] Robert Walton, "$1B Montana Pumped Storage Hydro Project Secures Funding," *Utility Dive*, 2019, July 19, https://www.utilitydive.com/news/1b-montana-pumped-hydro-project-secures-funding/558833/.

> To qualify as a closed-loop pumped storage facility for the purpose of the expedited [hydropower] licensing process, a project should cause little or no change in existing surface and groundwater flows and uses and must not adversely affect threatened or endangered species under the Endangered Species Act. The final rule also adds qualifying criteria to ensure that a qualifying pumped storage project utilizes only reservoirs situated at locations other than natural waterways, lakes, wetlands, and other natural surface water features; and relies only on temporary withdrawals from surface waters or groundwater for the sole purposes of initial fill and periodic recharge needed for project operation.[107]

Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) facilities use ambient air that is compressed and stored under pressure in an underground cavern. When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production. There are two CAES power plants currently operating in the world. Both plants store air underground in excavated salt caverns. The older plant in Huntorf, Germany has a 290 MW capacity, and was commissioned in 1978. A second plant was commissioned in McIntosh, Alabama in 1991, with a capacity of 110 MW.[108] The Huntorf plant is reported to be capable of delivering power at its rated capacity for up to 4 hours, while the McIntosh plant is reported as able to provide generation at its rated capacity for 26 hours.[109]

Air heats up when it is compressed for storage. This heat energy is largely lost to the environment in the two CAES plants currently operating, as they use a diabatic process.[110] When the air is decompressed to generate electric power, it loses this thermal energy and cools down. Therefore, the stored high-pressure air must be heated with natural gas before it is returned to the surface and expanded through a turbine that runs a generator. However, new systems may be able to store the thermal energy produced in the compression phase, thus avoiding the use of natural gas and its emissions. Compression and expansion of air introduces energy losses, resulting in a relatively low efficiency of energy to electricity conversion of 42%.[111]

CAES plants can use lower cost energy from the grid during off-peak hours for the compression cycle, including renewable electricity from excess wind generation at night that might not otherwise be used. While the McIntosh plant recovers some waste heat to reduce fuel consumption, some new designs for CAES power plants are looking at ways to increase energy conversion efficiency by capturing the waste heat from the compression process and storing it in molten salt for the decompression cycle.[112] Since geological salt formations are rare, the U.S. Department of Energy (DOE) is looking at adapting CAES technology to more common porous and permeable rock formations.[113]

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[107] FERC, "FERC Finalizes Expedited Hydro Licensing Process," Docket No. RM19-6-000, April 18, 2019.

[108] Pacific Northwest National Laboratory, *Compressed Air Energy Storage*, June 2019, https://caes.pnnl.gov/.

[109] John Gardner and Todd Haynes, *Overview of Compressed Air Energy Storage*, Boise State University, ER-07-001, December 2007, https://www.necec.org/files/compressedair.pdf.

[110] "Diabatic process: A thermodynamic change of state of a system in which the system exchanges energy with its surroundings by virtue of a temperature difference between them." American Meteorological Society, *Glossary*, http://glossary.ametsoc.org/wiki/Diabatic_process.

[111] Energy Storage Association, *Compressed Air Energy Storage (CAES)*, 2019, https://energystorage.org/why-energy-storage/technologies/mechanical-energy-storage/.

[112] Ibid.

[113] Pacific Northwest National Laboratory, Compressed Air Energy Storage, June 2019, https://caes.pnnl.gov/.

> Underground CAES storage systems are most cost-effective with storage capacities up to 400 MW and discharge times of 8 to 26 hours. Siting such plants involves finding and verifying the air storage integrity of a geologic formation appropriate for CAES in a given utility's service territory.[114]

Liquid Air (Cryogenic) Energy Storage

Liquid air or cryogenic[115] is a type of thermal energy storage that uses liquefied air to create an energy storage resource in a manner with characteristics of both HPS and CAES. Electricity, generated at off-peak demand times, can be used to cool air until it liquefies (as mostly liquid nitrogen since air is approximately 78% nitrogen).[116]

The process uses currently available equipment and technologies, and proceeds as follows:[117]

1. Charging the system—an air liquefier uses electrical energy to draw air from the surrounding environment, clean it, and then cool the air to subzero temperatures until the air liquefies. Seven hundred liters of ambient air become 1 liter of liquid air.
2. Storing the energy—the liquid air is stored in an insulated tank at low pressure, which functions as the energy store. These tanks are currently used for bulk storage of liquid nitrogen, oxygen and liquefied natural gas, and have the potential to hold several GWh of stored energy.
3. Generating power—when power is required, liquid air is drawn from the tank(s) and superheated to ambient temperature, producing a high-pressure gas that drives a turbine.

According to one developer of cryogenic technology, the energy storage capacity is determined by the size of the tanks. The tanks can be located anywhere they need to be, unlike HPS which depends on the water resource and geography. Off peak renewable energy can be used to charge the system which, when fully charged, can provide electricity to support a large peak demand load for several hours.[118]

Storage of excess cold produced during the liquefaction of air can be captured and reused in a later liquefaction cycle. The low boiling point of liquefied air means the efficiency of the system cycle (from liquefaction and storage to power production) can be improved with the capture and storage of heat produced during the liquefaction process that can be used in the expansion process when power is generated.[119]

Flywheels

Flywheel energy storage systems are comprised of a rotating cylinder (i.e., the flywheel rotor), balanced in a vacuum over an electricity-producing stator[120] via magnetically levitated bearings.

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[114] DOE/EPRI, p. 38.

[115] "Cryogenic" refers to the production and effects of very low temperatures, generally below -150 °C (-238 °F).

[116] Energy Storage Association, *Liquid Air Energy Storage,* p. 2019, https://energystorage.org/highview-power-unveils-cryobattery-worlds-first-giga-scale-cryogenic-battery/.

[117] Ibid.

[118] T&D World, *Highview Power Unveils Giga-Scale Cryogenic Battery,* June 19, 2019, https://www.tdworld.com/energy-storage/highview-power-unveils-giga-scale-cryogenic-battery.

[119] Ibid.

[120] In a generator, a rotor and the stator are the two components that generate electric power. A shaft rotates the rotor, spinning it past wire coils, surrounding a fixed iron core that makes up the stator.

The rotor in many flywheels was often made of steel, but some newer, higher speed flywheels use fiber composite materials able to store more energy per unit of mass. Flywheels store kinetic energy in the cylinder that spins in a nearly frictionless environment. To charge the flywheel, a small electric motor using electricity from an external source brings the cylinder up to an extremely high speed—up to 60,000 rotations per minute. As the rim in the flywheel spins faster, it stores energy kinetically in the rotating mass, with a small amount of power used to maintain the operating speed. When energy is needed, the flywheel is slowed and the kinetic energy is converted back to electrical energy.[121]

Flywheels are used in applications where a large amount of power is needed over a short timeframe. While they are generally charged using power from the grid, they can go from a discharged to a fully charged state within a few seconds. According to the Energy Storage Association, flywheels generally require low maintenance. Some flywheel technologies can undergo more than 100,000 full discharge cycles or more without performance impacts.[122]

> Today's flywheel systems are shorter energy duration systems and not generally attractive for large-scale grid support services that require many kWh or MWh of energy storage.… They have a very fast response time of four milliseconds or less, can be sized between 100 kW and 1650 kW, and may be used for short durations of up to one hour. They have … lifetimes estimated at 20 years.[123]

Storage of Electricity in Battery Systems

This section describes several technologies for the storage of electricity in battery systems. These systems can be large, monolithic systems (such as flow batteries) or modular battery systems aggregating the capacity stored in smaller cells to provide larger amounts of power.

Flow Battery Systems

Flow batteries are large battery systems that store an electrical charge in tanks of a liquid electrolyte (e.g., a liquid solution with dissolved chemicals that stores energy). Electric charge is drawn from the electrolyte as it is pumped through electrodes to extract the electrons, and the spent liquid returns to the storage tank. Flow battery technology is scalable. The active chemicals are stored separately until power is needed, thus reducing fire safety concerns. Most flow batteries require the electrolyte to be separated by a membrane, as shown in **Figure A-2**. Some newer flow battery technologies use a single flow loop design with no membrane, where "energy is stored in a plated metal on the surface of titanium electrodes."[124]

Vanadium and zinc bromine are currently the most-used liquid electrolytes. Vanadium has become a popular electrolyte component because the metal charges and discharges reliably for thousands of cycles. However, one article cited vanadium's increasing price and its toxicity as leading researchers to look at other cheaper and less toxic chemistries (e.g., such as iron or organic compounds) for flow batteries.[125] New electrolyte chemistries are being investigated that

[121] Energy Storage Association, *Flywheels*, 2019, http://energystorage.org/energy-storage/technologies/flywheels.

[122] Ibid.

[123] DOE/EPRI, p. 91.

[124] Kathie Zipp, "What Is a Flow Battery?," *Solar Power World*, December 4, 2017, https://www.solarpowerworldonline.com/2017/12/what-is-a-flow-battery/.

[125] Robert F. Service, *New Generation of 'Flow Batteries' Could Eventually Sustain a Grid Powered by the Sun and Wind*, American Association for the Advancement of Science, October 31, 2018, https://www.sciencemag.org/news/2018/10/new-generation-flow-batteries-could-eventually-sustain-grid-powered-sun-and-wind.

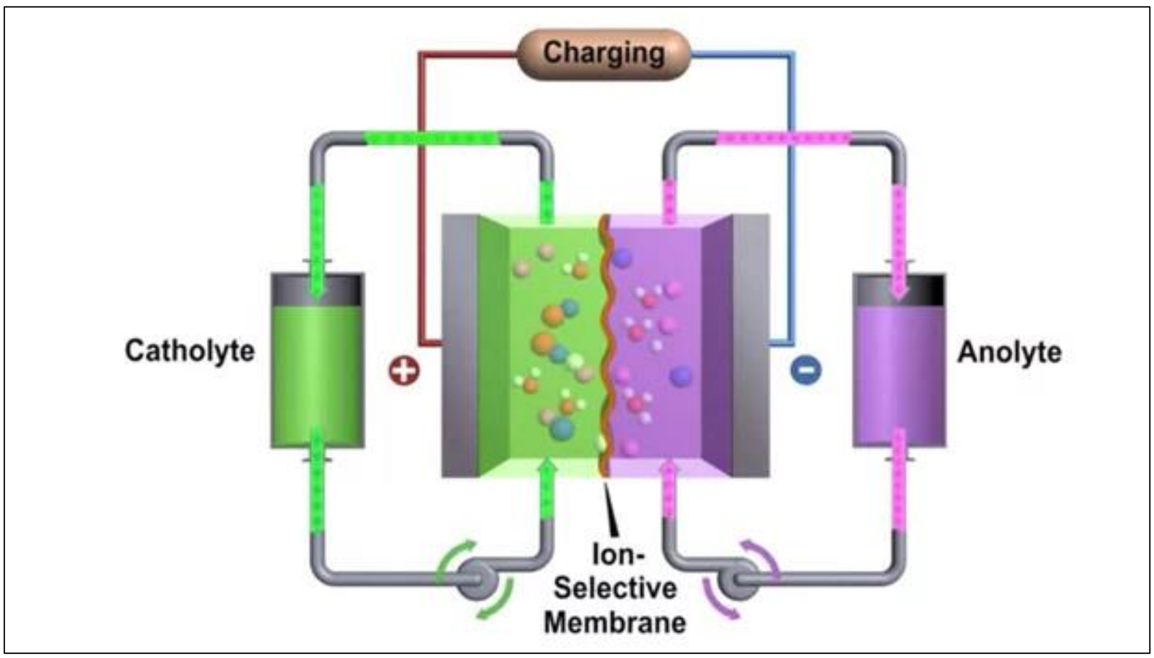
are able to maintain a high number of charge cycles, and retain a low viscosity to ease pumping between tanks.[126]

Any source of power can be used to charge flow batteries, including renewable electricity from wind and solar sources. Since flow batteries are scalable in size and able to undergo a large number of charging and discharging cycles, they are considered as a potential option to store off-peak electricity generation from renewable sources.[127]

Redox Flow Batteries

Redox batteries are a specific type of flow battery. The name "redox" refers to the chemical reduction and oxidation reactions employed in the redox flow battery to store energy in liquid electrolyte solutions which flow through a battery of electrochemical cells during charge and discharge.[128] Redox batteries can be further classified as either aqueous or nonaqueous systems, with aqueous systems using water as the electrolyte solvent. While aqueous flow batteries are generally safer, they do not currently store as much energy per unit of volume as nonaqueous chemistries. Redox flow batteries are said to offer an economical, low vulnerability means of storing electrical energy at scale, with greater flexibility to design a system based on power and energy rating for a given application. Redox flow batteries are suitable for energy storage applications with power ratings ranging from kiloWatts (kW) to the tens of MW over periods from two to 10 hours, and are capable of 10,000 or more charging cycles.[129]

Figure A-2. Redox Flow Battery Concept



Source: Pacific Northwest National Laboratory, Zinc-polyiodide redox flow battery concept at https://www.pnnl.gov/news/release.aspx?id=4182.

Notes: Catholyte—electrolyte with positively charged ions. Anolyte—electrolyte with negatively charged ions.

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[126] Ibid.

[127] Ibid.

[128] DOE/EPRI, p. 53.

[129] DOE/EPRI, pp. 54-57.

The redox flow battery concept shown in **Figure A-2** produces power by pumping liquid from external tanks into the battery's stack, a central area where the liquids are mixed. When the battery is fully discharged, both tanks hold the same electrolyte solution (which is a mixture of the positively charged ions and negatively charged ions. When power is needed, the two liquids are pumped into the central stack. Inside the stack, positive ions pass through a selective membrane and change into a solid on the stack's negative side thus generating electricity.

According to EPRI, vanadium redox flow batteries have an important advantage among flow batteries as the two electrolytes are identical when fully discharged, which simplifies electrolyte management during operation.[130]

Modular Battery Technologies

Modular batteries are used in many aspects of everyday life. They generally store electrical energy in chemical form, and consist of standardized individual cells. The individual cells have relatively small power and voltage capacities that can be aggregated to serve larger power loads. Battery energy storage can also provide ancillary services for the electric grid such as frequency regulation, voltage support and spinning reserves. This section of the report focuses on some of the major rechargeable modular battery technologies that currently serve applications from cell phones to electric or hybrid vehicles, and can provide some backup power or services to the electric grid.

Modular battery systems may be suited to arbitrage opportunities. Such opportunities may be economically available to storage systems ranging from one to 500 MW, with a discharge duration range of one hour or greater. Some storage projects may be able to cycle their charging and discharging to meet such opportunities perhaps 250 or more times in a year.[131]

Lithium Ion Batteries

Lithium ion (Li Ion) represents a family of battery chemistries, each with its own strengths and weaknesses regarding different applications and uses.[132] Li Ion batteries store and release energy through a process called "intercalation," which involves lithium ions entering and exiting microscopic spaces in between the atoms of a battery's two electrodes. The most commonly used type of Li Ion cell has a positive electrode (i.e., the cathode) of made of lithium-cobalt oxide ($LiCoO_2$), and a negative electrode made of carbon. Batteries are charged as ions of lithium move through the electrolyte (typically a lithium salt solution) from the positive to the negative electrode (i.e., the anode), and attach to the carbon. When discharged, lithium ions move back to the positive electrode.[133]

Li Ion batteries are used in many applications because lithium is highly reactive and has a high specific energy, which means it can store approximately 150 Wh of electricity in a one kilogram

[130] EPRI, *VRB Energy Storage for Voltage Stabilization: Testing and Evaluation of the PacifiCorp Vanadium Redox Battery Energy Storage System at Castle Valley, Utah*, EPRI ID 1008434, 2005, https://www.epri.com/#/pages/product/1008434/?lang=en-US.

[131] DOE/EPRI, pp. 2-3.

[132] For more information on the lithium supply chain, see CRS Report R45810, *Critical Minerals and U.S. Public Policy*, by Marc Humphries.

[133] Energy Storage Association, *Lithium Ion Batteries*, p. 2019, http://energystorage.org/energy-storage/technologies/lithium-ion-li-ion-batteries.

battery. Li Ion batteries hold their charge well over time, losing only about 5% per month,[134] and generally have no memory effect.[135] Li Ion battery packs have electronic circuitry built in to regulate charging and discharging of the batteries to prevent overcharging and excess heating of the batteries, which can potentially result in explosions or fires.[136] However, the components of fuel, oxygen, and an ignition source exist in the battery system providing the prerequisites for combustion.[137]

Unlike other rechargeable batteries, Li Ion does not require a deep-discharge cycle to maintain the battery's ability to recharge to full capacity. Over time however, that ability to fully recharge weakens. Nevertheless, the Li Ion battery packs used for EV systems may still have as much as 50% to 70% of their original energy storage capacity at the end of their EV service life. This would allow EV Li Ion battery packs to have a second life in a variety of electricity storage uses from residential storage to renewable generation and other back-up power applications.[138]

However, Li Ion battery packs can catch fire (due to a flammable liquid electrolyte) if, for example, an electric vehicle car crash punctures the battery pack.[139] The development of a solid-state battery (i.e., a battery with a solid instead of a liquid electrolyte) may make Li Ion batteries safer. It may also remove the issue with dendrite formation, the crystal-like buildup of lithium metal in the electrolyte that can puncture the cathode-anode separator, causing a short circuit that will destroy the battery and can cause a fire.[140]

The potential uses of Li Ion batteries at end-of-life highlights issues with the materials used in the construction of the battery cells. Cobalt is used in the construction of the cathode of the battery. While cobalt is not on a list of "conflict materials" that the federal government regulates from conflict zones,[141] cobalt is mostly mined in the Democratic Republic of Congo (DRC), a recognized conflict zone from which about 70% of the world's cobalt originates.[142]

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[134] Marshall Brain, *How Lithium-ion Batteries Work*, Howstuffworks.com, 2019, https://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm.

[135] The memory effect can reduce a rechargeable battery's ability to fully charge, due to incomplete discharge of the battery in previous uses.

[136] Chris Woodford, "Lithium-Ion Batteries," Explainthatstuff.com, August 3, 2018, https://www.explainthatstuff.com/how-lithium-ion-batteries-work.html.

[137] Qingsong Wang, Jinhua Sun, and Guanquan Chu, *Lithium Ion Battery Fire and Explosion*, State Key Laboratory of Fire Science, University of Science and Technology of China, 2005, https://www.iafss.org/publications/fss/8/375/view/fss_8-375.pdf.

[138] David Stringer and Jie Ma, "Where 3 Million Electric Vehicle Batteries Will Go When They Retire," *Bloomberg Businessweek*, June 27, 2018, https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire.

[139] Kevin Bullis, *Are Electric Vehicles a Fire Hazard?*, Massachusetts Institute of Technology Technology Review, November 26, 2013, https://www.technologyreview.com/s/521976/are-electric-vehicles-a-fire-hazard/.

[140] Robert Triggs, *Solid State Battery—the Successor to Li Ion—Takes Another Step Closer to Our Smart Phones*, Android Authority, April 23, 2019, https://www.androidauthority.com/solid-state-battery-978899/.

[141] "In 2012, the U.S. Securities and Exchange Commission introduced rules requiring companies to report detailed information about their supply chains for so-called "conflict minerals," including gold, tungsten and tin. The rules were put in place to ensure that companies were not inadvertently financing or benefiting armed groups in the DRC when buying these minerals." Alanna Petroff, "Carmakers and Big Tech Struggle to keep Batteries free from Child Labor," CNN, May 3, 2018, https://money.cnn.com/2018/05/01/technology/cobalt-congo-child-labor-car-smartphone-batteries/index.html.

[142] Antony Loewenstein, "From Blackwater to Batteries," ForeignPolicy.com, January 25, 2019, https://foreignpolicy.com/2019/01/25/from-blackwater-to-batteries-erik-prince-congo-drc-minerals-cobalt-afghanistan-mercenaries/.

Until recently, as much as 20% of Congolese cobalt was estimated to be produced in unregulated artisanal mines (i.e., informal mines, often small-scale operations in local communities) that reportedly use child laborers in unhealthy conditions.[143] The DRC regulates the large mines responsible for most of the cobalt supply, but unrest and economic conditions has driven people to artisanal mining. Even after a recent collapse of cobalt prices, child labor in Congolese artisanal mines reportedly continues to be a problem. However, a recovery of cobalt use from projected growth in EV adoption could exacerbate the issue.[144]

Due largely to concerns about child labor in artisanal mines, companies have been under pressure to document their cobalt supply chain to show where their cobalt is sourced. While some companies are now buying cobalt directly from the regulated mines in the DRC, the mixing of cobalt supplies in the refining process (which was reported as taking place mostly in China) complicates tracking efforts.[145] Other companies are reducing their use of cobalt to "minimize" exposure to the issue.[146]

Since Li Ion battery manufacture utilizes a number of potentially toxic elements if improperly disposed of (i.e., in landfills where groundwater contamination could occur), and have rare earth and other valuable components with potential value, some countries have passed laws to ensure recycling of the batteries. China, where about half the world's EVs are sold, was reportedly implementing rules to make carmakers responsible for expired batteries. The European Union also has regulations for EV battery disposal.[147]

Recycling of Li Ion batteries may also help to reduce the need for new supplies from mining of cobalt. But the reuse of EV Li Ion batteries was reported to be more attractive than recycling at this time. Projected demand growth for EVs may overtake the immediate benefits of recycling on supply needs.[148]

Lithium Iron Phosphate

Lithium Iron Phosphate (LFP) is another Li Ion chemistry for rechargeable battery cathodes. LFP can be used in similar high power applications as lithium-cobalt oxide cells, but LFP's chemistry has a lower specific energy at about 120 Wh/kg (compared to the $LiCoO_2$ chemistry with a specific energy of about 150 Wh/kg). However, LFP has a longer cycle life than lithium-cobalt oxide, and is reportedly a safer battery chemistry as it is less flammable.[149]

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[143] Ibid.

[144] William Clowes, "Congo's Swing Producers Turn to Copper After Cobalt Meltdown," Bloomberg, July 8, 2019, https://www.bloomberg.com/news/articles/2019-07-08/congo-s-swing-producers-turn-to-copper-after-cobalt-meltdown.

[145] S&P Global, *Cobalt—Production Remains Steady but Supply Security Fears Remain High*, Mining.com, July 16, 2018, https://www.mining.com/web/cobalt-production-remains-steady-supply-security-fears-remain-high/.

[146] Angela Chen, "Elon Musk Wants Cobalt Out of His Batteries—Here's Why That's a Challenge," *The Verge*, June 21, 2018, https://www.theverge.com/2018/6/21/17488626/elon-musk-cobalt-electric-vehicle-battery-science.

[147] David Stringer and Jie Ma, "Where 3 Million Electric Vehicle Batteries Will Go When They Retire," *Bloomberg Businessweek*, June 27, 2018, https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire.

[148] Ibid.

[149] "LFP cathodes also offer the safety advantage of having more thermal and chemical stability than $LiCoO_2$ cathodes. Because of stronger chemical bonds between the elements involved, oxygen atoms are not as readily removed from LFP cathodes due to abuse (overheating, short-circuiting, etc.). In similar circumstances, $LiCoO_2$ batteries undergo non-linear expansion that affects the structural integrity of the cell. Oxygen loss in $LiCoO_2$ cells also leads to exothermic reactions which can in turn lead to ignition in the event of mishandling." House of Batteries, *Lithium Iron*

Nickel Cadmium and Nickel-Metal Hydride Batteries[150]

Nickel cadmium (NiCad) has been in use as a rechargeable battery since about 1910, and was the mostly widely used chemistry for rechargeable batteries until the commercialization of NiMH.[151] NiCad and nickel-metal hydride (NiMH) were the mainstay of rechargeable battery applications before the widespread adoption of Li Ion batteries just over a decade ago.

NiMH began to replace NiCad in applications requiring a higher power density in smaller package applications or where performance was more important, and can store about 70 watt-hours per kilogram. NiMH also does not suffer from a memory effect, thus will not require a full discharge cycle to maintain the ability to fully charge. But NiCad retains a charge longer and performs better than NiMH in cold weather applications, or in off-grid renewable energy storage or telecom operations (e.g., situations where near maintenance-free operation is needed with respect to the electrolyte).[152]

Lead-Acid Batteries

One of the oldest and most widely used forms of energy storage is the lead-acid battery. These batteries are a mainstay of gasoline-powered vehicles, providing energy storage for the spark ignition system of internal combustion engines (ICEs). Lead-acid batteries used in passenger cars commonly have six cells, each with an electromotive force of about 2 volts (V). They can be discharged at a high rate but can require more than 14 hours to recharge. The battery cells are constructed in a grid made of a lead alloy that holds an electrolyte solution of water and sulfuric acid.[153] **Figure A-3** shows a wet-cell (also called a "flooded" battery due to the liquid electrolyte) lead-acid battery design with several cells with the electrodes connected to each cell.

Phosphate, 2019, https://www.houseofbatteries.com/lithium-iron-phosphate.

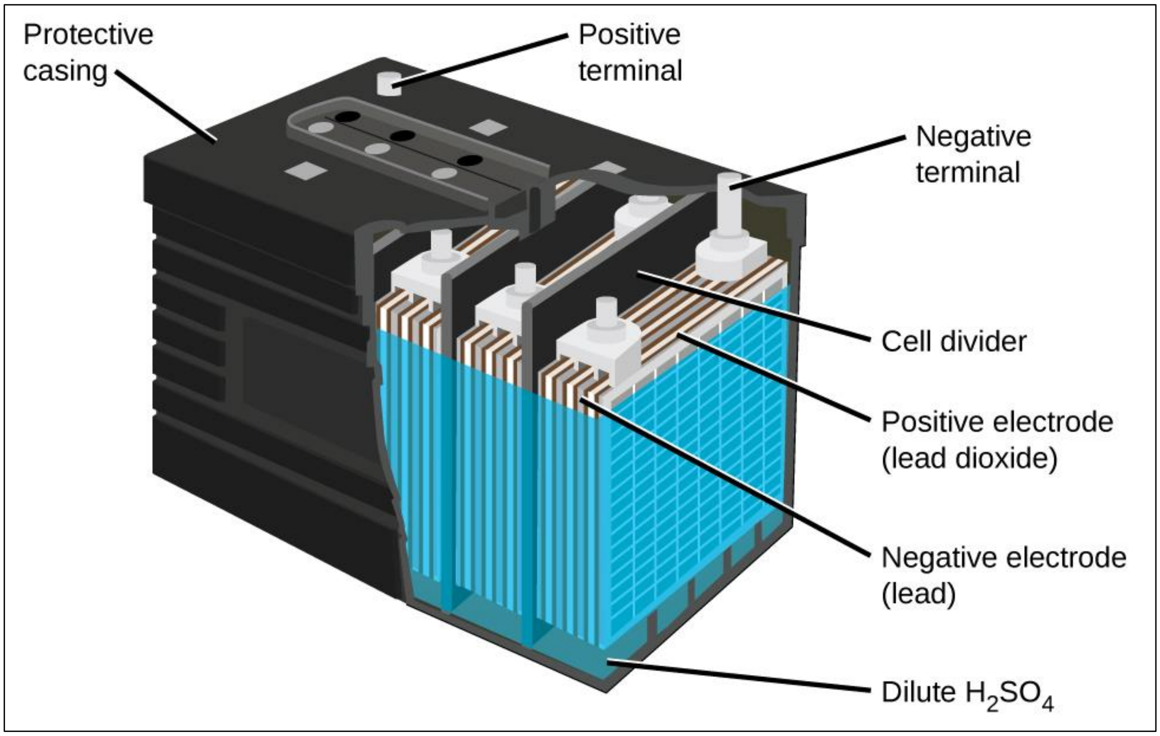
[150] Battery Depot, *What Is the Difference Between NiCad and NiMH?*, March 9, 2017, https://www.batterydepot.com/blog/difference-between-nicad-and-nimh/.

[151] Energy Storage Association, *Nickel-Cadmium Batteries*, 2019, https://energystorage.org/why-energy-storage/technologies/solid-electrode-batteries/.

[152] Battery University, *Nickel-Based Batteries*, 2019, https://batteryuniversity.com/learn/article/nickel_based_batteries.

[153] Battery Council, *What Is a Lead Battery*, 2017, http://aboutbatteries.batterycouncil.org/What-is-a-lead-battery.

Figure A-3. Lead-Acid Battery



Source: Courtesy of Electrical Academia at http://electricalacademia.com/batteries/secondary-cell-definition-types/attachment/cnx_chem_17_05_lead/.

Notes: H_2SO_4 = Dilute sulfuric acid electrolyte.

Wet-cell lead-acid batteries are usually made with vents and removable caps to allow for gases to escape while charging, and refilling with water when too much of the electrolyte has been converted to gas. A lead-acid battery can store perhaps 25 watt-hours of electric power per kilogram. Passenger car batteries are often called "starter" batteries as they provide a surge of power during the ignition stage to start the engine, and store power generated by the electrical system to prevent damage to system components. Lead-acid batteries can also be designed as "deep cycle" batteries to provide a low, steady level of power for a longer duration than a starting battery. Some applications require "dual purpose" batteries with characteristics designed to have a high starting power for cranking engines, but are able to withstand the cycle service demands from multiple accessory loads. Lead-acid batteries can be aggregated for "back-up" power applications to supply electrical power to critical systems in the event of a power outage. Batteries used for back-up power can also function as voltage stabilizers that smooth out fluctuations in electrical generation systems.[154] However, a lead-acid battery would require six kilograms to store the same amount of energy that a one kilogram lithium-ion battery could store.[155]

[154] Ibid.

[155] Marshall Brain, "How Lithium-ion Batteries Work," Howstuffworks,com, p. 2019, https://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm.

Batteries designed for industrial uses provide a low, steady power for a longer duration than a typical deep cycle battery. This makes a higher amount of total energy available for a longer period of time.

> Industrial batteries have the ability to last for years and can be used in stationary applications that provide critical back-up power to systems that need constant power supply. Industrial batteries are often not called upon to deliver power, but when they are, it is required that they deliver an abundance of power that will last long enough for reserve generators to take over. Often times, industrial batteries are configured as systems to accommodate large power demands.[156]

Lead-acid battery components are often recycled at the end of the battery's useful service life. Even the spent sulfuric acid can be "neutralized" or converted to sodium sulfate and reused.[157]

Advanced Lead-Acid Batteries

A key problem with lead-acid batteries is the growth of lead sulfate crystals in the electrolyte that eventually limits lead battery performance and is a key cause of battery failure. Researchers at the Argonne National Laboratory announced that they are working with industry to better understand the underlying chemistry of lead-acid batteries to find a solution to sulfation, and resulting dissolution issues (i.e., as the electrolyte loses much of its dissolved sulfuric acid and becomes primarily water). A main goal of the research effort is to unlock "a significant portion of…unused potential [in lead-acid batteries that] would result in even better low-cost, recyclable batteries for mobile and stationary market applications."[158]

Since lead-acid batteries do not have as high a fire risk as Li Ion batteries, some researchers are investigating new technologies that may allow for a greater use of lead-acid batteries in electric grid and transportation applications.

> Lead-acid carbon technologies use a fundamentally different approach to lead-acid batteries through the inclusion of carbon, in one form or another, both to improve the power characteristics of the battery and to mitigate the effects of partial states of charge. Certain advanced lead-acid batteries are conventional valve-regulated lead-acid batteries with technologies that address the shortcomings of previous lead-acid products through incremental changes in the technology. Other advanced lead-acid battery systems incorporate solid electrolyte-electrode configurations, while others incorporate capacitor technology as part of anode electrode design.[159]

Sodium Sulfur Batteries

Sodium sulfur (NaS) batteries are a liquid metal technology that operates at high temperatures to keep sulfur molten at both the positive and negative electrodes. A solid ceramic separates the

[156] Battery Council International, *Types of Lead Batteries: Industrial*, 2017, https://aboutbatteries.batterycouncil.org/What-is-a-lead-battery.

[157] "The acid is neutralized with an industrial compound similar to household baking soda. This turns the acid into water. The water is treated, cleaned and tested to be sure it meets clean water standards. Then it is released into the public sewer system." Battery Council International, *Lead Battery Recycling*, 2017, http://aboutbatteries.batterycouncil.org/How-do-I-recycle-my-lead-battery.

[158] Argonne National Laboratory, "Battery Mainstay Headed for High-Tech Makeover," press release, October 16, 2018, https://www.anl.gov/article/battery-mainstay-headed-for-hightech-makeover.

[159] Abbas A. Akhil, Georgianne Huff, and Aileen B. Currier, et al., *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA*, Sandia National Laboratories, SAND2013-5131, July 2013, https://www.energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf.

electrodes and serves as the electrolyte, allowing only positively charged sodium-ions to pass through during the charging cycle. As the battery is discharged, electrons are stripped from the sodium metal producing free sodium-ions that move to the cathode compartment. One battery set currently available has a one MW capacity providing up to 6 MWh of energy from 20 modules each capable of supplying 50 kW.[160]

Sodium Nickel Chloride Batteries

Sodium nickel chloride batteries are another high-temperature battery. When charging a Sodium-nickel-chloride battery at normal operating temperatures, salt (NaCl) and nickel (Ni) are transformed into nickel-chloride (NiCl2) and molten sodium (Na), with the chemical reactions reversed during discharge. The electrodes are separated by a ceramic electrolyte that is conductive for sodium ions but an isolator for electrons. Therefore, the cell reaction can only occur if an external circuit allows electron flow equal to the sodium ion current. Cells are hermetically sealed and packaged into modules of about 20 kWh each. The DOE/EPRI report says that utility systems were beginning to be deployed systems in the size range of 50 kW to 1 MW.[161]

New Modular Battery Technologies

According to one observer of the modular battery industry, a new technology for grid scale storage "will be needed to hit the cost levels for continuous deployment," if battery storage deployment is to be sustained beyond 2020. In that timeframe, a potential consolidation of the Li Ion industry was suggested by the observer, which would lead suppliers to potentially focus on new liquid metal technologies to achieve a "necessary cost-competitive, 20-year life performance."[162]

Research into permeable membranes may result in replacements for brittle ceramic separators in today's NaS batteries. A team from the Massachusetts Institute of Technology (MIT) described how novel mesh membranes could lead to new grid-scale batteries with electrodes made of sodium and nickel chloride. The MIT team projected that the membranes could result in new types of liquid metal batteries, enabling "inexpensive battery technology" to make intermittent power sources such as wind and solar capable of delivering reliable baseload electricity.[163]

[160] Alternative Energy, *Sodium-Sulfur Batteries*, 2019, http://www.altenergy.org/renewables/molten-salt-battery.html.

[161] DOE/EPRI, pp. 49-53.

[162] Herman K. Trabish, "Bigger Than Batteries: Why the Cost of Other Components Matters to Storage Deployment," *Utility Dive*, January 11, 2016, https://www.utilitydive.com/news/bigger-than-batteries-why-the-cost-of-other-components-matters-to-storage/411827/.

[163] David L. Chandler, *A New Approach to Rechargeable Batteries*, MIT News Office, January 22, 2018, http://news.mit.edu/2018/metal-mesh-membrane-rechargeable-batteries-renewable-energy-0122.

Appendix B. Ancillary Services for the Grid

Ancillary services are used by grid operators to ensure the reliability and stability of the power system, by helping to match power generation and demand. The Federal Energy Regulatory Commission (FERC) defines ancillary services as:

> Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services.[164]

According to one source, ancillary services can be put into three main categories.[165] These include:

- Flexibility-related services, which balance supply and demand, are provided by operating reserves,
- Frequency-related services, which maintain a constant rate of 60 Hertz, and are provided by regulating reserves, and,
- Voltage-related services, which control stability across the system.

Flexibility-related ancillary services include:

- **Ramping or load following** relate to the vital task of bringing online, or taking offline, power plants typically over the course of a few seconds or minutes to several hours to meet changing load or supply conditions. Such activity has long been a part of daily grid operations, particularly to meet expected changes in demand throughout the day. Demand for power commonly fluctuates sub-hourly, hourly, daily and seasonally. Natural gas-fired power plants, for example, have the flexibility to quickly ramp up or down their energy output as system conditions change throughout a given day.[166]
- **Operating reserves** are ancillary services that explicitly provide the ability to quickly fill in new energy supply when needed because of unexpected changes in the supply/demand balance, as well as supporting voltage and frequency. Most systems rely on two types of operating reserves: (1) contingency spinning (or synchronous) reserves that usually can respond very quickly, within ten to fifteen minutes, and (2) non-spinning (or supplemental) reserves that typically have response times on the order of ten to 30 minutes or more.[167]
- A reserve margin is the "percentage of installed capacity exceeding the expected peak demand during a specified period,"[168] and varies according to regional

[164] Federal Energy Regulatory Commission, *Guide to Market Oversight—Glossary*, Ancillary Services, March 15, 2016, https://www.ferc.gov/market-oversight/guide/glossary.asp.

[165] Reichus Consulting, *Electricity Ancillary Services Primer*, New England States Committee on Electricity (NESCOE), August 2017, http://nescoe.com/wp-content/uploads/2017/11/AnxSvcPrimer_Sep2017.pdf (Hereinafter, NESCOE).

[166] NESCOE, p. 11.

[167] NESCOE, p. 12.

[168] Federal Energy Regulatory Commission (FERC), *Guide to Market Oversight—Glossary*, March 15, 2016, https://ferc.gov/market-oversight/guide/glossary.asp#R.

regulatory requirements. For instance, a reserve margin of 15% means that an electric system has excess capacity in the amount of 15% of expected peak demand.[169]

- **Spinning reserves** are provided by generation units that are actively generating (and whose turbines are "spinning") and thus can quickly increase or decrease their output when called upon within the required time. Non-spinning or non-synchronized reserves are provided by generation resources that are not actively generating, but are ready and able to start up quickly and begin providing energy to the grid within a specified timeframe. In some regions, these non-spinning reserves are referred to as fast-start resources.[170]

Frequency-related services include:

- **Regulating reserves** are actions that can respond in seconds to grid fluctuations or emergencies to stabilize frequency and to rebalance supply with demand.[171]
  - Technical Considerations:

    Storage System Size Range: 10-100 MW

    Target Discharge Duration Range: 10 minutes-1 hour

    Minimum Cycles/Year: 20-50

- **Down regulation** can be provided by energy storage resources as they charge and absorb energy from the grid. However, the storage operator must pay for that energy. That is notable—especially for storage with lower efficiency—because the cost for that energy may exceed the value of the regulation service.[172]
  - Technical Considerations:

    Storage System Size Range: 10-40 MW.

    Target Discharge Duration Range: 15-60 minutes.

    Minimum Cycles/Year: 250-10,000.

  The rapid-response characteristic (i.e., fast ramp rate) of most storage systems makes it valuable as a regulation resource.

Voltage-related ancillary services include:

- Voltage control is managed by injecting or absorbing "reactive power" at the site of generation, transmission, and distribution to maintain the appropriate level of voltage at a given location. Reactive power (measured in kilovolt-amperes reactive (KVAR)) is an integral part of generating alternating current, along with active (or real) power. Real power is what most would refer to as electricity, measured in kiloWatts (kW).[173] Reactive

[169] Energy Information Administration, *Reserve Electric Generating Capacity Helps Keep the Lights On*, June 1, 2012, https://www.eia.gov/todayinenergy/detail.php?id=6510.

[170] NESCOE, p. 12.

[171] NESCOE, p. 13.

[172] DOE/EPRI, p. 5.

[173] "Reactive power: The portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment. Reactive power must be supplied to most types of magnetic equipment, such as motors and transformers. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such

as capacitors and directly influences electric system voltage. It is a derived value equal to the vector difference between the apparent power and the real power. It is usually expressed as kilovolt-amperes reactive (KVAR) or megavolt-ampere reactive (MVAR)." EIA, "Glossary: Reactive Power," 2019, https://www.eia.gov/tools/glossary/index.php?id=R.

- power must be available locally to transfer active power across the network. In other words, to get and maintain the desired voltage at a given location, a precise amount of reactive power must be present.[174]
- Normally, designated power plants are used to generate reactive power to offset reactance[175] in the grid. Many smaller coal-fired power plants that were transitioned to provide reactive power as they aged, are now being retired.[176] These power plants could potentially be replaced by strategically-placed energy storage within the grid at central locations or taking the distributed approach and placing multiple VAR-support storage systems near large loads.[177]
    - Technical Considerations:

      Storage System Size Range: 1-10 mega volt-ampere reactive (MVAR).

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[174] NESCOE, p.14.

[175] Reactance is a form of opposition that electronic components exhibit to the passage of alternating current because of capacitance or inductance components in the grid.

[176] Direct Energy, *What Is Reactive Power and Why Does It Matter?*, May 23, 2016, https://business.directenergy.com/blog/2016/may/reactive-power.

[177] DOE/EPRI, p. 9.