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Energy Storage

Meeting California's Climate and Energy Goals Through a Balanced Low-Carbon Grid

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Acknowledgments

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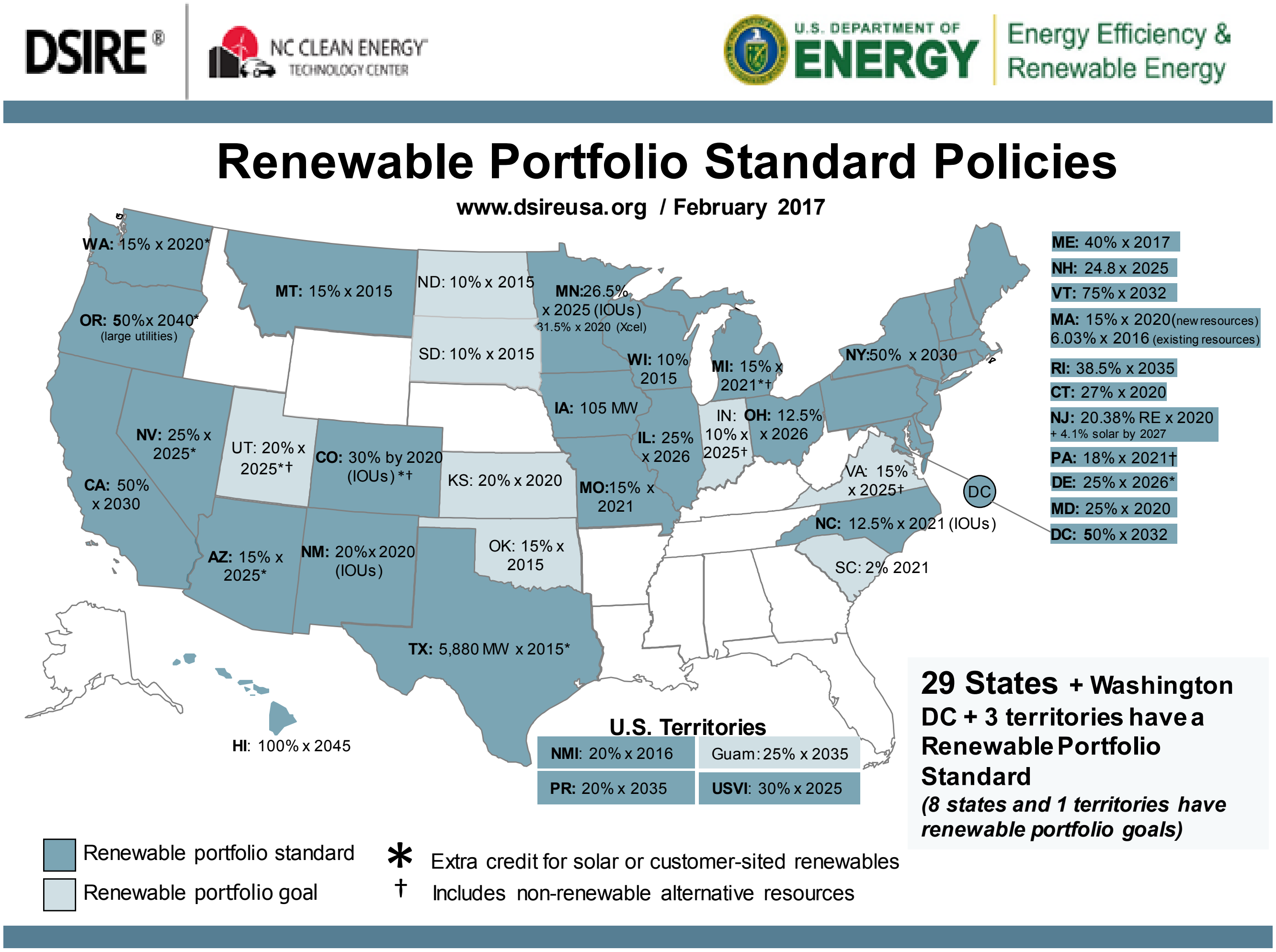
The Bay Area Council Economic Institute's 2016 report, *21st Century Infrastructure: Keeping California Connected, Powered, and Competitive*, underscored the need for a smart grid that improves reliability and resilience, supports the increased generation and use of renewable power, integrates energy storage, and with that enables the reduction of greenhouse gas emissions.[1] As California pursues ever more ambitious greenhouse gas and renewable energy targets, new challenges are emerging for the electric grid. In particular, the variable nature of renewable energy sources, which in large part depend on when the sun shines and the wind blows, requires increased attention as regulators and policy makers attempt to balance the grid and match power needs with available supply. This balance is critical to avoiding the situation where renewable power is increasingly not used ("curtailed") because of power being generated in excess of immediate demand.

Energy storage holds the key to managing a balanced, reliable, and sustainable grid in the face of these challenges. This report focuses on the emerging need for grid-scale storage, which must be prioritized but faces significant regulatory and market barriers. It presents an overview of projected energy storage needs, available technologies, market challenges, and regulatory policy developments, and it offers recommendations for how to accelerate investment in and deployment of new storage capacity. Accelerated progress toward meeting that goal will be essential to achieving a more flexible, balanced, low-carbon 21st century grid in California.

Renewable Energy in California’s Electric Grid

Driven by state and local energy policies, federal tax incentives, and a responsive industry, a transformational expansion of renewable power generation is changing the nature of the electric grid in the US. This change is occurring particularly in states with high Renewable Portfolio Standards (RPS), which require a certain percentage of electric generation to come from renewable resources. Several states’ RPS goals are shown in Figure 1. Among the most ambitious are California’s and New York’s goal of 50 percent renewables by 2030 and Hawaii’s goal of 100 percent renewables by 2045. California’s commitment to renewable power is growing: in October 2015, Governor Jerry Brown signed into law State Bill (SB) 350, which increased the RPS from the previous target of 33 percent to 50 percent by 2030. Reaching that 50 percent target would require about 2.2 gigawatts (GW) of storage.[2]

Figure 1: Renewable Portfolio Standards by State



Source: Database of State Incentives for Renewables and Efficiency (DSIRE), RPS Policies Summary Map, February 2017. <http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2017/03/Renewable-Portfolio-Standards.pdf>

SB 350 is a bookend to SB 32, California's global warming bill, which sets the goals of reducing greenhouse gas emissions by at least 40 percent below 1990 levels by 2030, doubling energy efficiency savings, and encouraging the electrification of transportation. To meet these ambitious targets, measures must be taken to integrate a higher level of renewable generation, while at the same time maintaining grid stability and reliability and ensuring overall resiliency in the system. SB 350 does not include in its RPS calculation behind-the-meter generation, which is generation for on-site use for a single building or facility "behind" the customer's meter. Over the past several years, however, behind-the-meter solar photovoltaic (PV) production has grown substantially, both changing load shapes and influencing grid operations.[3]

Recognizing all of this, the California Independent System Operator (ISO), which manages the state's grid, is planning for a 33 percent renewables portfolio by 2020. Its annual transmission plan for 2016–2017 takes particular note of the higher than anticipated development of behind-the-meter solar photovoltaic generation in recent years, which has contributed to changes in some load forecasts, thus requiring the ISO to reevaluate the need for certain previously approved upgrades to the grid that were driven by earlier projections of demand on the system.[4] For example, the ISO's projections now anticipate a later peak hour of demand, and as a result a higher peak, caused by significant behind-the-meter solar generation.[5]

Solar PV generation is a growing part of California's diverse portfolio of energy sources. The US Energy Information Administration's 2015 (most recent) data indicates that California's portfolio has a net summer generation capacity of 74,892 megawatts (MW). Of that total, fossil generation accounts for 42,485 MW and renewables account for 26,181 MW. Of the renewables generation, hydroelectric accounts for 10,186 MW, solar PV for 5,728 MW, wind for 5,727 MW, geothermal for 1,934 MW, biomass for 1,322 MW, and solar thermal for 1,284 MW.[6]

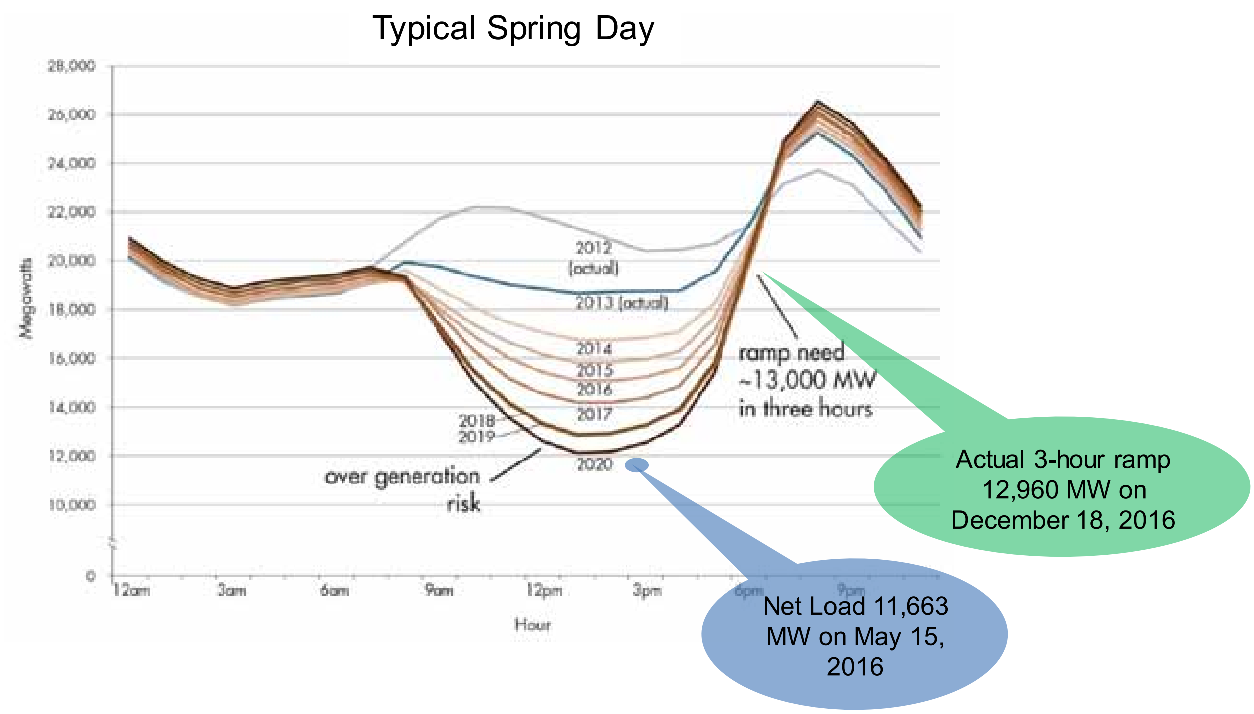
The challenge is that renewable energy sources such as wind and solar are variable, meaning that their output changes with external factors such as weather rather than operators' decisions. Wind turbines may power the grid erratically from minute-to-minute due to wind changes, and solar output can be cut instantaneously due to clouds. Generally speaking, solar production peaks at midday. For its part, wind power tends to peak after midnight, when demand is low. Electricity demand, however, increases around sundown. With solar power not available, non-renewable sources of supply are needed to compensate.

Variable power generation makes it challenging to keep the grid in balance. This is important because supply and demand must be in balance at all times to maintain a constant frequency on the grid, which for the US is 60 Hertz (Hz). Renewable sources, especially PV, can cause that frequency to vary, and significant deviation from 60 Hz can lead to instability and potentially to blackouts.[7] Increasing the contribution of renewables to the grid therefore requires compensating strategies that may include: (1) fast response natural-gas-fired power plants (*peakers*), (2) time-based rates and financial incentives to reduce consumption at peak periods, referred to as *demand response*, and (3) storage to hold energy for dispatch as needed.

Also contributing to California's grid reliability challenge is the scale of traditional base-load generation capacity that is going offline. The retirement of gas-fired plants with once-through cooling systems is pulling a significant source of base-load generation capacity off the grid. At the same time, the early retirement of the San Onofre nuclear power plant in Southern California and the expected retirement of the Diablo Canyon nuclear plant in Northern California by 2025 will remove sizeable sources of base-load, carbon-free generation capacity.

Air quality requirements and climate policy goals are accelerating the drive away from base-load non-renewable generation. An additional factor, which entails significant cost, is that non-renewable thermal generation backup plants must be run continuously, even when not needed, in order to be able to respond quickly to sharp increases in electricity demand in the afternoon hours. The resulting on-off and fast-ramping use of these thermal peaking generators, operating in their least efficient mode, increases air pollution and compromises greenhouse gas reduction goals.

Figure 2: The Duck Curve—Overgeneration in California, 2012–2020

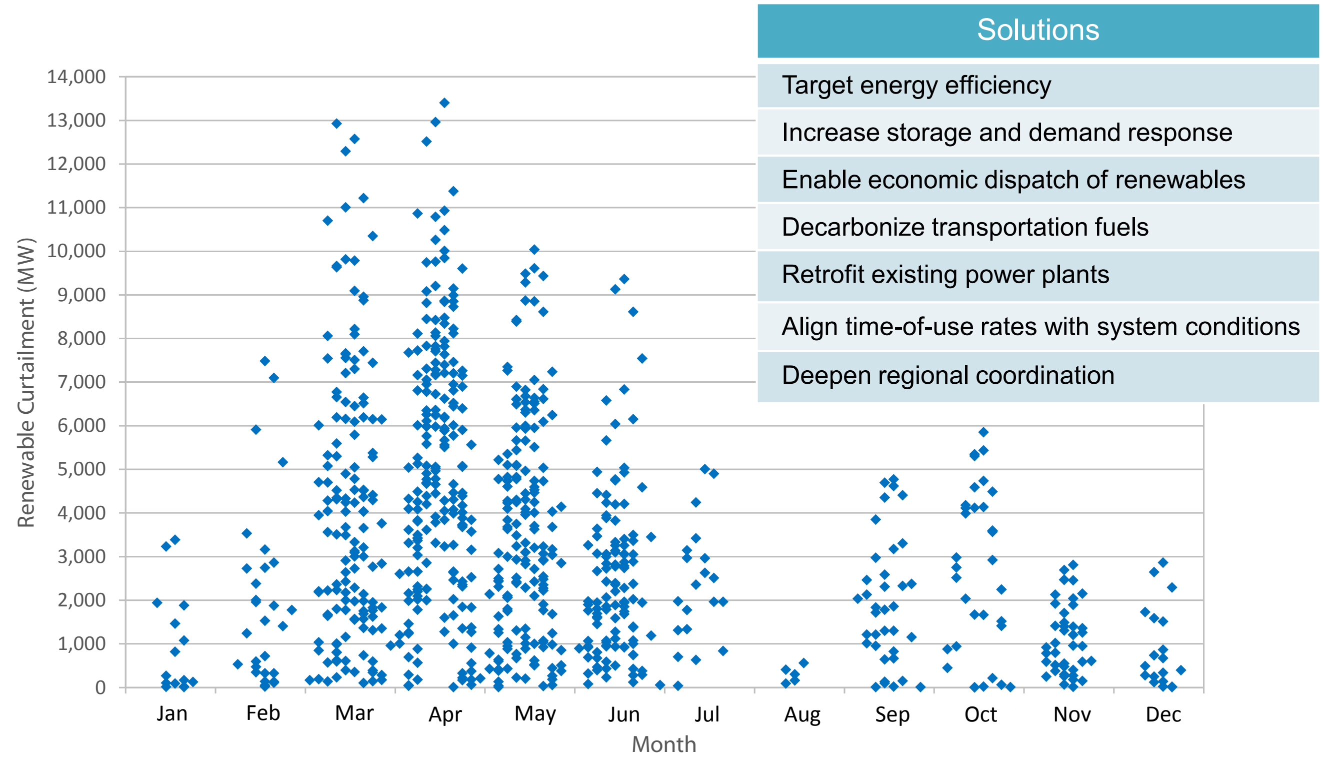


Source: California ISO, *Using Renewables to Operate Low Carbon Grid: Demonstration of Advanced Reliability Services from a Utility-Scale Solar PV Plant*. 2016. <https://www.caiso.com/Documents/UsingRenewablesToOperateLow-CarbonGrid.pdf>

Even as California continues to rely primarily on traditional generation sources such as nuclear and fossil fuels, the proportion of its electricity coming from variable sources such as wind and solar is increasing, and the potential for the grid to be at times affected by *overgeneration* is also increasing. During overgeneration conditions primarily driven by an oversupply of solar, the power being generated is in excess of real-time demand. This leads to what is referred to as the "duck curve" shown in Figure 2, which projects the supply-demand gap produced by variable power. The "belly" of the duck shows lowest net load, when solar generation is highest, followed by the afternoon upward ramp or "neck" of the duck. In the absence of an ability to store that excess energy, overgeneration is currently being addressed by *curtailment*—the purposeful reduction of renewable generation in order to keep the grid stable. This is done by decreasing the output from a wind or solar plant or disconnecting the plant altogether. Curtailment can be done for large renewable power plants but not for smaller or distributed systems like rooftop solar.[8] Curtailment results in the permanent loss of energy as well as the underutilization of the fixed cost component of renewable generation—an undesirable situation for a system in which underlying fixed costs drive the cost of energy.

We are already seeing the "duck curve" materialize. The California ISO has reported that during daytime hours on April 24, 2016, over 2 GW of renewable generation had to be curtailed to maintain reliable operation of the system.[9] And in the spring of 2017, Pacific Gas and Electric (PG&E) experienced negative pricing (indicating a surplus of supply) during the day on weekends. This represents a problematic situation for the state's climate and energy policy, as both the frequency and magnitude of overgeneration events increase with higher RPS goals, and curtailment rises exponentially with an RPS increase from 40 percent to 50 percent. The California ISO's studies also show that forecasted renewables curtailment in California at 40 percent RPS grows to over 13,000 MW (illustrated in Figure 3). In April 2017 alone, California curtailed over 80 gigawatt hours—breaking all previous records.[10]

Figure 3:The California ISO's study projected a large quantity of renewables curtailment in the 40 percent RPS in 2024 scenario.



Source: Liu, Shucheng. "A CASIO Bulk Energy Storage Case Study" (presented at the CPUC/CEC Joint Workshop on Bulk Energy Storage, November 20, 2015). <http://docketpublic.energy.ca.gov/PublicDocuments/15-MISC-05/TN206656_20151117T120924_Bulk_Storage_Workshop__ISO_Presentation.pdf>

In addition to the economic cost of overgeneration, curtailing renewables is counterproductive for meeting California's RPS goals, since it reduces the output from the renewable plants in which the state has invested. Counterintuitively, then, curtailment could drive a need to invest in even more renewable plants, or renewables overbuild, in order to meet the state's RPS goal of 50 percent renewables by 2030.[11] The lost benefit of this curtailed renewable energy production, which the state has invested in and consumers pay for, represents a significant economic cost and limits California's ability to effectively meet its climate and energy targets.

The Emerging Need for Grid-Scale Storage

Energy storage allows excess renewable energy to be retained during periods of low demand and injected back into the grid when needed to meet peak demand. This process is known as *peak-load shifting* and typically occurs over the span of a day.[12] Modern advanced energy storage also provides *ancillary services* that help stabilize the grid at the required 60 Hz frequency by matching supply to demand on a seconds to minutes basis. These ancillary services include voltage support and frequency regulation[13] without which *load shedding*, the intentional power shutdown for affected distribution regions, would be needed to avoid a blackout after the first several seconds of a disturbance or imbalance in the grid. While much of the policy focus in California has been on distributed (smaller-scale) storage, it is clear from the duck curve (Figure 2) and supporting studies that as the state moves toward higher RPS deployment, more comprehensive and larger scale solutions are needed, including bulk or grid-scale storage.

It is important at this point to distinguish between small-scale storage, particularly through emerging technologies, and bulk or grid-scale storage with the capacity to provide high volume response for extended periods. Both are necessary, as localized storage, especially behind-the-meter, addresses localized needs, improves local resilience and reduces the amount of power being drawn from the grid when the ISO needs power. Bulk storage is different in that it addresses large oversupply and ramping needs, principally through pumped storage hydropower.[14] It also potentially includes aggregated battery storage.

Beyond supplying power when needed, storage is a dispatchable resource (i.e., a power system that can be adjusted or turned on and off at will) that has a critical role in providing ancillary services. For example, frequency regulation can be achieved by increasing or decreasing the operating level from a dispatchable resource in order to compensate for a declining or growing contribution from a non-dispatchable resource like wind. Another high value ancillary service provided by storage is *spinning reserve*, which is a power source that can immediately increase output in response to sudden major outages and thus prevent blackouts. Storage can also provide voltage support by absorbing or injecting power to maintain voltage within the required range.[15]

These attributes of energy storage allow non-renewable thermal generation backup plants with their high startup requirements to be operated more efficiently and on an only-as-needed basis. In the absence of storage, these thermal plants essentially need to idle online in readiness for the quick deployment of ancillary services. Modern grid-scale storage can provide nearly seamless inertial response, reducing the need to run these older, carbon-emitting sources of backup generation on standby. The immediate challenge, however, is that it is not yet cost competitive.

It should be noted that renewable power is becoming more dispatchable, as modern solar and wind plants that utilize advanced controls have become better at responding quickly and accurately to dispatch signals from the California ISO. The Northern American Electric Reliability Corporation (NERC) task forces on Integration of Variable Generation and on Essential Reliability Services have developed recommendations for variable power generators (including solar) to provide a share of grid support that includes inertial response, frequency response, and the ramping capabilities that are essential to grid operations. Now, through sophisticated plant-level controllers called PPCs, photovoltaic (PV) power plants can have inverters that provide rapid response to commands from the PPC and can help to mitigate impacts on grid stability and reliability.[16] This rapid response capability can be combined with storage. For example, the 110 MW Crescent Dunes concentrated solar power plant in Nevada uses molten salt to store over 10 hours of electricity, which can be ramped to meet demand. When combined with storage, this kind of ability to provide near-continuous solar power could be transformative for grid operations and stability.[17]

With the state's ambitious goals of 50 percent RPS on the one hand and greenhouse gas emissions reduction to 40 percent below 1990 levels on the other—both by 2030—there is a growing need for cost-competitive storage solutions to enable the continued integration of renewable sources into California's grid and to manage the impact of their variable nature on its reliability and stability.

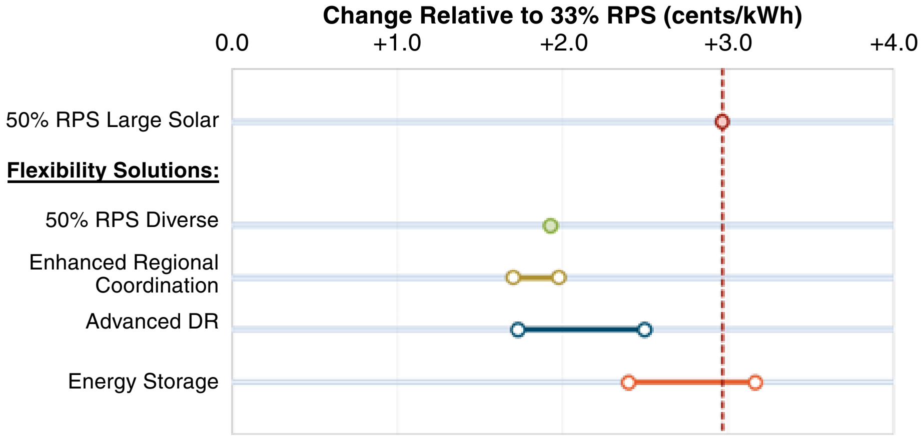
Cost Impacts of Energy Storage and Other Renewables Integration Solutions

The total installed capacity of energy storage in California is currently about 4.2 GW. Of that, pumped storage hydropower makes up the vast majority, about 96 percent,[18] with thermal storage and electrochemical storage (batteries) making up most of the rest. In response to the growing need for storage, Assembly Bill 2514 instructed the California Public Utilities Commission (CPUC) to determine procurement targets for energy storage, split between the state's three investor-owned utilities (Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Edison). In response, the CPUC in 2013 set the target of procuring a total of 1,325 MW of storage by 2020, and the three utilities have made considerable progress in meeting their sub-targets.[19]

Energy storage is one of the categories of solutions available to address the operational and flexibility challenges associated with integrating renewable resources into the grid in order to achieve California's 50 percent RPS goal. In an analysis published in January 2014, Energy and Environmental Economics (E3) reported that their renewable energy flexibility modeling indicated that the largest integration challenge is overgeneration, which is pervasive at RPS levels above 33 percent (where only a small amount of overgeneration is observed). E3's modeling of a 40 percent RPS scenario showed over 5,000 MW of overgeneration, while the modeling of a 50 percent Large Solar Portfolio scenario—relying mostly on large, utility-scale solar PV resources in keeping with current procurement trends—indicated over 20,000 MW of overgeneration. The "default" solution to this problem is curtailment, but implementation of one or more storage, flexible load, or regional coordination solutions could reduce the cost impacts by enabling a larger portion of renewable energy output to be delivered to the grid.

Figure 4 shows E3's estimates of the cost impacts (relative to a 2030 33 percent RPS scenario) of four flexibility solutions (a 50 Percent RPS Diverse Renewables Portfolio, Enhanced Regional Coordination, Advanced Demand Response, and Energy Storage)

Figure 4: Cost impacts of solution cases (assuming 5,000 MW change) under low and high cost ranges, relative to 2030 33 percent RPS scenario (2012 cents/kWh)



Source: Energy and Environmental Economics. *Investigating a Higher Renewables Portfolio Standard in California: Executive Summary*. January 2014. p. 29. <https://www.ethree.com/wp-content/uploads/2017/01/E3_Final_RPS_Report_2014_01_06_ExecutiveSummary-1.pdf>

using as a benchmark the 50 Percent Large Solar Portfolio scenario, with only the default curtailment solution, which is expected to increase average rates by 3 cents per kilowatt hour (kWh). The Diverse scenario reduced the average rate by 1 cent/kWh relative to the benchmark, and the Enhanced Regional Coordination and Advanced Demand Response solutions showed cost savings as well, even at the high ends of their ranges. Only the battery storage case at the high end of the Energy Storage scenario resulted in higher costs, and the low end of the Energy Storage range, which was modeled as 5,000 MW of low-cost pumped storage, was estimated to reduce the total cost of achieving the 50 Percent RPS Large Solar scenario by just over 0.5 cents/kWh.[20] Thus, while battery storage relies on still improving technology and is increasingly feasible as an option, proven sources of bulk storage can potentially provide greater economic value in the current environment.

E3's studies show that to achieve the 50 percent RPS scenario—with the default of curtailing renewables—average electricity rates will increase by 14 percent, or 3 cents/kWh, relative to the 33 percent RPS scenario. While wind and solar are projected to reach the same *levelized cost of electricity* (LCOE)[21]—or unit cost of electricity over their lifetime—as conventional resources,[22] overgeneration and other integration challenges may lead to further and significant upward impact on rates.

The more recent Low Carbon Grid Study published by the National Renewable Energy Laboratory (NREL) in January 2016, shows that California can achieve a low-carbon grid under a variety of scenarios. The most effective scenario for reducing costs, carbon emissions, and curtailment is "enhanced operational flexibility." In comparison to the "conventional flexibility" scenario, the enhanced scenario entails adding to the existing storage and 1.5 GW of mandated battery storage another 1 GW of new pumped hydropower plus another 1.2 GW of new out-of-state compressed air energy storage (for a total addition of 2.2 GW of storage). The enhanced flexibility scenario would require removal of institutional barriers to allow for the inter-state import and export of power, removal of minimum local generation requirements, and removal of limitations on ancillary services provision for hydropower and pumped storage. In comparison to conventional flexibility, operational costs under this enhanced scenario are reduced by up to $800 million, carbon emissions are 14 percent lower, and curtailment is kept under 1 percent. The conventional flexibility scenario, on the other hand, which includes just the 1.5 GW of mandated battery storage, leads to higher costs, higher emissions, and up to 10 percent curtailment.[23]

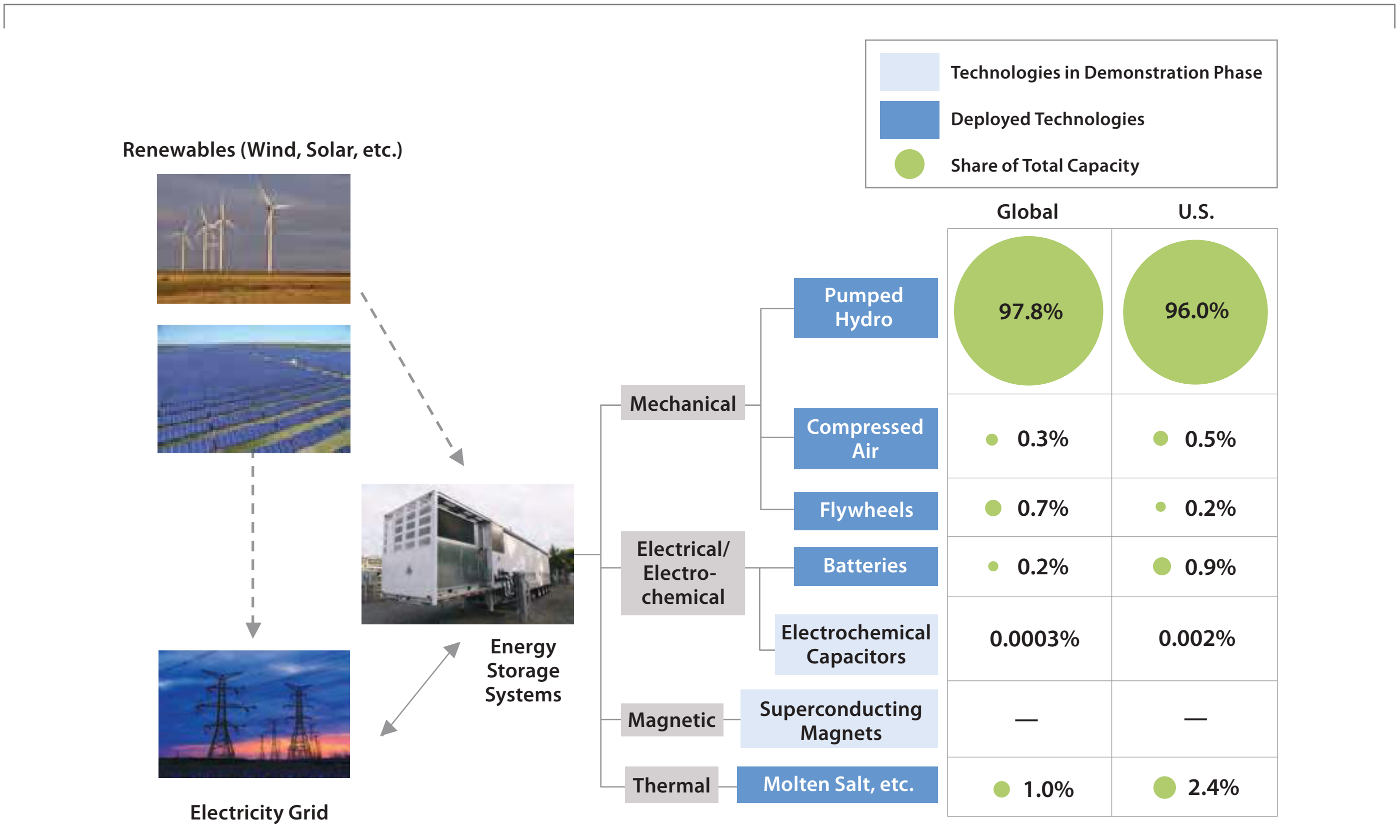
Energy Storage Technologies

The range of available energy storage solutions includes systems at various stages of development. These technologies include advanced pumped hydropower, electrochemical (batteries), compressed air, flywheel, and thermal storage. The following sections briefly describe these technologies, focusing on grid-scale applications. Figure 5 shows the US and global capacities of various storage systems.

Pumped Storage Hydropower

The most widely used form of energy storage is pumped storage hydropower, with 98 percent of installed storage capacity globally and 96 percent of installed capacity in the US. As shown in Figure 6, pumped storage facilities consist of two reservoirs, an upper and a lower. During periods of low demand, water is pumped to the upper reservoir and stored as potential energy to be released to the lower reservoir through a turbine for electricity generation during periods of peak demand. The US has a total of about 20 GW of conventional pumped storage hydropower spread across more than 40 facilities (see Figure 7), most of which entered service in the 1970s.[24] For bulk or grid-scale power management applications, pumped storage is widely considered to be the most demonstrated and most economic technology,[25] with the capacity to provide over a gigawatt of power over durations of 12 hours or more.

Figure 5: Total Capacity of Energy Storage Systems, US and Global



	Global	U.S.
Pumped Hydro	97.8%	96.0%
Compressed Air	0.3%	0.5%
Flywheels	0.7%	0.2%
Batteries	0.2%	0.9%
Electrochemical Capacitors	0.0003%	0.002%
Superconducting Magnets	—	—
Molten Salt, etc.	1.0%	2.4%

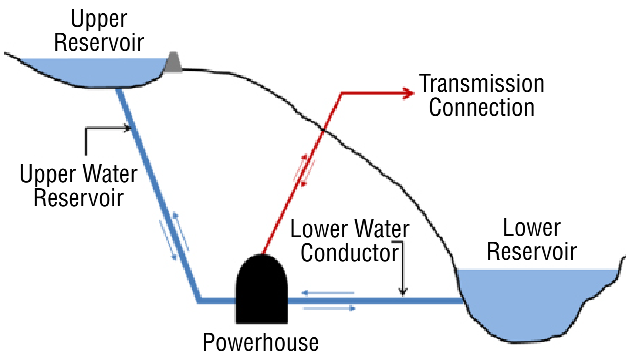
Total worldwide operational capacity: 145.3 GW
Total U.S. operational capacity: 21.2 GW

Source: MIT Energy Initiative. *The Future of Solar Energy: An Interdisciplinary MIT Study, Appendix C – Energy Storage Systems for the Electric Power Sector*. 2015. p. 289. <https://energy.mit.edu/wp-content/uploads/2015/05/MITEI-The-Future-of-Solar-Energy.pdf>

Technological innovations have dramatically improved the performance and efficiency of pumped storage resources internationally, but none of the advanced forms have been built in the US yet. There are several closed-loop (i.e., off-stream with significantly reduced environmental impact) advanced pumped storage projects proposed in the US, their main distinguishing feature being the ability to adjust the speed of the pump/turbine (conventional pumped storage uses fixed-speed turbines) and move more quickly from pumping to generating, thus enabling a much quicker response to grid disturbances.

The interplay between renewables and pumped storage can be seen in Northern Europe. Norway, which is home to half the hydro storage capacity in Europe, exchanges energy with Denmark through high-voltage DC interconnectors. Denmark's growing reliance on variable wind energy, and its reduced generation from coal, have increased the need to export excess electricity during peak generation times and to tap into Norwegian hydropower at other times. In effect, the availability of pumped storage from Norway allows Denmark to be on track to meet its high RPS of 100 percent by 2050. Already, on some days, Denmark is able to meet its electricity demands entirely from renewables. As renewables continue to grow in Northern Europe, so will the need for storage, with the Center for Environmental Design of Renewable Energy forecasting a "big storage" scenario in which Norway—with additional interconnections to the UK and Germany—serves as the "green battery" of Europe.[26]

Figure 6: Typical Pumped Storage Configuration



Source: Argonne National Laboratory. *Modeling and Analysis of Value of Advanced Pumped Storage Hydroelectricity in the United States*. June 2014. <https://energyexemplar.com/wp-content/uploads/2014/08/ANL-DIS-14-7_Advanced_PSH_Final_Report.pdf>

Figure 7: Existing Pumped Storage Facilities in the United States

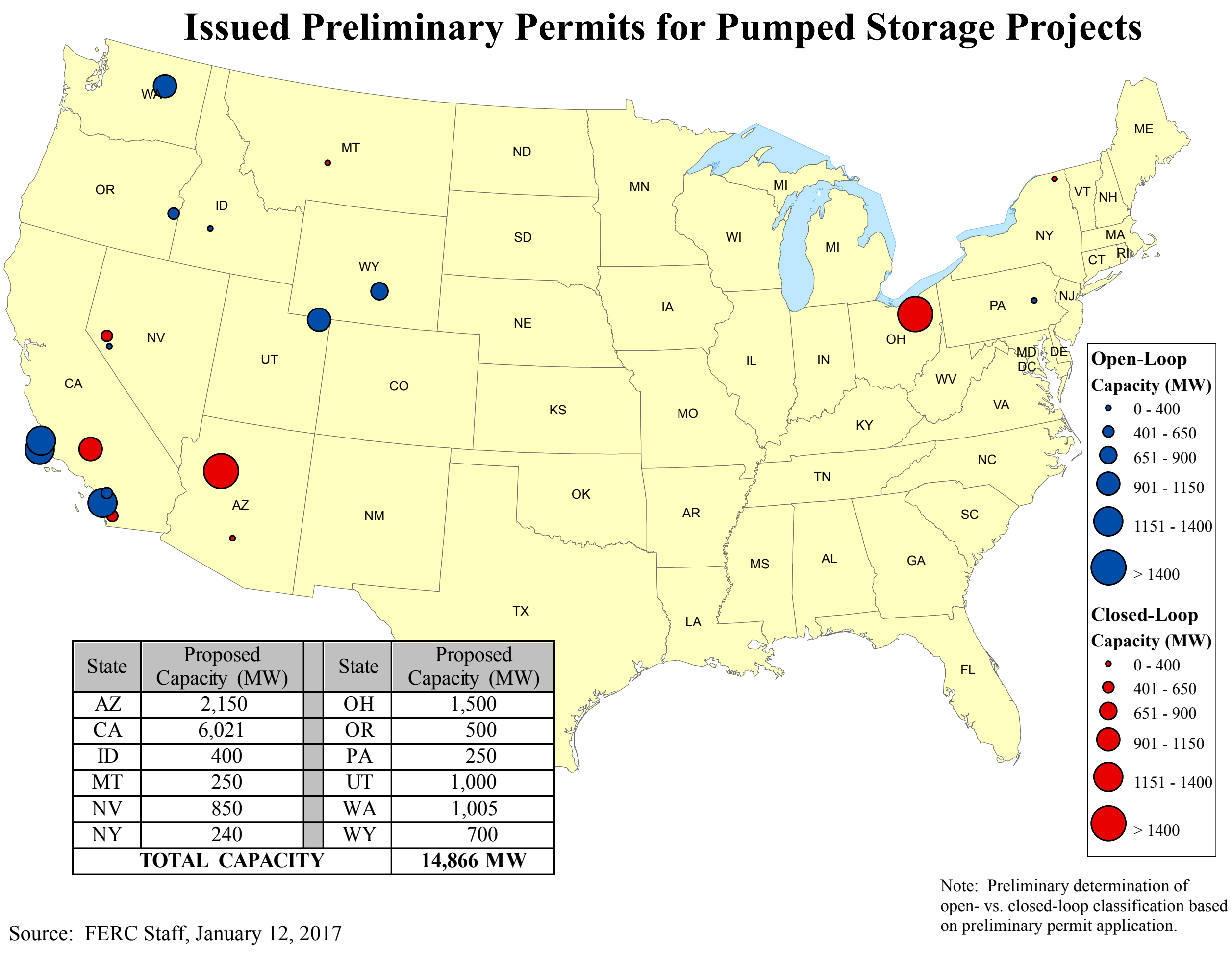
Source: Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest (Prepared by MWH for the USACE HDC, August 2009)

Pumped storage development in the US is most challenged by extraordinarily long and uncertain regulatory, environmental, and permitting lead times. It is also limited by the scarcity of suitable sites that allow for the location of two reservoirs with a large elevation difference and limited horizontal offset. These projects also carry significant construction risk associated with tunneling and may be vulnerable to uncertain water supply. There are currently six proposed advanced pumped storage hydro projects in California at various stages in the permitting process. Figure 8 shows pumped storage projects in the US that have obtained preliminary permits.

Compressed Air

Compressed air energy storage (CAES)—which works by compressing ambient air, storing it in an underground cavern, and then, when electricity is required, heating and expanding the pressurized air to run gas-fired turbine-generators (see Figure 9)—offers another potential storage solution. There are currently two operating utility-scale CAES facilities: one in Huntorf, Germany and one in McIntosh, Alabama.[27] The 110 MW McIntosh plant can run up to 26 hours at full capacity, stores the compressed air in a salt cavern, and utilizes a recuperator to reuse exhaust heat energy, thus

Figure 8: Issued Preliminary Permits for Pumped Storage Projects



State	Proposed Capacity (MW)	State	Proposed Capacity (MW)
AZ	2,150	OH	1,500
CA	6,021	OR	500
ID	400	PA	250
MT	250	UT	1,000
NV	850	WA	1,005
NY	240	WY	700
TOTAL CAPACITY			14,866 MW

Note: Preliminary determination of open- vs. closed-loop classification based on preliminary permit application.

Source: FERC Staff, January 12, 2017

Source: Federal Energy Regulatory Commission. "Issued Preliminary Permits for Pumped Storage Projects." January 12, 2017. <https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage/issued-permits.pdf>

reducing fuel consumption and increasing efficiency.[28] The advantages of CAES are that it can be used for bulk storage and has a long lifecycle, large capacity, and reasonably high efficiency. It also has a low levelized cost of electricity, comparable to pumped storage. Its main restriction is the availability of geographic locations with the necessary geologic formations (typically salt caverns). Pacific Gas and Electric has conducted a feasibility study to demonstrate the viability of CAES in a porous rock formation, specifically a depleted gas reservoir in San Joaquin County[29] (instead of a salt cavern), and they are exploring third-party offers to develop CAES projects in the future.[30] While compressed air storage has potential, particularly as more viable siting options are identified, it remains far from market scale.

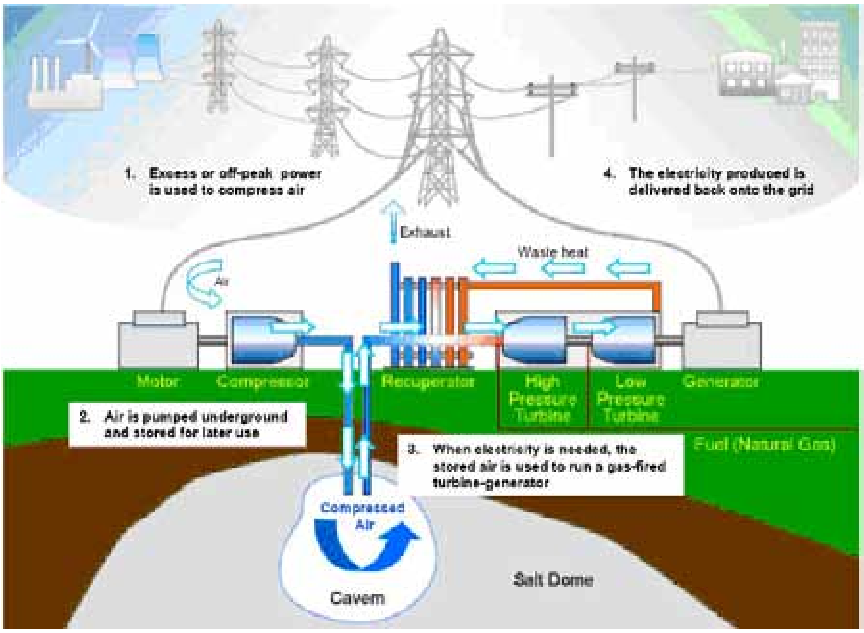
Battery Systems

Batteries store energy electrochemically through reversible chemical reactions and offer the most versatility in terms of potential services. Battery energy storage systems (BESS) costs have fallen significantly over the last five years and lithium-ion battery pack costs are projected to decrease by as much as 50 percent in the near future,[31] primarily as a result of developments in the electric vehicle industry, vertical integration, and economies of scale. Tesla, for example, estimates that one-third of the battery cells produced at its Gigafactory in Nevada will be used in stationary storage rather than cars.[32]

Due to a range of economic and technical challenges, including uncertainty surrounding cycle life and performance, safety, scalability and disposal, battery storage currently accounts for less than 2 percent of energy storage capacity in the US.[33] This will increase, however. According to Lux Research, although the market for stationary battery storage is still small, since 2011 the deployment of lithium-ion systems has grown at a compound annual rate (CAGR) of over 50 percent.[34]

The most widely used energy storage battery technology is *lithium-ion* (see Figure 10). Deployed extensively in electronics and electric vehicles, lithium-ion batteries have high efficiency and rapid response times, and can be installed comparatively quickly. PG&E's new Browns Valley substation in Yuba County includes 22 of Tesla's

Figure 9: Compressed Air Energy Storage Schematic



Source: Ridge Energy Storage & Grid Services. The Economic Impact of CAES on Wind in TX, OK, and NM. June 27, 2005. <http://www.ridgeenergystorage.com/re_wind_projects-compressed2005.pdf>

Powerpack batteries, which together can store half a megawatt of electricity and discharge at full power for four hours. Other facilities using Tesla batteries have recently opened in San Bernardino County (Southern California Edison) and Hawaii.[35]

Batteries are currently used for both distributed and bulk storage. Some lithium-ion technologies are modular and can stack-up to reach grid-scale, but at present only up to a limit and generally for durations of about 4 hours. Widely distributed batteries can also be aggregated to achieve grid-scale. Stem, for example, is a company that aggregates behind-the-meter storage and uses software to combine batteries into a fleet that can act like a "virtual power plant." They contract with utilities to provide grid services, bidding into the ISO's demand response auction mechanism on a day-ahead and real-time basis.[36] Because batteries are still expensive, Stem takes advantage of incentives like the CPUC's Self-Generation Incentive Program (R.12-11-005). There is a challenge, though, as storage assets have a non-exporting interconnection (R.11-09-011 Interconnection Rules and Regulations) and are not allowed to export to the grid in the same way as solar. Aggregators are also not incentivized to be charging up during times of excess capacity, or at the "belly" of the duck curve.

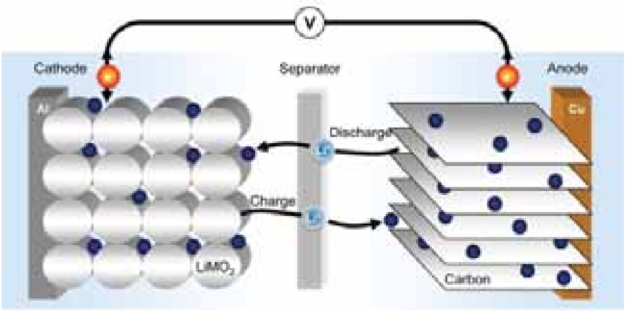
Lithium-ion batteries also have limitations, principally because the materials used to store the energy are expensive and the technology is more difficult to scale. The need for long-duration storage is another issue, particularly when the sun may not shine or the wind may not blow for several days in succession, and the need to draw on storage for longer periods of time correspondingly increases.

Another electrochemical technology for utility-scale storage is *flow batteries*, which store energy in electroactive solutions.[37] Flow batteries offer advantages in terms of longer duration, longer cycle life, improved safety due to the non-flammable, non-toxic nature of the materials used, and potentially larger scale. Flow batteries, however, are still largely at the demonstration stage of technological development and prices remain high.

One close-to-market battery technology for grid-scale application is *sodium sulfur*. Reliability and safety issues, however, remain a challenge,[38] a concern highlighted when NGK Energy Storage's sodium sulfur batteries caught fire in 2011.[39]

Lead-acid batteries are slightly more expensive than sodium sulfur batteries, with higher life cycle cost. The main disadvantage of lead-acid is lower energy density and limited cycle life.

Figure 10: Lithium-Ion Battery Schematic

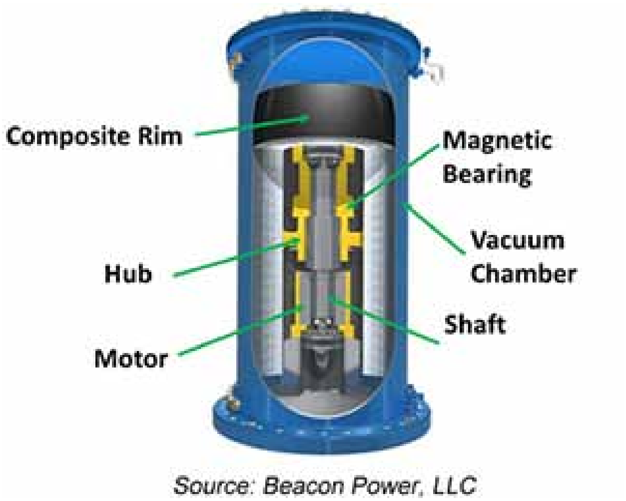


Source: "Correlative Light and Electron Microscopy (CLEM) for Battery Analysis." March 6, 2016. AZO Materials. <https://www.azom.com/article.aspx?ArticleID=8229>

Flywheels

Flywheel energy systems store rotational kinetic energy by using electric energy input to spin a rotor in a near-frictionless magnetic enclosure (see Figure 11).[40] Flywheels are best suited for applications that require high power and fast response times but are not as suitable for bulk energy storage, where technologies such as pumped storage or compressed air are more cost-competitive.[41] Flywheels have a long lifetime, making them cost competitive for higher value services such as frequency regulation.

Figure 11: Flywheel Schematic



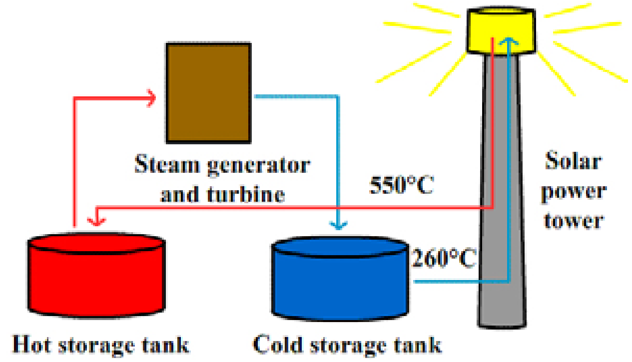
Source: Beacon Power, LLC as reprinted in "Flywheels." N.d. Energy Storage Association. <http://energystorage.org/energy-storage/technologies/flywheels>

Thermal

Thermal energy storage relies on the heating or cooling of a storage medium (see Figure 12). Thermal energy can be stored at temperatures from less than 40°C to over 400°C as sensible heat, latent heat, or as chemical energy using chemical reactions. *Sensible heat* storage is based on storing thermal energy by heating or cooling a liquid or solid, usually water, sands, molten salts, and concrete. *Latent heat* storage uses phase change materials, such as ice transitioning from solid state into liquid state. Ice Energy, for example, offers a battery that charges by making ice during off-peak hours and discharges by using the ice to cool buildings during peak hours. The company reports that this can reduce peak cooling electricity use by 95 percent for up to 6 hours,[42] and can provide permanent load reduction to the utility and/or the end use customer.[43] *Thermo-chemical* storage uses chemical reactions to store and release thermal energy[44] in, for example, methane steam reforming or ammonia dissociation.

Thermal energy storage is considered a flexible load solution rather than a storage solution and is typically associated with concentrated solar plants, accounting for 10–20 percent of total plant costs depending on the hours of thermal storage.[45]

Figure 12: Thermal Storage Example—Solar

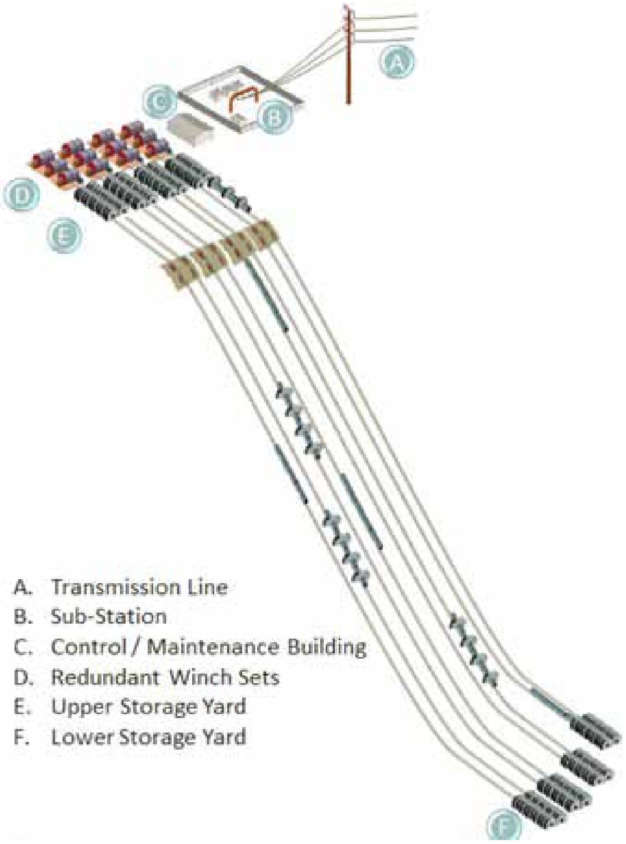


Source: Resolve Solar <https://www.revolvesolar.com/wp-content/uploads/2016/04/solar-thermal-diagram.gif>

Rail Based Energy Storage

The California-based Advanced Rail Energy Storage company is using excess renewable energy to power small locomotives and rail cars to push heavy concrete blocks to the top of an incline on a rail line; to release the energy, the trains roll back down the slope under the influence of gravity, generating power through their regenerative braking systems (see Figure 13). After a demonstration project with Tehachapi Mountain Energy, the first commercial facility, a 50 MW project located in Nevada, is expected to come on-line in September 2019.[46] First developed in 2010, advanced rail is in its very early stages. It is reported to provide long duration (8+ hours) of storage, round trip efficiency of over 80 percent, and levelized cost comparable to pumped storage. Its principal challenges have to do with price uncertainty and technology adoption.

Figure 13: Advanced Rail Energy Storage Schematic



Source: Advanced Rail Energy Storage. "Challenges of Storage Development—Advanced Rail Energy Storage (ARES)." (slide presentation at the Bulk Storage Conference, Sacramento, November 20, 2015) <http://slideplayer.com/slide/9319746/>

Regulatory Framework and Challenges to Energy Storage

As California moves toward more aggressive renewable energy goals and faces increasing integration challenges, a mix of bulk storage and distributed storage will be needed. This is likely to be combined with strategies such as the regional integration of the Western states grid and economic solutions like demand response. Storage also offers a reliability solution to the anticipated loss of non-intermittent conventional energy sources.

While there is value across the spectrum of the storage technologies described with regard to bulk or grid-scale storage, pumped storage is currently the most globally and domestically prevalent storage technology, with demonstrated long-term capabilities and low cycle life cost. As technology advances and costs continue to fall, the contribution of other technologies—particularly batteries—will grow. Whatever strategies are adopted, if it is going to meet its storage, energy, and climate goals, it is important for California to develop and enable a diverse portfolio of sources and to do so in a way that benefits consumers.

Already, existing traditional pumped storage plants are being used for voltage support and some grid reliability services. For example, Pacific Gas and Electric reports a dramatic shift in its utilization of the Helms pumped storage plant (built in 1984) over the past 3 years. On an example July day in 2015, Helms was used to address overgeneration on the order of 300 MW.[47] Similarly, the Los Angeles Department of Water and Power has utilized the Castaic pumped storage plant (built in 1978) for regulation, voltage support, and spin and non-spin reserves, and has noted the potential of advanced (variable speed) pumped storage for Southern California.[48] Ancillary services therefore factor significantly into future economic scenarios for pumped storage.

Advanced pumped storage has not yet been implemented in the US for a range of reasons, including development challenges. The lack of a defined market and a procurement framework that accurately values and pays for the ancillary services provided by storage is a particularly significant challenge. This uncertainty surrounding projected revenue, combined with protracted and complex regulatory and permitting processes, requires extreme patience and robust capitalization from would-be developers, public or private. However, advanced pumped storage is likely to compete favorably in the California ISO's Transmission Planning and the CPUC's Integrated Resource Plan (IRP) (R.16-02-007), an evolution of the Long Term Procurement Proceeding (LTPP) (R.13-12-010), to provide the long duration, high value, quick response storage and sub-hourly ancillary services needed as more renewables are brought online.

To date, California's energy storage procurement mandates have favored the deployment of technologies with shorter lead times and milder permitting and regulatory requirements over other bulk storage. The CPUC's mandated storage procurement for its three IOUs (investor-owned utilities Pacific Gas and Electric, Southern California Edison, and San Diego Gas and Electric) has focused on emerging technologies—primarily batteries—and has capped capacity at 50 MW. This setting has comparatively disadvantaged long-term bulk storage solutions such as pumped hydro and compressed air in utility storage procurement.

There is a balance between long-term storage at scale and capacity that can be brought on quickly and in smaller quantities. In 2016, Governor Brown proclaimed a state of emergency in response to the reduced gas supplies in the Los Angeles Basin associated with a natural gas leak and partial shutdown at the Aliso Canyon Natural Gas Storage Facility. This resulted in an emergency energy storage procurement mandate by the California Public Utilities Commission, in which the Commission required Southern California Edison to hold an expedited competitive energy procurement solicitation for over 100 MW to alleviate an outage risk due to the moratorium on natural gas injections into the Aliso Canyon facility. The Commission identified storage systems as a potential solution because they could be "fast-responding, firm, and dispatchable" and could help alleviate reliability risks due to the limited availability of gas supplies.[49] Less than 6 months after the emergency tender was issued, a total of 70 MW of battery storage was brought online: 30 MW by AES Energy Storage, 20 MW by Tesla, and 20 MW by Greensmith Energy.[50]

These issues are on the table in the Legislature and at the CPUC. Assembly Bill 33, approved by Governor Brown in September 2016, gives the CPUC authority to evaluate options and determine targets for long-duration bulk energy storage resource procurement for each load-serving entity, to be achieved by December 31, 2020. The Integrated Resource Plan explicitly includes all load-serving entities (LSEs) including electric service providers, community choice aggregators,[51] and small and multi-jurisdictional utilities. The CPUC's Rulemaking to develop an Integrated Resource Planning Framework (R.16-02-007) in 2016 pointed to a need to evaluate approaches to the procurement of resources that have very long lead times, such as pumped storage or transmission interconnections to other states in the West.[52] Some market participants expressed concern that the IRP implementation process is taking too long, leaving behind projects deemed infeasible under near-term conditions.

Parallel with this, the California ISO's *2016–2017 Transmission Plan* explored the locational benefits of proposed large-scale pumped storage and evaluated two potential new bulk energy storage resources—one for 500 MW and another 1,400 MW—concluding that new pumped storage brought significant system-wide benefits, including reduced CO_2 emissions, reduced renewables curtailment, and reduced need for renewables overbuild to meet the 50 percent RPS target. The study also found, however, that the net market revenue of the pumped storage resources would provide only a portion of the projects' levelized annual revenue requirements, and that developing those pumped storage resources "would need other sources of revenue streams, which could be developed through policy decisions."[53]

This points to a primary obstacle to energy storage, particularly at grid scale, which is the regulatory uncertainty around cost recovery for the myriad ancillary services that storage provides, such as frequency regulation. A 2015 Rocky Mountain Institute study of *The Economics of Battery Energy Storage* identifies 13 services, provided by battery-based energy storage to three distinct stakeholder segments, that could potentially be compensated through different revenue streams.[54]

One encouraging aspect of the Aliso-Canyon-driven storage mandate discussed above is the precedent it sets for storage facility cost recovery. The CPUC explicitly recognized in that mandate that the grid reliability provided by a storage facility benefits all grid users, not just those in the affected IOU's service territory. This approach is significant, in that it results in the use of a payment cost allocation mechanism that spreads the facility's cost more affordably and less contentiously over the entire ISO footprint of ratepayers. This assures the purchasing IOU that the cost of its storage procurement won't negatively affect its rates relative to other service providers.

The complexity of defining value and compensation for ancillary services is considerable. The California ISO administers formal markets for ancillary services on a day-ahead, an hour-ahead, and a real-time basis. In doing so, it is implementing FERC Orders 755 and 784 that require regional transmission organizations (RTOs) and independent system operators (ISOs) to compensate for "fast" responding sources like batteries or flywheels that are bidding into the markets. The payment is based on the actual service provided, including a capacity payment that includes the marginal unit's opportunity costs and a payment for performance that reflects the quantity of service provided (such as frequency regulation) following the dispatch signal.[55] The ancillary services for which the California ISO currently has markets are regulation-up, regulation-down, spinning reserves, and non-spinning reserves.[56]

The present challenge is that the ancillary services that storage provides are not bought and sold on a *capacity* basis, the way that peaking capacity is purchased.

This impacts the willingness of banks to lend for storage projects, restricting the cash flow needed to service debt, and thus slowing the deployment of storage and the development of a storage market. Furthermore, with low gas prices and an established market for independent power producers, natural gas combined-cycle plants provide a low-cost alternative that makes it challenging for utilities to implement rate changes to procure bulk storage. The development of a storage market and the more rapid deployment of storage would be greatly enabled by a regulatory strategy that enables utilities to spread the cost of ancillary services to the grid across all ratepayers in the state, treating storage capacity as a system-wide asset that benefits multiple users and the ISO, and expanding cost recovery beyond the specific asset.

The agencies represented in the Energy Principals Group (the California Air Resources Board, the California Energy Commission, the California PUC, the California ISO, the State Water Resources Control Board, and the Governor's Office) should collaborate to specifically address the barriers of lead times and of environmental, regulatory and permitting risk that prevent pumped and other bulk storage facilities from advancing. While challenging, success in streamlining the California Environmental Quality Act (CEQA), the National Environmental Policy Act (NEPA), and water quality permitting processes on the one hand, while working with the Federal Energy Regulatory Commission (FERC) to reduce delays and improve hydro licensing on the other, would significantly improve the prospects for pumped storage in California. FERC's current licensing process is complex and extremely slow (taking 3 to 5 years for new pumped hydro licenses pre-construction),[57]—constituting perhaps the largest barrier to pumped hydropower storage in the US—and must be streamlined. Recent policy developments such as House Resolutions 1967 and 2880 attempt to stimulate development of pumped storage. HR 2880 encourages an alternative licensing and permitting approach for closed-loop pump storage sites,[58] and HR 1967 modifies the existing Reclamation Project Act by opening Bureau of Reclamation facilities to non-federal pumped storage development.[59]

The viability of future projects and of projects currently in the pipeline will be impacted by how these issues are addressed. This includes the San Diego County Water Authority-issued Request for Proposals for a 500 MW closed-loop pumped storage project at the existing San Vicente Reservoir, owned by the City of San Diego. The project is to provide 500 MW of renewable energy and 5–8 hours of energy storage and the proposals were due in September 2017.[60]

Recommendations

The California ISO and the CPUC have a number of options that can help to establish the necessary conditions for increased investment in bulk energy storage. These apply most immediately to pumped storage but could also apply to any of the technologies discussed above that have the potential to provide bulk storage at competitive prices.

The immediate challenge is to create a marketplace for storage and a valuation methodology that enables energy and storage providers to plan for and meet grid needs with a clear cost recovery path. There is also a need to implement bulk storage procurement through a mechanism that is technology-neutral and competitive.

This report makes two main recommendations:

I. Establish cost recovery for ancillary services that reflects the full range of services being offered by advanced energy storage.

The procurement mechanism should value and compensate the ancillary services that advanced energy storage can provide. Reflecting systemic benefits to the grid, the costs of storage procurement by utilities should be able to be spread beyond their immediate service areas to benefiting customers across the state. Its valuation should also reflect the integration of renewables and reductions in greenhouse gas emissions.

This procurement mechanism would advance investment in storage by more comprehensively recognizing the value provided to the grid by storage capacity.

II. With the growth of behind-the-meter storage, more of that capacity should be dispatchable. Policymakers should focus on facilitating and encouraging both the aggregation and the dispatch of these resources to meet grid-scale needs.

In addition to its main recommendations on bulk storage, this report makes recommendations to address further issues in the move towards a balanced low-carbon grid in California:

III. Improve and streamline bidding into the market in a way that is technology-neutral. Aliso Canyon demonstrated that fast track deployment is possible, but it should be applied to the range of energy storage solutions. For example, allow faster permitting for the development of a range of bulk storage technologies, including ones with longer lead times such as pumped storage.

IV. Implement appropriate rate structuring to encourage storage to absorb renewable overgeneration and reduce curtailment. This could include incentivizing storage assets to be charging up during the "belly" of the duck curve when solar generation is highest and net load is lowest.

V. Modernize grid operations and management, particularly for distributed sources, and utilize software tools and platforms for decision making to optimally manage and dispatch various advanced energy storage resources. Bulk storage would not require as sophisticated controls, but the overall utilization of storage resources would benefit from drawing upon advancements in artificial intelligence and tools for decision making under uncertain conditions.

VI. Authorize load-serving entities to pre-pay to own storage infrastructure at completion or at close of long term (30-year) concession agreements with private partners, with rate-based recovery included. A private partner could finance and deliver the facility to a load-serving entity owner in return for a capital charge and a service agreement to operate the facility, with performance guarantees by the private sector partner. Public-private partnerships of this kind have the potential to inject more investment capital into storage and help accelerate deployment. The state can also enhance the financial viability of storage assets by providing credit support, in which the state can act as an underwriter or reinsurer of storage-related debt, or the tax code could be amended to allow for accelerated depreciation of the storage asset, which would increase the investor's rate of return.

Conclusions

This report aims to contributes to the discussion around bulk or grid-scale storage. There is broad agreement that bulk storage will play a key role in California's energy storage portfolio and overall grid management strategy. But there is a lack of clarity about the amount of bulk storage needed and how best to support the range of options to meet those needs.

The need for energy storage and the energy storage market are growing rapidly as renewable generation, energy policies, and greenhouse gas reduction goals impact how the grid needs to be managed. Storage offers a clear solution, allowing excess renewable energy to be stored, not curtailed, during times of overgeneration, and then released to meet demand and ramping needs. It also provides important ancillary services that help to stabilize the grid. While uncertainty remains around contract structures and mechanisms to recognize the full value offered by advanced energy storage technologies, promising market opportunities are emerging that are financeable.

Policy shifts towards longer-term procurement, longer contracts, and bulk storage procurement mandates make technologies like advanced pumped storage and compressed air energy storage attractive. While no *advanced* pumped storage projects have been built in the US, many have been proposed, particularly in California. The recent Request for Proposals for the 500 MW San Vicente closed-loop pumped storage project in San Diego is a positive indication. Pumped storage remains the most installed storage solution globally at the largest demonstrated scale among existing energy storage solutions, and it can grow in California if cost recovery mechanisms and regulatory uncertainty are resolved.

Cost reductions and technological advancements are bringing electrochemical storage, such as lithium-ion batteries and flow batteries, more prominently into the mix of technologies available for bulk applications. With speed to deployment an advantage, battery storage can significantly increase its contribution as well, particularly if ways can be found to aggregate and dispatch production from behind-the-meter renewable sources.

With a suite of technologies available, the issue now is how to accelerate deployment by making storage of all kinds more attractive for investment.

With slow and complex permitting for pumped storage, and an assumption that battery costs will continue to fall, utilities are primarily investing in small-scale projects. While this approach is understandable, policy should focus on strategies with the long-term potential to deliver bulk storage capacity. This is essential if California is to secure the full benefit of the renewable resources it has invested in, and to meet its climate and energy goals, without excessively burdening ratepayers.

APPENDIX A

Interviews and Informational Support

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Paul Smerchanski, Energy Storage and Business Development, Recurrent Energy

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Todd Strauss, Senior Director, Grid Strategy and Analytics, Pacific Gas and Electric Company

Ben Tarbell, Energy Principal, Foundry Team, X (formerly Google X)

Brittany Westlake, Engineer/Scientist, Electric Power Research Institute (EPRI)

Mason Willrich, Independent Energy Consultant, Author of *Modernizing America's Electricity Infrastructure*, and Former Chair of the Board of Governors of the California Independent System Operator

Marcus Woodson, Government Relations Officer, Sandia National Laboratories

Appendix B

California Public Utilities Commission Proceedings[61]

Rulemaking 10-12-007: to set a policy for California's utilities and load-serving entities to procure energy storage systems

Energy Storage Compliance Decision 14-10-045 and Energy Storage Procurement Framework and Design Program 13-10-040: approve the three IOUs energy storage procurement proposals for the period 2014-2016

Rulemaking 15-03-011: refinements to the Energy Storage procurement framework and design program

Rulemaking 11-09-011: Rule 21 Interconnection Rule and Regulations Proceeding to facilitate the interconnection of new facilities to the grid

Rulemaking 16-02-007: 2016 Rulemaking to develop an Integrated Resource Plan, superseding the 2014 Long-Term Procurement Proceeding (R.13-12-010)

Rulemaking 12-11-005: the 2012 California Solar Initiative and the Self-Generation Incentive Program

The CPUC has also established the Distributed Energy Resources Action Plan, a roadmap that aims to align the development and implementation of policies related to distributed energy resources, including distributed energy storage.

Appendix C

Legislation Overview

The following is a summary of legislation related to energy storage.

Assembly Bill 33: Electrical corporations: energy storage systems: long duration bulk energy storage resources. Introduced by Assembly Member Quirk. Signed into law September 26, 2016. Required the PUC to evaluate the potential for all types of long-duration bulk energy storage, to help integrate renewable generation into to grid. Section 1d states: "Long duration bulk energy storage and pumped hydroelectric storage, in particular, when constructed in a sufficiently large scale, possesses the characteristics to meet our electrical grid's need for rapid ramping capability and the capacity to utilize over-generation from renewable energy resources."

Assembly Bill 2868: Energy storage. Introduced by Assembly Member Gatto. Approved September 26, 2016. Requires IOUs to file applications with the CPUC for programs and investments to accelerate widespread deployment of distributed energy storage systems with a total capacity not to exceed 500 MW (divided equally among the state's three largest electrical corporations), 125 MW of which can be behind-the-meter distributed storage.

Assembly Bill 2861: Electricity distribution grid interconnection dispute resolution process. Introduced by Assembly Member Ting. Signed into law September 26, 2016. Authorized the CPUC to expedite dispute resolution (within 60 days) for grid interconnection, streamlining the interconnection of generation and storage facilities.

Assembly Bill 1637: Energy: greenhouse gas reduction. Introduced by Assembly Member Low. Signed into law September 26, 2016. Doubled the annual budget amount authorized in 2008 for the self-generation incentive program (SGIP) for distributed generation resources and energy storage.

Assembly Bill 398: California Global Warming Solutions Act of 2006: market-based compliance mechanisms: fire prevention fees: sales and use tax manufacturing exemption. Introduced by Assembly Member Eduardo Garcia. Signed into law July 25, 2017. This bill to extend cap-and-trade bill added a use tax exemption for storage.

Assembly Bill 914: Transmission planning: energy storage and demand response. Introduced by Assembly Member Mullin. Pending: Amended in Assembly March 20, 2017. Would require the CPUC, in its participation in the ISO's transmission planning process, to promote the use of non-wire alternatives before use of transmission wires.

State Bill 700: Energy Storage Initiative. Introduced by Senator Wiener. Pending: Amended in Assembly July 5, 2017. Would require the PUC to establish the Energy Storage Initiative to provide rebates to consumers for the installation of energy storage systems.

Assembly Bill 546: Land use: local ordinances: energy systems. Introduced by Assembly Member Chiu. Pending: Signed into law September 30, 2017. Provides guidance on streamlining energy storage permitting for local government, including factors such as fees for permitting and inspection, and state-mandated local programs.

Notes

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