# Pumped Energy Storage: Vital to California's Renewable Energy Future

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## Executive Summary

California is a world leader in renewable energy. The state already sources nearly one-third of its power from renewables, mainly solar and wind. With recent legislation in place, renewable energy will increase to 60 percent or more by 2030. In tandem with renewable energy goals, the state is striving for 100 percent clean energy by 2045 to fight global warming. Shifting to more renewable energy requires forward thinking to balance supplies and demands while optimizing the use of these renewables for California ratepayers. Since renewable energy sources in California are largely from solar and wind, leveraging these resources requires additional electrical grid flexibility that can be best provided by energy storage.

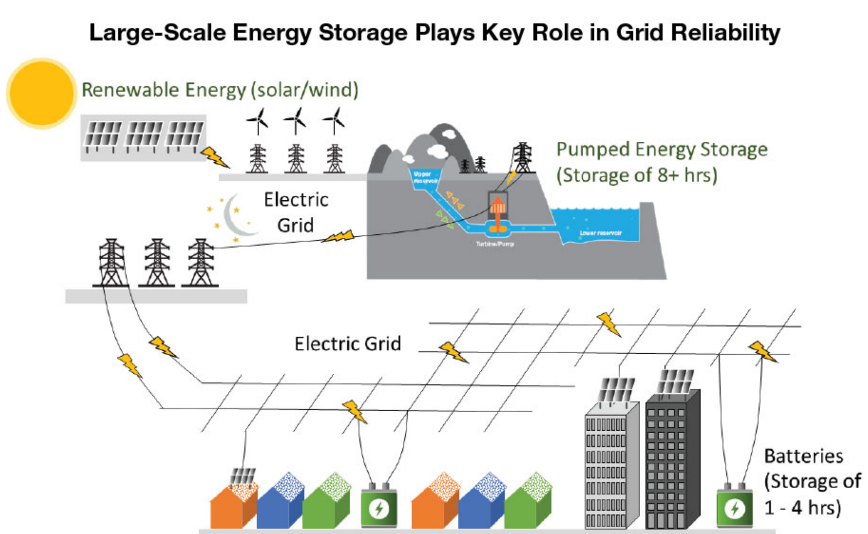
This renewable energy revolution is attractive for California, but it requires sustained support that will hinge on three factors. First, California must assure its ratepayers that a renewable grid will be cost-effective and reliable. Second, it must show that the renewable energy revolution will promote inclusive growth—with good jobs created in California and kept in California. And finally, it must ensure that the shift to renewables also delivers on the state's goals to fight climate change.

**The central purpose of this paper is to articulate the opportunities and challenges for large-scale energy storage in the evolving California grid. In particular, this paper examines the need for a decisive push to deploy pumped energy storage. The lead times for such projects are long. Having projects operationally starting in the mid 2020s requires clearer policy and market signals today.**

### Making Renewable Power a Reality

A massive shift to renewables will require new kinds of investments, markets, and business practices. Electric grids will need to be more flexible; new kinds of power supplies will help deliver energy flexibility when needed; and new pricing systems are needed to send clear signals to consumers so that they adjust their energy usage based on the times of day when electricity is most plentiful. What's unclear is how quickly or effectively all these changes will be realized and how these changes will align with what is best for California. For example, large electric grids across the Western U.S. can help import renewable electricity, but such investments won't create jobs from a renewable energy revolution in California.

**Solar and wind energy sources are variable; making best use of these resources requires additional electrical grid flexibility that can be best provided by energy storage.**




Energy generated by renewable sources, like wind and solar, can be captured by energy storage facilities and then distributed when needed. Batteries and pumped energy storage will provide the needed energy storage for both short-term needs (batteries, less than 4 hours) and long-duration needs (pumped energy storage, 8 hours or more).

While many pieces are needed in California's energy puzzle to make the shift to renewable power, there is one piece that will become pivotally important: energy storage. Perhaps more than anything else, energy storage will be the key to a successful California renewable energy revolution.

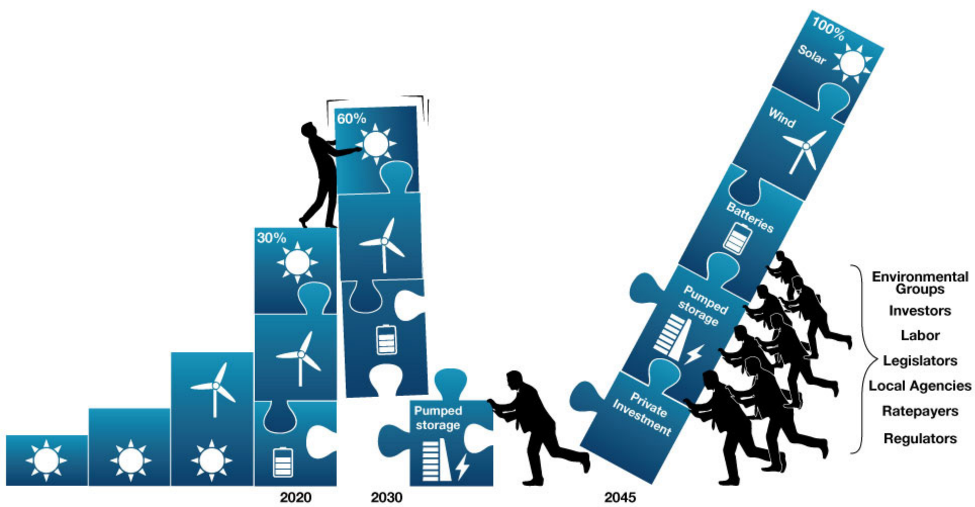
## The Pivotal Role of Large-Scale Energy Storage

**While many pieces are needed in California's renewable energy puzzle, one piece that will become pivotal: energy storage.**

Large-scale energy storage provides four interconnected services that are essential to facilitating California's big shift to renewables: 1) balancing generation with demand; 2) improving transmission efficiency; 3) providing electric grid stability; and 4) shifting power supply over long periods.

Large-scale energy storage is a highly cost-effective way to provide each of these services. Academic research and practical experience show that energy storage is vital to integrating renewable power in ways that keep the electric grid reliable. Energy storage can also help ensure that renewable power is used both day and night, making it easier to move beyond fossil fuels and help California meet its ambitious climate goals.

**Pumped Storage Elevates Renewables to 100%**




The target for renewable energy in California in 2030 is 60 percent – and large-scale energy storage in the form of pumped energy storage will play a pivotal role reaching that goal. State policymakers will need to work with local agencies and private investors to provide cost-effective energy while lowering risk to the electric grid.

## What Kind of Storage, How Much, and Where?

There are many different forms of energy storage ranging from very short periods to long durations (8+ hours and overnight, days, or longer). Batteries will play a role, but as demonstrated in this paper, their short storage duration (typically less than 2 hours) leaves the most cost-effective solutions for the largest and longest duration storage to pumped energy storage. This large-scale energy storage will be essential to demonstrating that California can move to 60% renewable power and approach the 100% mark. Many expert studies have been performed that demonstrate the value of pumped energy storage, including CAISO's Bulk Energy Storage Case Study, which found that a 500 megawatts (MW) pumped energy storage project in Southern California would provide ratepayers with a savings of up to $51M per year from improved efficiencies in system operation. Numerous studies show a rapidly rising need for large-scale, long duration energy storage in California (and the west) as the region moves rapidly to renewable power while retiring or reducing its use of fossil fuel power plants. By contrast, the proven experience with battery systems is for much smaller projects with much shorter duration. Without significant new large-scale energy storage, California will likely be required to import more energy from other states, including potentially power generated with higher carbon emissions, such as coal and gas.

The State will be unable to meet its renewable and climate goals reliably without large-scale energy storage. Failure to invest adequately in pumped energy storage could also require more costly overbuilding of renewable energy generators and transmission lines, leading to even higher power and transmission charges in the State.

## Turning Pumped Energy Storage into Reality: Policy, Finance, and Investment

To be consistent with California's energy vision, active new policy support is needed to facilitate the development of pumped energy storage. Those policies should recognize the long lead times in building pumped energy storage projects (5 to 10 years). New policy efforts must begin now.

Among the needed actions are state-backed support for some early projects that would jump start investment in this proven technology. This support can demonstrate viable business models and investment strategies that will pave the way for more private sector-led projects in the future. The best early projects will be those that have low environmental footprints and are located close to renewable energy supplies and load centers. Care will be needed to ensure that financial support for such projects is aligned with the communities that gain most of the benefits.

New studies are also needed to understand the value of all forms of renewable energy and storage in the long-term evolution of California's energy system. Such detailed planning studies must look at the critical role for large-scale energy storage when, as is likely, other strategies for integrating renewables such as regional grid integration fall short. It should quantify the financial and environmental value to the state as investment in storage helps to ensure the shift to renewables and lower emissions is successful.

This white paper examines the complex and little understood challenges to achieving California's renewable energy and climate goals, and the critical role long-duration pumped energy storage will play in overcoming them.

### Key Facts

- **Renewable energy integration requires new thinking about energy grid operation.**
- **Large-scale energy storage is a vital part of renewable energy integration.**
- **Properly integrated into the electric grid, solar and wind can help California achieve its goal of deep cuts in greenhouse gas emissions.**
- **Pumped energy storage is a cost-effective, long-term energy storage solution with a proven track record.**
- **The State will be unable to meet its renewable and climate goals reliably without large-scale energy storage.**

# Pumped Energy Storage: Vital to California's Renewable Energy Future

**A White Paper by David G. Victor, PhD, et al**
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## The Big Picture

California is a world leader in renewable energy. Already, the state sources nearly one-third of its power from renewables, mainly solar and wind.[1] Under new legislation, renewables will rise to 60% of California's power supply by 2030 and then, by 2045, California will shift completely to 100% clean energy with no emissions of the gases that cause global warming.[2] In the history of electric power, no other major grid has seen such a massive transformation so quickly.

**Without more energy storage and new grid management, renewable energy will be costly to integrate fully into the grid. Making the clean energy transformation affordable and reliable will require new investments, policies, and planning.**

### Affordable and Reliable Energy

Making the clean energy transformation affordable and reliable will require new investments, policies, and planning. The wind does not always blow, and the sun does not always shine at times when electricity is needed the most.

One consequence of the variability in solar and wind generators is that they are often over-built to meet the need for power, leading at times to excess generation that requires grid operators to reduce output from other generators and curtail renewable energy. Without strategic planning and investment in storage, the amount of over-building and curtailment can rise sharply as excess generation events become more frequent. During these periods power prices can also swing wildly—leading even to negative prices. Other harmful consequences include under-utilization of expensive transmission lines and heavy reliance on natural gas power plants to fill in the gaps—a process that leads to emissions of carbon dioxide and other pollutants, which undermines the state's climate goals.

**A lesson learned from previous energy crises in California is that ratepayers will only support the shift to a 100% clean energy grid if isn't too costly and does not jeopardize reliability of electric power.**

The telltale signs of this problem are already evident in California. In 2018, the California Independent System Operator (CAISO), the organization that runs the state electric grid, stopped or curtailed approximately 460,000 megawatt-hours (MWh) of renewable energy from being used on the electric grid.[3] That wasted energy is equal to about 80,000 households' total annual energy consumption.[4] It's also about equal to a $150 million solar project sitting idle all year.[5] These costs are vitally important to keep under control. One lesson from earlier energy crises is that Californians will support the shift to an all clean energy grid only if that isn't too costly and does not jeopardize reliability of electric power.

**Recent California legislation to lower emission levels coincides with increases in renewable energy generation. To benefit from an increase in carbon-free renewable energy, it will be important to reduce curtailment of renewable energy through large-scale energy storage.**

Curtailment is relatively small in the big picture. Of all the power generated for Californians, only about 0.2% is curtailed.[6] But that is because renewables, today, account for just one-third of California's power supply.[7] That situation is changing, with California planning to double the capacity of renewable power plants installed in just the next decade alone.[8] In 2018, CAISO had the single largest day of curtailment at about 10,000 megawatt-hours. On that day, April 28, the rate of curtailment (about 2%) was 10 times the annual average.[9] The California grid operator has warned that these curtailments are merely the start of a much bigger problem as the grid moves to higher fractions of renewable power.[10]

Without more storage and better grid management, curtailment is poised to grow exponentially. One study, by the reputable Union of Concerned Scientists, projects curtailments climbing 70-fold as the fraction of renewables on the state grid rises from 33% to 50%.[11] As the grid moves to renewables there will always be some curtailment. The grid of the future will need the right mix of resources (generation, storage, transmission, and demand response) to deliver low carbon electricity at the lowest cost, while reducing curtailment to just the minimum level that is needed to keep the grid reliable.[12]

**Failure to make the needed investments in the California grid will jeopardize the State's ability to meet aggressive goals for renewables and emission controls.**

## Meeting the State's Environmental Goals

California is making the shift to renewables in tandem with other important energy goals, such as preserving the local environment and making deep cuts in emissions of carbon dioxide and the other pollutants that cause global warming.[13] The best scientific research summarized in the latest review by the Intergovernmental Panel on Climate Change (IPCC), shows that the most cost-effective strategies for achieving deep decarbonization will involve massive electrification.[14] It is easier to generate carbon-free power and then distribute the energy by wires than to manage the emissions from potentially millions of diffuse sources such as the engines in cars, hot water heaters, and industrial combustors in buildings and factories.

**Avoiding the 460,000 megawatt-hours of renewable power curtailed in 2018 would have cut about 720 million pounds of greenhouse gases—the equivalent of nearly one billion miles driven by the average American passenger car.**

California is following exactly this logic with its program to shift the state's major energy services to the grid, providing deep decarbonization through electrification. Those energy services include mobility (e.g., electric cars), heating (all electric), and industrial processes (shifting away from direct combustion of conventional fossil natural gas, such as for heating).[15] Current California law requires a 40% cut in emissions below 1990[16] levels by 2030, which is an ambitious goal since current emissions are similar to 1990 levels. A recent executive order would achieve net zero emissions across the whole California economy by 2045.[17]

Much of the political support for California's shift to renewable energy is rooted in the state being a leader in the effort to stop global warming. Delivering on that goal requires a well-managed grid so that renewables can help lower emissions in the most cost-effective way. Avoiding the 460,000 megawatt-hours of renewable power curtailed in 2018 would have cut about 720 million pounds of greenhouse gases—the equivalent of nearly one billion miles driven by the average American passenger car.[18] In the real world, curtailment will never get to zero because in well-designed electric grids that integrate lots of renewables, a measure of curtailment is one of the many ways to help keep grids stable. Some plans for integrating renewable power into the California grid involve building larger regional grids across the entire west—an approach that could raise the risk that Californians import electricity generated by coal or gas from those other states. While that outcome is prohibited under Senate Bill 100, in the real world it is exceptionally difficult to monitor and enforce when electrons co-mingle on a single grid.[19]

## Making Sure Transformation of the Electric Grid Includes all Californians

Sustaining the political support needed for the renewable energy revolution requires paying close attention not just to costs but also other key elements of the political landscape.

The clean energy revolution must be inclusive. All communities must benefit. Investments need to flow to areas outside established wealthy urban zones so that the infrastructure needed for a renewable grid creates good paying jobs for Californians. A politically viable clean energy revolution will require addressing these concerns, such as articulated by the environmental justice community.

It is also vitally important that California's investment program include attention to the number and quality of jobs that it creates. Large infrastructure projects often generate important jobs. Focusing those jobs in the state, for Californians, is an important objective and vital to building and sustaining the broad political support needed for transformation and deep decarbonization of the power grid.

**All communities should benefit from the clean energy revolution. Investments need to flow to areas outside established wealthy urban zones so that the infrastructure needed for a renewable grid creates good paying jobs for Californians.**

## Assembling California's Energy Puzzle

Meeting the state's goals of creating a clean, cost effective and reliable grid for the benefit of all Californians is like composing the pieces of a giant puzzle. The pieces to the puzzle are represented by the various ways to generate, transmit, store, and use energy. Achieving the vision for a clean energy future will require massive changes in how California plans, builds, and operates its grid. Changes will be needed in all levels of the grid, from the state's electricity markets to how individuals use electricity. Today, nobody knows the exact size and shape of all the puzzle pieces. Some pieces, such as creating regional grids or shifting electricity consumption, may prove very hard to craft and implement in practice.

Preparing for the real-world future requires options that we know work and will keep the grid reliable, such as large-scale energy storage, including pumped energy storage. Private investors responding to market signals won't deliver enough investment in these options, which is why active policy measures are needed to boost investment in these large-scale energy storage projects and address the long lead times. The project development period (between when a project is conceived and it is ready to serve Californians) is between 5 and 10 years. Active new policies are needed now to ensure pumped energy storage projects enter commercial operations when they will be critically needed.

**Private investors responding to market signals alone won't deliver enough investment to meet the needs of the future electric grid without active policy measures to support large-scale energy storage projects that have long lead times for project implementation.**

Unfortunately, the electricity planning system in California is not, at present, designed to understand the magnitude of the renewable integration challenge. Nor is it able to assign the right value to large-scale, long-duration energy storage projects that will be needed to keep the grid reliable in the most cost-effective ways. Most planning takes its cue from the California Public Utilities Commission (CPUC) Integrated Resource Plan (IRP), an effort to develop a comprehensive plan for needed generation, storage, and other elements of the grid. CAISO looks to the IRP when doing its planning for the transmission grid. Many other vital policy makers also consult the IRP when checking to see if the state is on track to deliver its important energy, economic, and environmental goals. Currently, the IRP looks out only about one decade into the future and does not reflect the need for a longer term outlook to support the speed at which California is planning to reduce its emissions of warming gases. Furthermore, retirement scenarios for existing gas-fired generation plants are not fully taken into account in these plans. As a result, local capacity values of proposed storage projects are being estimated based on historical instead of potential future capacity needs; failing to provide the necessary market signals to trigger investment. To meet the State's plans for zero emissions by 2045, the power sector is expected to do the heavy lifting to cut emissions through the retirement of the fossil fuel fleet of generation because emissions from other sectors will be harder to limit.[20]

Those blind spots in the IRP process translate into blind spots in planning for the need to build large-scale energy storage facilities. These energy storage facilities are needed to store clean renewable power and integrate it into the grid while replacing the flexible generation now provided by fossil fuel generators. Other jurisdictions have a better grasp of how much storage they need by planning further into the future. For example, a recent Portland General IRP extended the planning out several decades to capture that market's similar shift to renewables and lower emissions.

It also extended the analysis of storage needs from 4 hours (typical of many power planning systems, including in California) to overnight storage of 8 hours and longer. From this more appropriate perspective, Portland General discovered the need to invest in much more large-scale, long-duration storage, including pumped energy storage facilities with 8 hours of capacity.[21]

## The Cost of Getting it Wrong

Failure to prepare for the State's renewable energy future could undermine the reliability of the California grid, which will harm consumers and undermine the State's economic competitiveness.[22] California's electricity costs, which are already among the five most costly in the nation, could rise sharply.[23] Failure to make the needed investments and changes in the California grid will also jeopardize the ability to meet aggressive goals for promoting renewables and reducing emissions. Under current state law, California's shift to renewables will slow down at 60% after 2030 unless there are demonstrated technologies and practices that make viable the push beyond 60% to 100% by 2045.[24]

# Four Ways to Keep the Grid Affordable, Clean and Reliable

The California Energy Commission (CEC), the CPUC, and CAISO have all been rightly focusing on the strategies needed to keep the grid affordable, clean, and reliable as the state shifts to renewables. CAISO, for example, has identified eight "solutions" that offer "promising concepts and technologies" that can help integrate renewables into the grid.[25] Here we take a step back from those details and focus on how grid operators and expert analysts around the world have analyzed and begun to solve the challenges of renewables integration.

In every electric power system that has shifted to renewables, grid operators have relied mainly on a mix of four different strategies for maximizing the use of renewables – price signals, interconnecting grids, flexible generation, and energy storage. The right mix of strategies depends on which options are available and their associated costs. California is learning that price signals, interconnecting grids, and flexible generation will be harder to use in practice. As those difficulties become more apparent large-scale energy storage becomes a particularly important option as the State tries to stay on track with its clean energy goals.

**Maximizing renewable energy on the grid requires the use of four strategies:**

- **Price signals**
- **Interconnecting grids**
- **Flexible generation**
- **Energy storage**

## 1. Price Signals:

Sending price signals to customers can enable them to adjust their behavior to reflect real time dynamics. When electricity is scarce, prices can rise and consumers will cut back on consumption. When supplies are flush, the opposite happens as prices tumble. "Time of use" rates – where electricity prices differ based on the time of the day – are one example of a price signal. California is already rapidly shifting to such an approach; starting in 2019, for example, the default rate charged for residential users will be "time of use," thanks to the installation of smart meters across the State.[26] Consumers can also participate in demand response programs, which incentivize them to reduce consumption during certain events.

**When electricity is scarce, prices can rise and consumers will cut back on consumption. The problem with demand response is that consumers can only adjust so much.**

The problem with demand response is that consumers can only adjust so much and exactly how much is very hard to pin down. The need for air conditioning, for example, increases in the late afternoon because people are returning to their homes when it is hot. This demand increase comes at exactly the same time as the sun is setting and solar output sharply declines each day. In contrast, businesses are open and consume more electricity during the day when people are awake and working. Energy experts are learning new ways to help customers become more responsive to power markets, but the overall conclusion from that work is that the total level of response is small.[27] This realization

– that demand response depends on human behavior, which may not always respond predictably to price signals: is particularly important when looking at the future of electric vehicles. Huge amounts of excess solar electricity can be used in the middle of the day, in theory, to charge electric vehicles on California roadways. Already 9% of new light duty vehicle sales are electric, and that fraction has been rising steadily. The problem is that a charging infrastructure for mid-day charging may not be available and many users will prefer to charge at home at night when they return from work even though power supplies from California's solar-dominated grid will be more scarce and costly.

There are good reasons to expect that analysts who are using models of ideal consumer behavior will over-estimate the amount of demand response that actual consumers display. Real world demand response depends on lots of factors that are hard to pin down in the models that analysts use to estimate demand response. Some examples of variables that influence the accuracy and predicatability include the detailed availiabity of infrastructure, how consumers process information, and how consumers make choices.

This unknown and often low level of demand responsiveness is one reason why grids that shift to renewables often have many periods when power prices are actually negative. In 2017, California had 110 hours of negative power prices—more than any other market in the world.[28] The full story behind negative power prices is complex. For example, in California these market conditions depend partly on precipitation in the hydroelectric system area, storage levels, and on subsidies that give power generators an incentive to keep producing even when the markets offer no reward. It is highly likely this problem will keep getting worse with the shift to more renewables.[29] Negative power prices are already leading to some market behaviors that aren't good for California's ratepayers and the state's vision of an affordable and sustainable power grid. For example, in March 2017, CAISO paid Arizona Public Utilities to take California's excess renewable energy for about $25 per megawatt hour. This is a great deal for Arizonans (who have invested less in renewables compared with California), but not for California's ratepayers.[30]

## 2. Interconnecting Grids:

A second strategy involves interconnecting grids. Academic studies of renewable power systems show that big shifts to renewables are almost always more cost-effective when they are combined with larger and more capable power grids.[31] That's because renewables are more variable in small geographical locations than when averaged over large areas. A cloud deck sitting over southern California will reduce solar output in that location. But if the grid has access to supplies in other areas, the average impact on renewable generation will be much less. This logic is part of the reason why China has invested to become the world leader in ultra-high voltage long distance power lines that make it possible to move power around the country where it is needed.[32] These power lines are costly, of course. For example, SDG&E's Sunrise Powerlink cost $16 million per mile to build. Australia and Germany—two other markets making a big shift to renewables—are also investing in much larger grid interconnections. The other large grid system making a comparable effort to shift toward renewables is Europe. Studies in Europe show that ideally configured grid systems could help integrate renewables by integrating more information about weather (e.g., wind speed and timing) into grid planning systems.[33]

The problem with the interconnecting grid strategy is that even massive grids that cover the entire western United States can't assure reliable energy all the time.[34] Massive interconnected grids are also politically very challenging to create. California already has some limited interconnections to other states, notably the hydro system in the Pacific Northwest. Legislation to allow much bigger interconnections and to operate the western grid as a single unit has been debated extensively in California and rejected every time. There are many concerns that grid interconnections will make it possible to "shuffle" contracts that provide new clean energy only on paper even as the western grid still relies on coal and gas.[35]

**Massive interconnected energy grids are politically challenging to create, could shift jobs out of California, and can't assure power will remain reliable all the time.**

While Californians have been concerned regarding an interconnected western grid, key stakeholders in other states are also politically concerned that California would dominate any regional grid, giving them less control over their own energy futures. These forces have created a key tension. On the one hand, the expert studies show that interconnections across the west will rise sharply in value as the region moves to renewables. However, at the same time grid interconnections could become more valuable technically, the political foundations for that strategy are eroding. One of those foundations is organized labor, which is concerned that grid interconnections will lead to a renewable future that is less inclusive of Californians as the beneficiaries. For example, by shifting jobs to infrastructure investments and new power plants in other states, California labor does not benefit because the California-based jobs necessary to achieve the state's ambitious renewable and zero-carbon emission goals would be effectively "exported" out of the state.

## 3. Flexible Generation:

Almost every power grid that has experienced an influx of renewable resources has responded by increasing its reliance on flexible generation. These plants can adjust their output up and down with the variation in renewable generators.[36] This has included increasing the quantity of natural gas and large-scale hydropower generation, as well as cycling power plants that were originally designed to run at maximum design capacity (known as "baseload" generators) up and down during the day in response to variability in the supply of renewables. Academics have quantified the benefits of these flexible supply options including the benefits of lowering the minimum output from power generators that are sitting nearly idle but ready to ramp up when needed. [37] For example, nuclear plants in the northeastern United States and on the French grid are ramping up and down due to the value of generation flexibility. [38]

**With reliable hydroelectric power already at its maximum and nuclear power phasing out, California has limited ability to rely on flexible generation that can adjust to compensate for the variability in renewable power and demand for energy.**

The problem with flexible generation is that the power plants needed to provide this service are not availalable. California will close its last nuclear plant in 2024 and there are no serious plans to build any more.

Flexible hydropower (hydroelectric energy production that can be ramped up and down with demands) is already used in California to its maximum, and the availability of these traditional hydroelectric facilities depends on seasonal fluctuations and can be reduced when precipitation is poor. Flexible hydropower from the Pacific Northwest may be shifted, increasingly, back to that region as they close more fossil plants and build more wind and solar.

**Flexible generation supports grid variability, but sufficient options to ramp power plants up and down must exist to make it a reality.**

Flexible fossil generators lead to higher emissions. Germany learned this lesson after its big investment in wind and solar did not lead to a significant reduction in national emissions. In California, the remaining flexible fossil fuel generators are all fired with natural gas. To meet its emission goals, California is trying to limit and perhaps even eliminate combustion of conventional natural gas—an action that could bring large political and technical tensions into the debate over the future of the grid.[39]

The future of fossil fuel power is shifting quickly in the west. Most planning systems have not yet caught up to the implications for the reliability of the grid, nor the need for new strategies to integrate renewables onto the grid. For example, a fresh analysis of reliability in the Pacific Northwest has shown that as fossil fuel generators are closed, there will be a much bigger need for technologies that can ramp up and down in line with variable power generators. This analysis specifically calls out "ultra-long duration electricity storage," of which pumped energy storage is the prime example.[40]

In the future, some renewable energy projects may operate in a hybrid mode—with onsite storage of heat or electricity—which could allow them to provide some of the functions of flexible generators. Under real world conditions, however, these so-called hybrid energy systems have had many problems and may not offer the longer-term flexibility and ramping needed for a grid as high levels of renewables are brought online.

## 4. Energy Storage:

**Challenges with other renewable integration strategies leave large-scale energy storage as the central option to meet California's renewable energy goals.**

Difficulties with these first three strategies leaves a major role for energy storage. The energy storage systems that will be needed come in many forms. Some will be smaller, decentralized battery systems, located at individual residences along with commercial and industrial (C&I) facilities. Indeed, California is already deploying many of these systems, but not necessarily with the goal of improving operations of the electric grid. Rather, these systems are being procured more in response to local incentives, such as the desire of C&I customers to shift their peak demand usage and reduce electricity bills. New kinds of power plants will also embed energy storage into their generators to help make output smoother and more controllable at times when power is needed. All these energy storage systems will play a role, but the most important foundation for an affordable, reliable and clean electricity system will be large-scale energy storage systems directly connected to the electric grid that can respond to the variability of renewable resources and consumer needs.

### Possible Locations for Grid-Connected Energy Storage

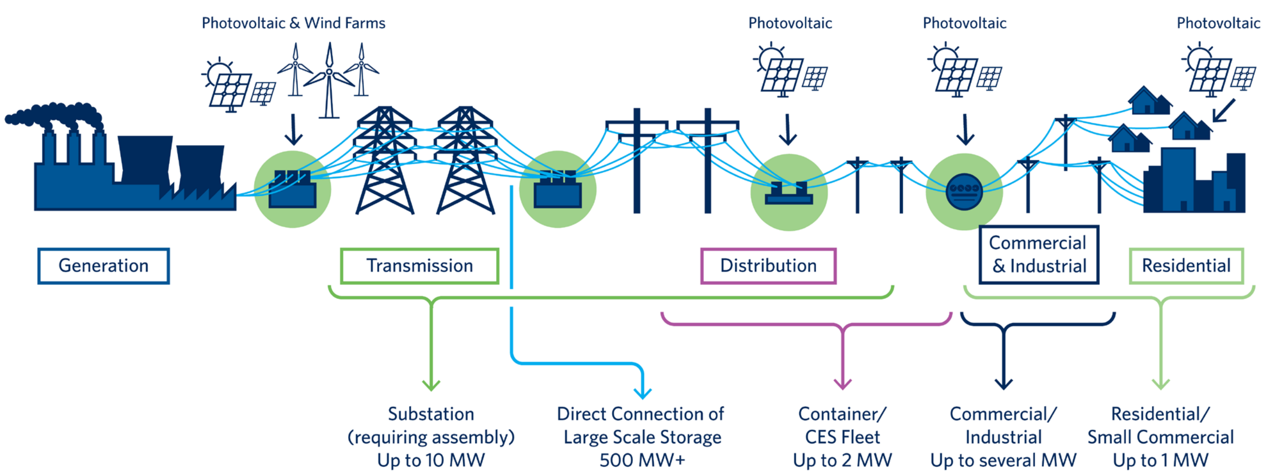



Figure 1 – Figure 1 is a schematic of the electrical grid indicating the different roles various technologies play in the energy storage arena. Multiple energy storage technologies will likely be needed to support California's renewable and clean energy goals.

## The Pivotal Role for Large-Scale Energy Storage

Large-scale energy storage provides four interrelated services that are essential to keeping the lights on, while facilitating a big shift to renewables including:

- Balancing generation and demand
- Improving transmission efficiency
- Providing electric grid stability
- Shifting power supply over long periods

**Pumped storage provides benefits beyond energy storage, including services that help make the grid reliable and avoid the need for costly transmission upgrades.**

### Balancing Generation and Demand

Large-scale energy storage allows large quantities of renewable energy to be saved, thereby reducing the need for curtailment. Typically, the large-scale energy storage systems that are in operation charge and discharge one or two times per day. The pumped energy storage systems operating elsewhere in the United States and the large pumped energy storage systems in Spain are examples of systems operating in this manner. Integrated with solar generators, as in Spain, pumped energy storage systems recharge during the mid-day peak of output and, often, also at night when power demand is low and there is excess power on the electric grid. The systems discharge twice daily — once during the morning rise in energy demand (before the rising sun raises solar output) and then again in the evening as the sun sets and net energy demand rises. Therefore, one important function of large-scale energy storage is measured by its ability to store and dispatch energy throughout the day to balance generation with demand.

**Large-scale energy storage provides multiple benefits needed for a reliable and stable electric grid.**

### Improved Transmission Efficiency

Second, large-scale energy storage makes it possible to use existing transmission lines more completely, avoiding the cost and political difficulty of building new transmission systems. Under CAISO, California has already invested in some relatively small energy storage systems that delay or avoid more costly transmission upgrades. CAISO, for example, has already approved several small (few megawatts to tens of megawatts) energy storage systems based on this logic.[41] Recent guidance from the Federal Energy Regulatory Commission (FERC)[42] could make more use of energy storage in this way.

The same logic is now leading to some energy storage systems that can replace retiring gas-fired power plants. CAISO has been exploring a much larger role for energy storage that could lead some large-scale storage being treated as an integral part of the state's reliable transmission system.[43] But delivering on a full new plan for integrating energy storage and transmission has proved technically and politically difficult, which is evidence that even when ideal policy outcomes can be imagined, they can be hard to put into practice. Which is why planning for California's carbon-free future requires focusing heavily on options that are known to be reliable and scalable.

### Providing Electric Grid Stability

A third function of large-scale energy storage is assuring stability of the electric grid. Managing an electric grid requires keeping voltage and frequency of the entire system within extremely narrow tolerances. Imbalances, when they occur, can damage sensitive equipment and even destabilize the electric grid. Australia experienced this when extreme storms damaged power lines in 2016 and problems managing renewable wind resources amplified the problem. One of many remedies to electric grid instability was investment in a large battery storage project to provide voltage support across Australia's largest two grids. At the time, this

**Pumped storage provides large amounts of energy stored as inertia in the spinning rotors that provide grid stability needed when electric grid conditions change quickly.**

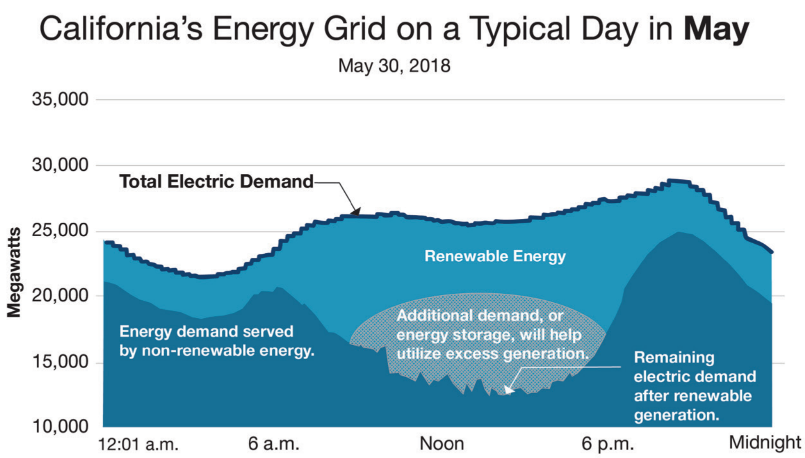
facility was the world's largest installed battery (100 MW). Periodically, massive electric grid failures are a reminder of why electric grid reliability is so important. For example, the world's largest electric grid failure in India (over two days in 2012) left 700 million people without power.[44]

Traditionally, operators have kept the electric grid stable by drawing on large amounts of energy stored as inertia in the spinning rotors of conventional generators like hydroelectric machines. These are known as "primary services" because they are are an intrinsic, physical part of a conventional grid. They work in tandem with a host of "ancillary services," which are an array of market-based products like automatic generation control (AGC), black start, and voltage support. Physically, many of these primary services have come from power generators that have large spinning turbines that can provide stability even when electric grid conditions change quickly. Spinning mass provides inertia, a form of energy storage, and primary voltage support through automatic voltage regulation (AVR's), Power System Stabilizers (PSS) and primary frequency support through governors. Unlike ancillary services, which are signals for response that the grid operator (CAISO in California) sends several seconds after some event that creates instability on the grid has occurred, the primary response from energy stored in the spinning rotor and primary voltage and frequency response is immediate. The value of both these services—primary and ancillary—is huge in assuring stability of the grid. However, these services today are largely supplied by conventional generators that already exist on the grid, and thus there isn't much of a formal market that actually reveals this value. The absence of those full market signals is emerging as a major challenge in the shift to renewable power—where the energy systems do not rely on spinning turbines, but are electronics such as inverters that convert DC current (from solar panels and batteries) into AC for the grid.

New power electronics, including smarter inverters, make it possible to provide some ancillary services without spinning turbines. In Australia, for example, a project that at the time became the world's largest installed battery (100 MW) has helped provide voltage support for an electric grid that otherwise would have difficulty integrating renewables as coal-fired plants and their large spinning turbines were being retired in that country. Such illustrations are encouraging, but by themselves they do not offer a roadmap for assuring grid reliability for at least two reasons. One is that in the real world the performance of these electronic systems has been uneven. For example, during fires in 2016 and 2017 inverter-based technologies were unable to provide the services needed to assure reliability in California—leading the national authority that oversees electric grid reliability to issue alerts to CAISO.[45] Second, while primary and ancillary services create value for society as a whole, the efforts to create special markets for ancillary services that can encourage private investors to build the needed systems remain immature. So far, these markets are rarely lucrative enough on their own to make large-scale private sector solutions to electric grid stability feasible.

**A big shift to renewables is likely to create a much larger need for the services required to keep the grid reliable, such as the systems that manage the frequency and voltage of the electricity on the grid.**

A big shift to renewables is likely to create a much larger need for the services required to keep the grid reliable, such as the systems that manage the frequency and voltage of the electricity on the grid.[46] For electric grids that are making the shift to renewables quickly, the need for primary response services may rise much faster than markets can keep up. For example, in 2018, comparisons across different days reveals how a larger role for renewables can create highly variable electric grid conditions that managers must handle to keep the lights on reliably. Figure 2 shows two typical days in 2018 on the California electric grid—one in late May (top) and the other in July (bottom). For each, the top line of the chart shows total demand for power (much higher in hot July than cooler May) and the bottom line shows net demand that remains after available renewables have served the load. The bottom line is known, famously, as California's "duck curve." What is interesting is the speed at which the lower line rises in the late afternoon as the sun sets but energy demand keeps rising. Today we typically see between 5,000 to 12,000 MW changes in just three hours. The net demand at night remains high as people keep using electricity even as solar output trends to zero.



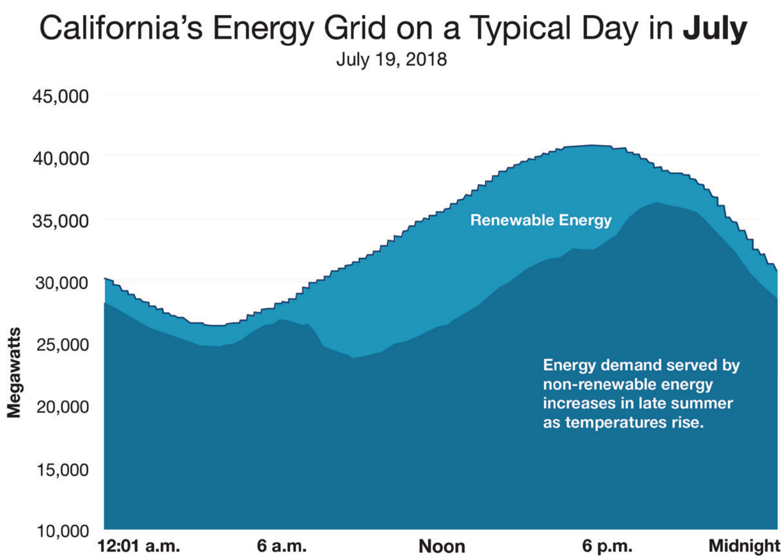




Figure 2 – California's Grid on a typical day in May (top, 30 May 2018) and July (bottom, 19 July 2018). Source: CAISO.

## Shifting Power Supply Over Long Periods

A fourth function of large-scale energy storage, which is expected to increase in importance, is the ability to shift power supplies over longer time horizons, such as several days. The need to start thinking about long duration energy storage is revealed by looking at how California curtails its renewables. Nearly all curtailment happens in the late spring. Figure 3 shows monthly data from CAISO. Looking closely at the data shows large day-to-day variability. Big reductions in wasted renewable energy can be achieved if there is the capacity to store that energy over several days. Some studies suggest that an all-renewables grid will need the capacity to arbitrage energy over even longer time periods—such as months to seasons.[47]

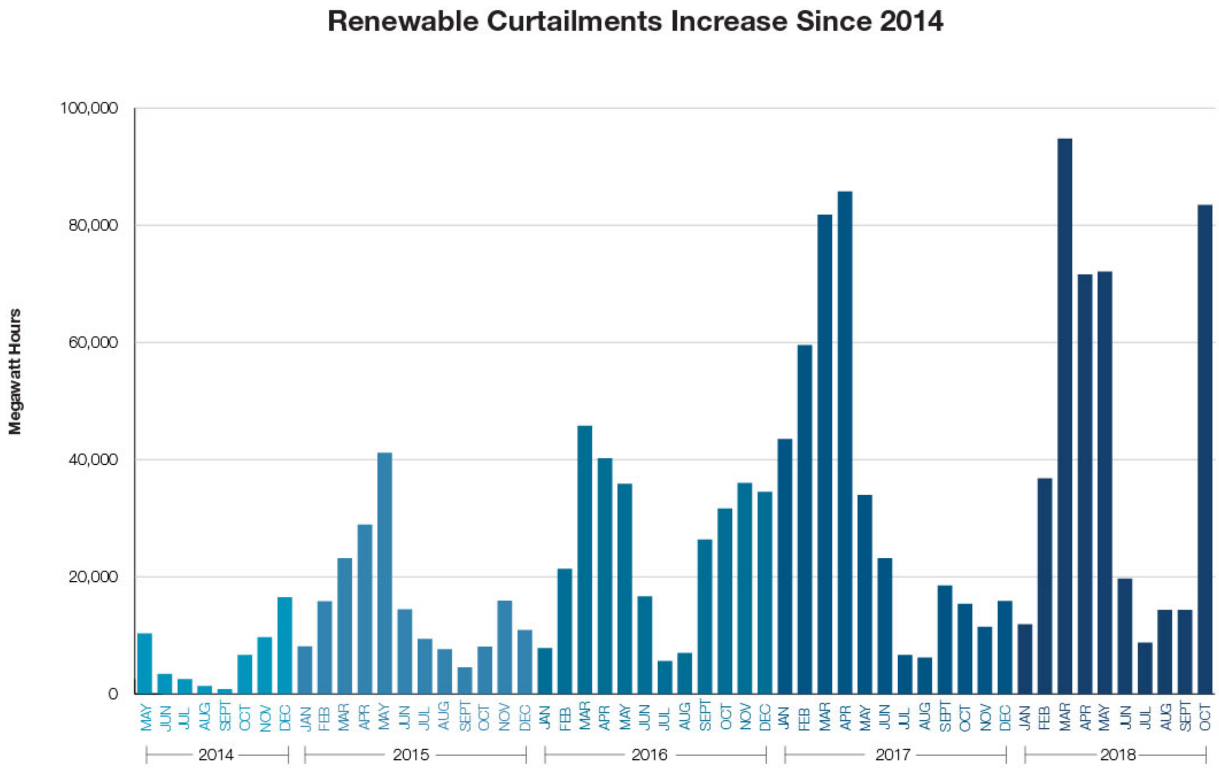



Figure 3: Curtailments, Month-by-month since 2014. The chart here shows monthly curtailments, which is the available renewable power that was rejected by grid operators, measured in Megawatt-hours. Source: CAISO.

At present, California obtains this multiday energy storage by relying on hydropower in the Pacific Northwest and on fossil fuel generators that can be turned on and off as needed. With decarbonization of the electric grid, the option of using fossil generators will decline. The existing hydro systems in the Pacific Northwest, along with the electric grid interconnections into that system, are limited, and hydro capacity itself can vary widely from year to year with variations in rainfall and other environmental constraints. While there have been many visions for a rapid shift to an all solar and wind power grid, one of the central critiques of those visions is that they are often unrealistic in their assumptions about the need for massive multi-day, multi-week and inter-seasonal energy storage of electricity.[48]

**To meet California's renewable energy goals, it's necessary to shift supplies from when energy is generated to when it is needed.**

No country or market has yet to figure out how to invest in large-scale long-duration energy storage systems that could provide this fourth function. None of the big battery systems presently in operation or being contemplated can do that. For example, Australia's 100 MW battery has a less than two-hour capacity, which is why Australia is now considering whether to build 2,000 MW of reliable pumped energy storage integrated into the country's existing hydroelectric system. This will create the ability to store massive amounts of energy for weeks to months.

**While batteries provide short-duration energy storage, pumped storage is needed to provide long duration energy storage (8 hours or more). That allows for increases in the amount of renewable energy that is put on the grid.**

California already has some experience with pumped storage at eight locations. However, nearly all of these projects were built in an earlier era under a different policy environment. Moreover, most were built for purposes other than large scale storage of energy, such as to facilitate water supply. A lot more large-scale energy storage will be needed—especially located close to renewable energy facilities and load centers. In Spain, the country's massive deployment of solar and wind power has run in tandem with building about 5,500 MW of pumped energy storage for a grid with a peak power consumption similar to California (about 43,000 MW).[49] Even with such a high investment in pumped storage there will be a need for more in the future. At present, about one-quarter of Spain's electricity comes from wind and solar and, like California, Spanish policy makers are pushing ahead to 100% renewables.[50]

## What Kind of Energy Storage, How Much, and Where?

Since energy storage must perform many different functions, energy storage systems will be deployed in many different forms with different technologies and attributes. The different types of storage are also likely to require different market and funding mechanisms to encourage their development. Conceptually, the many different types of energy storage are shown on Figure 4. These include systems that operate over short time periods—nanoseconds to seconds and minutes—with a relatively small power rating. Those are shown in the lower left corner and include supercapacitors and battery systems that smooth out power flow and keep the electric grid reliable. At the opposite extreme are large-scale, longer-duration energy storage systems such as pumped energy storage—hundreds of minutes to hours of storage. The rest of this white paper will focus on those systems.

**Batteries and pumped storage will be soon needed to provide large-scale energy storage to meet the escalating challenges associated with increasing renewable curtailment.**

### A Snapshot of Many Types of Energy Storage Technologies

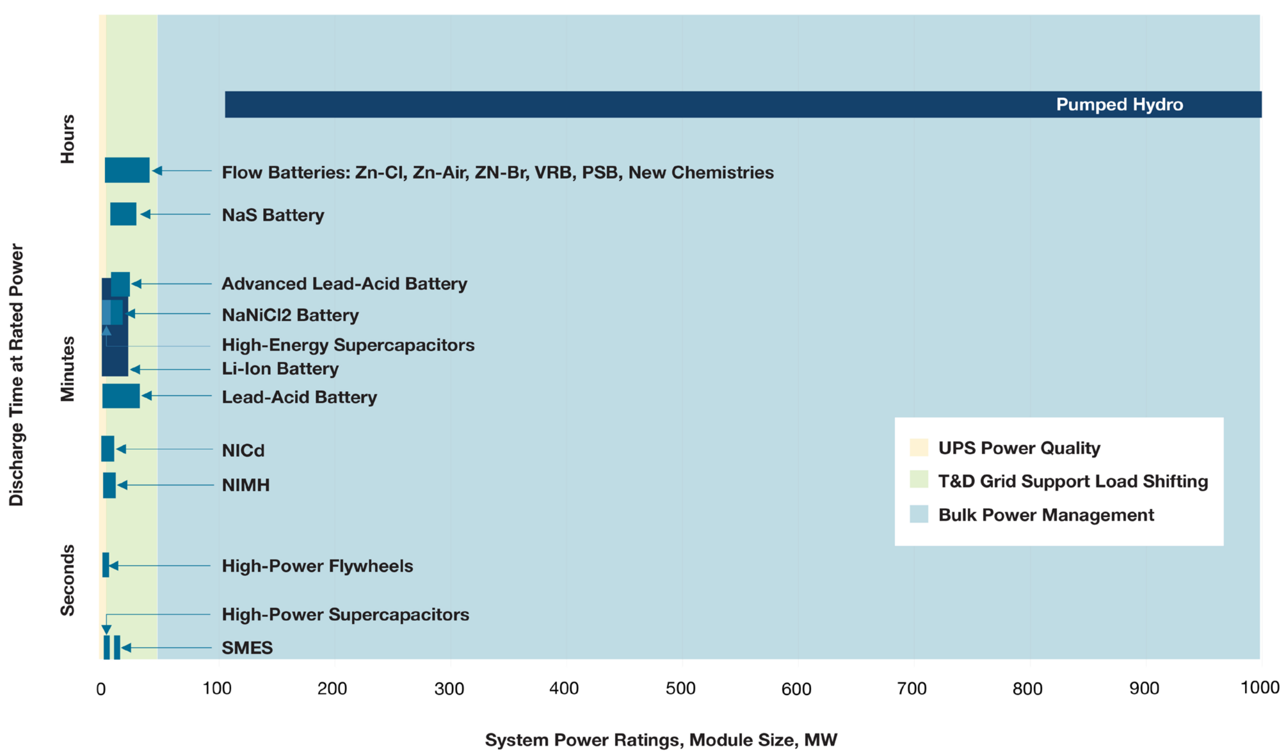



Figure 4: The "What": Many Different Types of Storage and Services. The figure shows power rating (horizontal axis) and time horizon for services (vertical axis). Various types of battery systems provide similar functions ("Li-Ion" systems are the most widely discussed battery systems today, but Nickel-Cadmium (NiCd), Nickel Metal Hydride (NiMH) and lead acid systems are earlier generation variants). There are many kinds of "flow batteries" that use large vats of liquid for storage and thus are easier to scale to larger size and long duration. Pumped hydro is at the top; other large-scale storage systems include compressed air energy storage (CAES) which so far has proved expensive to scale. Source: adapted from 2014 DOE/EPRI storage roadmap.[51]

California is moving so quickly to renewables that nobody, at present, knows exactly how much large-scale storage will be needed nor exactly where it will be needed. What is clear is that the needs are poised to rise quickly and exponentially. A series of studies (some by California government agencies and some by independent laboratories and academics) can help to provide some answers.

The exact need for large-scale energy storage will depend on progress on the other fronts that can help integrate renewables. For example, if progress on electric grid interconnectedness and demand response remain slow, as is likely, even more energy storage will be needed. Moreover, the best location for storage resources will be located close to the large renewable generators or the existing power lines that bring that generation to places where power is used. As a practical matter that means located along the state's power corridors and close to load, such as near the cities in Southern California and in the broader Bay Area.

**The best locations for energy storage will be close to renewable energy sources and power loads—such as cities in Southern California and the Bay Area.**

CAISO has sponsored an illustrative study on these questions. Published in November 2015, the CAISO Bulk [large-scale] Energy Storage Case Study (BESCS) specifically looked at the value of building a 500 MW pumped storage project in southern California. The study found that such a project could avoid the need for 348 MW of solar overbuild or 179 MW of wind overbuild. This project, over its lifetime, would avoid nearly 4,000 gigawatt hours (GWh) of curtailment due to a lesser need to over-build solar. Compared with a grid that didn't have the 500 MW pumped storage project, the BESCS analysis showed that the savings would amount to $36M-$51M per year due to more efficient system operation. Those savings would accrue after the full costs of building the pumped energy storage system were factored into the analysis. This study demonstrated a massive increase in the value, such as grid stability and less curtailment of renewables, that society gets from a pumped energy system. All told, CAISO concluded that large storage projects of this type would "reduce curtailment, CO2 emission, production costs, and the overbuild of renewables".

**According to a CAISO Large-Scale Energy Storage Case Study, a 500 MW pumped storage project in Southern California would provide a savings of $36M to $51M per year due to improved efficiencies in system operation.**

Studies from other organizations have analyzed the question of "how much" energy storage is needed using different methods of analysis and have arrived at comparable conclusions. That is, a significant amount of large-scale energy storage will be needed and energy storage projects, with the right market rules and policy incentives, add value. Notably, a 2016 study by the National Renewable Energy Laboratory (NREL) finds that the storage already being installed is sufficient to allow up to 40% solar photovoltaic (PV) generation on the California grid, but that the need for storage rises exponentially as solar rises to higher proportions of the generation mix. Another 15 Gigawatts of energy storage would need to be built by 2030 to allow just an extra 10% of power to come from solar sources.

**Another 15 gigawatts of energy storage will be needed by 2030 to allow just 10% more power to come from solar sources.**

The NREL study adopted optimistic assumptions about the flexibility of the electric grid, with robust interconnections and a shift of one-quarter of California's light duty passenger cars to electric vehicles, most of which are charged optimally (during mid-day) to take in excess electricity from the grid. But if the electric grid proves to be less flexible, then storage needs are even higher—for example, if electric vehicles aren't charged optimally but instead are charged when drivers get home at night because that is convenient.[52] The study is a warning sign about the risks to the reliability of the electric grid from inadequate investment in the energy storage capabilities that will be needed quickly and how much more will be needed if the California electric grid falls short of what engineers would like to have as an optimal electric grid. Of course, "energy storage" comes in many different forms, as discussed already in Figure 4, but the NREL team focused on the role of long-term energy storage (systems sized for 8 hours), which is typical of large pumped energy storage systems. Indeed, there is no other technology proven with extensive experience that can provide such large-scale and long-duration storage.

Of course, there are many different visions for the future of energy storage. Some reporting and analysis suggests less energy storage will be needed and that batteries can fully do the job.[53] But these studies tend to be based on highly optimistic assumptions, with optimal implementation and operation of flexible generation resources, regional electric grid interconnectedness, and lots of demand response, such as optimal electric vehicle charging, are all optimally implemented and operated. In the real world, where that doesn't happen, large-scale energy storage offers Californians a compelling option that can ensure cost-effective, reliable and clean energy supply.

**In the real world, where many strategies for integrating renewables don't fully materialize, large-scale energy storage offers Californians a compelling option that can ensure cost-effective, reliable and clean energy supply.**

## The Special Value of Pumped Energy Storage: Comparisons with Batteries

The rapidly rising need for large-scale storage requires clear thinking about the cost and flexibility of the options for providing this vital service. With the continued improvement in battery technology in the news, one view that has emerged is that batteries can "do it all." The reality is different. There are roles for batteries and pumped energy storage (and perhaps other large-scale storage technologies) to provide services in tandem.

The key question that must be answered is for each storage service, which options are least costly and offer the greatest value? Here we offer some answers by comparing financial analyses of pumped storage (PS) and battery energy storage systems (BESS). Our analysis is financial in orientation. Rather than just focusing on the engineering attributes of the different technologies, we must include important details such as the following:

- How will PS and BESS projects be financed (debt and equity)?
- What are the borrowing costs and equity returns?
- What project risks are there?
- What are the time horizons for the projects?
- What are the tax and profit implications?

A successful strategy for building large-scale storage in California must address financial realities and cost-effectiveness that will be central to whether projects can attract capital from private and public sector entities.

A perfect comparison between pumped storage and batteries in providing the service of large-scale storage is impossible at this stage. That's because while there are many pumped storage projects in the world with long histories of operations revealing key facts such as capital costs and reliability, there are no similar battery projects. Some large battery projects are entering service, but typically these are still much smaller than pumped storage facilities. The full-service lifetime of battery projects is unknown, and essentially all warranties and regulatory approvals do not extend beyond 20 years. Typical financial and

**A successful strategy for building large-scale energy storage in California must address financial realities and can attract capital from private and public sector entities.**

**California's rapid increase in renewables energy creates an urgent need for a big increase in large-scale, long-duration, energy storage services. Many pumped storage projects in other markets offer models for that service, but there is no comparable experience with batteries.**

**The timeframe for assessing energy storage costs matters. Projects that have a longer useful life trend towards lower costs for ratepayers.**

engineering time horizons for pumped storage projects are 40 years and beyond. Finally, most battery projects have useful storage durations of less than 2 hours (a few offer longer, four hour storage service). Pumped storage systems are designed for longer storage (typically 8 hours or more) and are easier to scale beyond that duration.

These untested comparisons are a central finding of this white paper. While one can imagine battery configurations that are comparable with large-scale, long duration storage services offered by pumped storage, it is not possible to find real world analogs to those projects to understand their financial and technical attributes, including their reliability. California's rapid shift to renewables guarantees the urgent need for a big increase in large-scale, long duration storage services. Many such pumped storage projects in other markets offer models for that service, but there is no analogous experience with batteries. Mindful of these facts, we offer our financial comparisons using the best data. We document our assumptions in the footnotes and in tables in the Appendix.

## Levelized Cost of Storage

Our analysis is in two steps. First, we calculate the "levelized cost of storage (LCOS)" for a large pumped storage project comparable to the one that CAISO analyzed, as noted above: 500 MW of storage over 8 hours. Multiplying those two numbers together provides the total volume of usable storage for such a project: 4000 MWh. LCOS is a widely used calculation that estimates the constant revenue "levelized" stream in $/MWh over the life of the project needed to finance a project, pays all operational costs, services debt, and allows a reasonable return for equity investors.

We project the capital cost for the year 2026 at about $1.9 billion, or about $475,000 per MWh of storage capacity.[54] The year 2026 represents when such a project could reliably be operational if a clear signal is given soon. As we will show, when the long useful project life is incorporated into the analysis, pumped storage projects have a very attractive cost per MWh, even lower than battery projects. We also estimate the cost of pumping energy based on cycle efficiency, O&M costs, debt service, taxes on project profits (28%), and a host of other factors.[55] Any such analysis necessarily involves a swarm of assumptions, but through extensive sensitivity analysis we have identified one of the most important assumption is capital cost. The costs we assume are based on extensive experience building comparable civil works. These costs also anticipate a project designed with a low environmental footprint, one that uses an existing large reservoir (there are many in California) and builds a smaller new upper reservoir.

Figure 5 shows the LCOS for pumped storage over three different time horizons. First is 40 years, the minimum practical time horizon for a California pumped storage project, the duration that is widely used in the industry. This time horizon is long enough that the fuller value of capital-intensive pumped storage investments can be amortized, offering the benefit of large-scale storage services at costs that are beneficial to ratepayers. Second is 50 years, which is the longest operating license for pumped storage facilities offered by FERC today. The third is beyond 50 years. This time horizon represents a project that is upgraded at modest cost around year 50 and then relicensed for another 50 years. This scenario represents a practice already widespread for large hydropower facilities and is entirely plausible for a California pumped storage project.[56] Indeed, all U.S. pumped storage projects that have completed or are nearing their original FERC license terms have or will be re-licensed.

**While the cost per MWh of storage capacity is higher for pumped storage than for batteries, the longer useful lifetime of pumped storage projects more than compensates for this by lowering the levelized cost of storage. The overall costs for pumped storage are far lower.**

**All U.S. pumped storage projects that have completed or are nearing completion of their original FERC license term, have or will be re-licensed, demonstrating their value.**

**Pumped storage systems have well-known costs and performance, and they are highly cost-effective for large-scale, long-duration energy storage.**

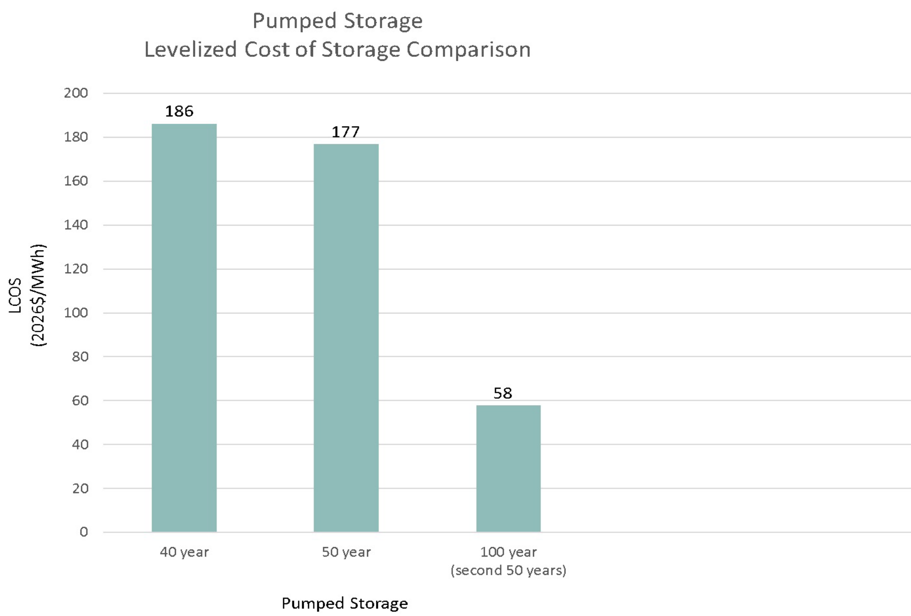



Figure 5: Pumped Storage cost per megawatt hour decline as the project life extends. Pumped storage projects operate over many years, making them a highly cost competitive options for large-scale energy storage. (sources: see Appendix.)

**Extending the cost analysis of pumped storage projects from 50 years to 100 years reveals a significant drop in cost. The LCOS for the second 50 years of a 100 year project, when the original costs are all paid off, is almost half the cost of the first 50 years.**

A central insight from this analysis is that the time horizon matters—longer time horizons mean lower costs for ratepayers. Extending from 40 years to 50 years lowers the cost of storage modestly (about 4%). The savings from an extra decade for amortizing the capital cost are offset, in part, by compounding inflation in operation and maintenance costs.[57] Extending from 50 years to 100 years sees a massive drop in cost. The LCOS for the second 50 years of a 100 year project, when the original costs are all paid off, is almost half the cost of the first 50 years.[58]

## Battery Comparison

**Reputable studies of battery systems show that huge uncertainties remain to determine the real cost of battery storage systems. Those unknowns are particularly large for battery systems deployed in ways that are unfamiliar and untested—especially for large-scale, long-duration batteries beyond 2 or 4 hours.**

In the second step of our analysis we compared pumped storage with battery systems. Here we rely on published, authoritative studies by other experts who are tracking the battery industry closely. In particular, we focus on Lazard, which publishes a widely used and regularly updated survey, and the Electric Power Research Institute (EPRI), the most authoritative research arm of the electric power industry.

Figure 6 shows Lazard's estimates for Lithium-based battery projects that are designed to operate over typical warranty periods (20 years) and sized at 4 hours storage duration, which is already on the outer edge of commercial experience (most of which focuses on shorter duration). Compared with pumped storage, the capital cost for these projects is lower ($285,000/MWh to $452,000/MWh), but that cost must be paid back more rapidly because the lifetime of these projects is shorter. The overall effect is to make batteries more expensive than pumped storage when those costs are levelized over the relevant time period. We underscore that there remains substantial uncertainty especially for battery projects because nearly all of the operational experience with these technologies is for much smaller systems operating over shorter time horizons (typically 1-2 years). Efforts to reflect some of those uncertainties, as illustrated with Lazard's low and high numbers on Figure 6, suggest that batteries will remain overall more expensive than pumped storage—possibly 50% more expensive than pumped storage.[59]

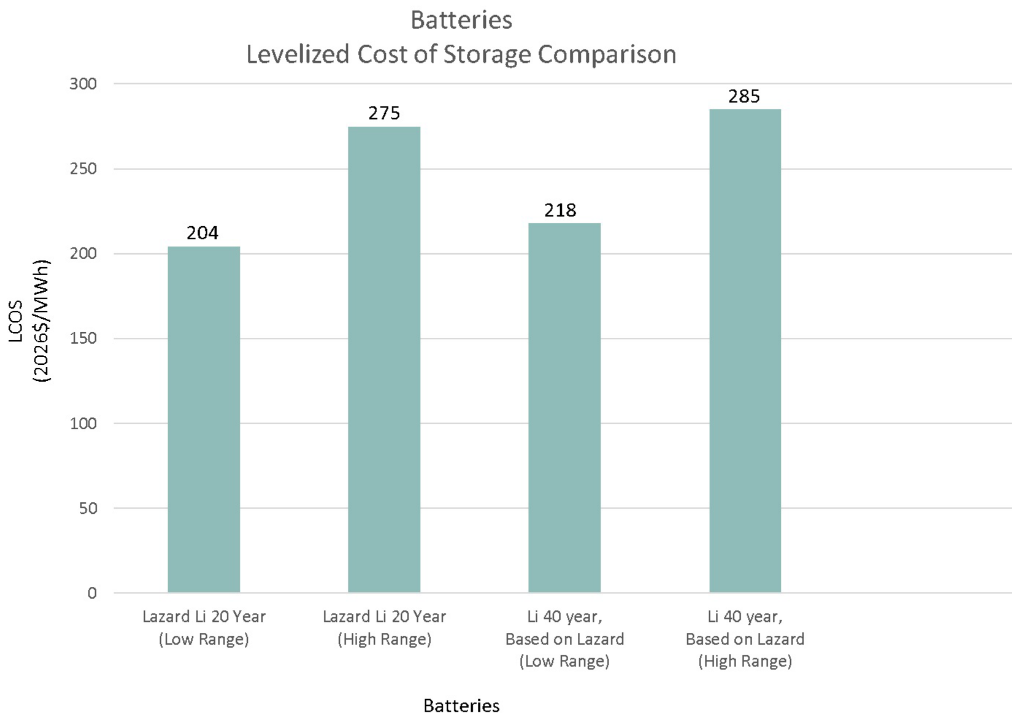



Figure 6: Lazard and EPRI have highly credible battery analyses that were used to support the cost per megawatt hour of batteries used in this analysis. (Sources: see Appendix.)

One of the many strengths of the Lazard analysis is that it uses the same parameters that we include in our analysis of pumped storage. The Lazard analysis includes pumping costs (charging) and is attentive to debt/equity ratios, costs of capital and equity return, and includes taxation. Such comparisons must be made, of course, with the many remaining differences in mind. For example, today's battery projects are typically structured very differently from pumped storage projects because the technology is newer, business models are still evolving, and low-risk long-term contracts are therefore less widely used. For these reasons, today's battery projects typically involve more risk and thus a greater role for equity (and higher costs of raising capital).[60]

**The battery levelized cost of storage shown in this study may be optimistic given the unknowns associated with the lifetimes of battery systems, the duration of storage, and vital operational issues such as the depth at which batteries can discharge without suffering costly damage.**

There are some key differences between our evaluation of pumped storage and Lazard's reputable study of battery projects that point in the opposite direction. In at least two ways, the data shown from Lazard understates the cost of battery projects that provide bulk energy storage services comparable with pumped storage. Two of the largest items are the duration of storage and time horizon for projects. Regarding duration, the data shown on Figure 6, taken directly from Lazard, are for 4 hour projects using the rated storage capacity and duration of battery systems. In the real world, the useful storage in a battery system is often lower than the rated capacity because today's battery systems often suffer damage at full discharge. A recent project in Southern California, for example, purchased a 50MW rated battery system to yield reliably only 20MW of capacity. We ignored these real-world differences between rated and useful capacity, a phenomenon rarely observed with pumped storage projects. Indeed, most studies do not distinguish between the purchased and useful size of battery projects, with the result that most existing studies may underestimate the actual costs of these battery systems when deployed under real-world conditions. For instance, Lazard assumes a 100 percent battery discharge. This means that the cost data on Figure 6 could be quite optimistic about real world costs of battery systems.[61]

Because time horizon is so important for understanding the financial analysis of large-scale energy storage, we can't ignore those differences. Pumped storage projects offer value at 40 years and beyond whereas the Lazard analysis on Figure 6 is only for 20 years and essentially all other reputable studies of battery systems have a similar time horizon. To indicate the effects of building a 40-year battery project we extend the Lazard analysis. This analysis is based on the lowest-cost assumptions for battery modules and other costs of a BESS. We estimate the cost of replacing the battery modules as they wear out. The replacement effort in this analysis takes place over 5 years starting at year 15. Because battery technologies are getting better over time, we assume that the batteries themselves are one-third cheaper starting in year 15 which is consistent with industry estimates. Even though batteries are much cheaper in the future, this 40-year time horizon leads to a more expensive battery project. This is because even as the capital costs from batteries decline as a portion of the overall project cost, the inflation on other elements of the system more than offsets the improvement in battery replacement costs.

To complement the Lazard analysis, we make some comparisons between Lazard's analysis and work by the EPRI. While the EPRI analysis does not focus squarely on the financial engineering of these projects, it is exceptional on the physical engineering and performance of these projects, including factors such as real depth of discharge and real-world costs for all the balance of system technologies needed for an operational battery system. The EPRI analysis is more conservative than Lazard and other studies in an effort to reflect the reality that there is limited experience with battery projects at this scale. It also has two other attributes that help round out our evaluation. First, it looks at battery technologies over longer storage periods (8 hours)—a difficult and somewhat speculative effort because the operational experience of battery systems is so much shorter. Second, it includes a detailed estimate of the end-of-life recycling and disposal costs for battery systems, which can be significant. These factors lead EPRI, generally, to assume that the capital cost for battery systems (which, like pumped storage, are the largest single component of LCOS) is about 10% higher than assumed by Lazard.[62]

## The Big Picture: Comparing Pumped Storage and Battery Systems

Looking across all the reputable studies of battery systems it is clear that significant uncertainties remain around the real cost of battery storage systems.[63] Those unknowns are particularly large for battery systems deployed in ways that are unfamiliar and untested—especially for large-scale, long-duration storage.

This analysis underscores that pumped storage systems have well-understood costs and performance and are highly cost-effective for large-scale, long-duration energy storage. California will need exactly those services if it is to integrate massive amounts of renewables into the grid. While it is hard to pin down exactly when those storage services will be needed, it is plausible they will rise rapidly in the 2020s and scale roughly in exponential fashion. Understanding that timing and scale—and the costs of delay—is a study item we discuss in more detail below.

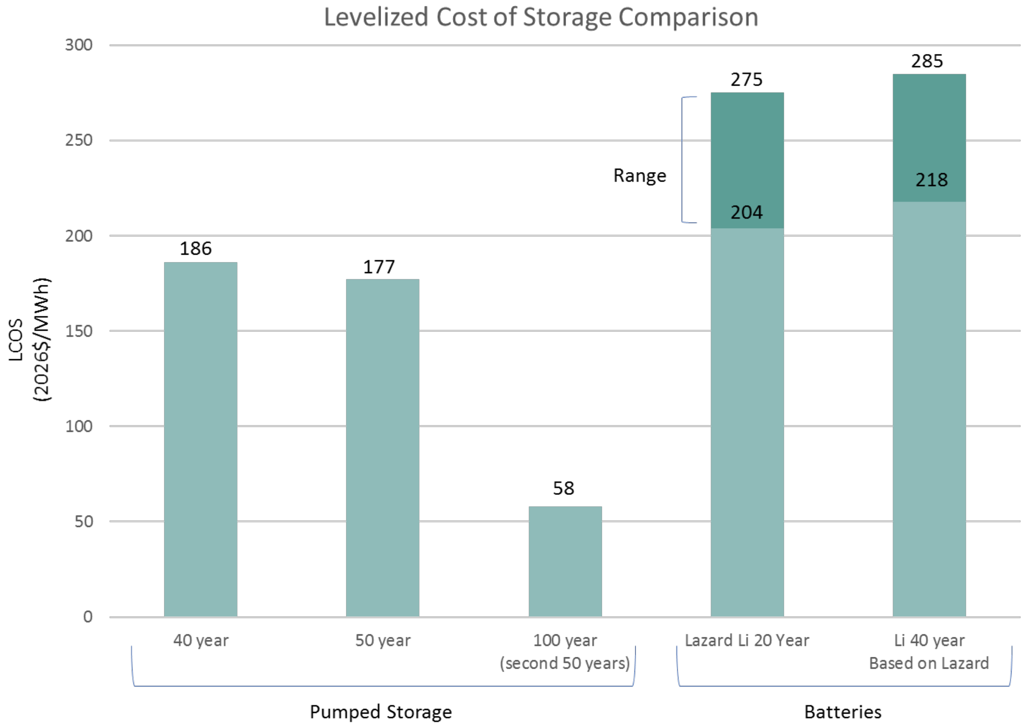



Figure 7: When evaluating large-scale energy storage options, the two most mature technologies demonstrate favorable options to cost effectively integrate renewable energy on the California grid. With the long, reliable project life of pumped storage, investments today will offer greater savings for future generations. (Sources: combination of Figures 5 and 6).

Finally, we close our financial analysis by reiterating that these kinds of comparisons hinge on many uncertainties and assumptions. By far, the most important sensitivity is capital cost. Reducing the capital cost of a pumped storage project by 10% would lower the LCOS for a 40-year project from $184/MWh to $173/MWh. Policy attention should be focused on ways to improve these high leverage variables, such as the capital cost for building large-scale energy storage. Policy initiatives that create more certainty for investors and that lower risk for early projects are examples of approaches that could reduce capital cost along with the debt and equity returns needed to finance that expenditure.

**Policy attention should be focused on ways to improve high leverage variables, such as the capital cost for building large-scale energy storage.**

## Other Benefits of Large-Scale Energy Storage

The analysis we present here focuses on large-scale energy storage—that is, the ability to “move” electricity from periods when it is in excess (e.g., noon on sunny days) to other times of the day or week when renewable generators can’t meet demand (e.g., at night or on cloudy days). A full-blown comparison of pumped storage and battery systems would also look at the relative cost and performance of these storage systems in providing a variety of ancillary services. Some of those services are equally well served by pumped storage and batteries. For example, both types of technology can provide voltage support, a key service for keeping the grid reliable. There are good reasons to think that pumped storage systems are better at keeping grid frequency stable at 60 cycles per second. In the past, the spinning turbines at central station power plants, including hydroelectric plants, provided this vital service. These plants used inertia—stored as steam, water, and spinning turbines—in response to changes in demand. Simple governor controls sensed minute changes in frequency and adjusted output to maintain frequency within an extremely high level of accuracy that is critical to reliability and quality of electricity on the grid. Increasingly, users of electricity require clean and reliable power for advanced electronics and other sensitive equipment.

The shift to renewable, distributed, and battery technologies has meant that the grid is less able to tap physical inertia and must rely on digital control systems. Utilities, system operators, and the FERC are increasingly concerned about the future where frequency control relies on digital equipment. Those same concerns apply to large-scale battery storage systems—which will rely on digital controls—and suggest that reliable and accurate frequency control will remain a major advantage of pumped storage systems that, like other large generators, use spinning turbines and physical storage of water.

## Turning Pumped Energy Storage into Reality: Policy, Finance, and Investment

Today's markets and regulatory systems do not create incentives needed for investors to build these pumped energy storage systems. Despite the high social value from pumped storage for California (a value that will rise sharply over the next decade), the attributes of the technology and California's power markets don't yet create the right incentives for investors to put capital into pumped energy storage. At present, the incentives to deploy energy storage are much weaker than the expected needs for energy storage in the next decade and beyond. Where rules do exist, they do not allow large-scale pumped energy storage to compete.[64]

**Without more energy storage, California may be forced to import more electricity from other states, including power from high carbon sources such as coal or gas.**

Failure to create the right incentives could undermine California's efforts to create an affordable, reliable, and clean electric power system. Without more energy storage, California may be required to import more electricity from other states, including potentially power generated with higher carbon emissions, such as from coal or gas. The state would be required to keep more gas-fired generators operational in-state to ensure reliability of the electric grid. With more gas will come more emissions. Failure to create incentives, specifically for pumped energy storage, could foreclose investment in the most cost-effective option that creates special advantages. Jobs created for construction of a pumped energy storage project will be more lucrative and longer-lived than those needed to clear and wire staging pads for BESS. Properly sited and configured, large-scale energy storage with spinning turbines can help optimize California's transmission system, including the Sunrise Powerlink that brings clean solar power into southern California. Pumped energy storage is a proven technology with a long track record. It is resistant to types of natural disasters like fires and earthquakes and can provide relief when blackouts occur. The viability of heat-sensitive BESS in fire-prone areas remains unknown. The 40+ year lifetime of pumped energy storage projects helps anchor the state's long-term commitment to renewables.

The advantages of pumped energy storage are becoming clearer, as is the diagnosis of why the state, so far, has not created the right incentives for private investments in pumped energy storage. The central problem is the difficulty under current market and policy arrangements to develop reliable long-term contracts for storage services. This includes energy services agreements and other arrangements that would be needed to arrange long-term debt financing and to minimize the cost of servicing the needed capital. There has been movement at the CAISO in this regard under a concept of energy storage as a transmission asset, but has yet to result in a long-term procurement strategy. [65]

The staff at the CPUC Energy Division have also recognized the challenge of creating incentives for long-term energy storage.[66] In a 2013 report, the CPUC staff noted that the value of a large-scale energy storage system (like pumped energy storage) is rooted in the fact that it operates as an independent asset, similar to a power generator (but not necessarily located at a generation facility), and is controlled independently of other generation sources. It adds value to the energy markets by providing and using energy and offering ancillary services. At present, however, the markets don't create adequate long-term signals to offer this value. For example, the present determination of resource adequacy (RA) is based on short-term needs. Among the possible fixes explored by the CPUC staff include a large-scale storage Net Qualifying Capacity (NQC) value for energy storage that would offer more appropriate RA valuation, along with multi-year contracting in RA. Also useful, according to the CPUC, would be a project-specific scoring system for evaluating the full range value offered by large-scale energy storage. The CPUC has further elaborated on the benefits of large-scale storage with a "Use Case Analysis" for large-scale storage that explores in more detail how various policy reforms could unlock this value.[67]

## What is Needed?

The central purpose of this paper is to articulate the opportunities and challenges for large-scale energy storage in the evolving California grid. In particular, this paper examines the need for a decisive push to deploy pumped energy storage. The lead times for such projects are long. Having projects operationally starting in the mid 2020s requires clearer policy and market signals today. A detailed playbook for making investment in pumped energy storage happen is beyond the scope of this paper, but the elements of a California strategy would include:

- **Jump-starting a new wave of investment.** At present, while pumped energy storage is a proven technology globally, the specific arrangements for encouraging pumped energy storage investments in California are still uneven. Jump-starting investment in this area will require incentives for investment in projects along with parallel efforts to remove bottlenecks in the regulatory and policy environment, even as these projects are evaluated through all the normal environmental assessments that accompany any such large infrastructure investment. Specific incentives can encourage rapid and early investment in a few pumped storage projects that can help demonstrate business models and strategies that will make it easier to attract a larger number of projects in the future. This effort aimed at catalyzing private-sector investment and public-private partnerships could take many forms. Policymakers should begin to consider state policies that would provide reliable signals to investors to procure a suite of pumped storage projects in tandem with the most rapid buildout of renewables on the grid during the 2020s. A fresh mandate for CAISO to back procurement of such projects, or new storage mandates implemented by CPUC are examples of such policies. While the exact form of policy may vary, what is clear is that at least a few new projects must break ground soon, be constructed and enter commercial operation by the mid- to late-2020s when the need for large-scale energy storage will become critical. The incentives offered to help jump start this market should be designed so that the major beneficiaries of new pumped energy storage projects are also those who pay for the costs. This principal is standard in public sector accounting and must be applied here so that new projects are built to make them financially and politically scalable.

- **Studying the future.** While it is clear that jump-starting projects in pumped storage will be highly valuable, California would benefit from a much more aggressive program to study how the grid must evolve with the rapid shift to renewables. Elements of such a study program are already in place at CAISO, CPUC, CEC, and some think tanks, but a much more sustained and systematic look at the future is needed. A particularly urgent need is an updated approach to the IRP to address the concerns noted above, including the need to examine the consequences of a rapid shift to renewables, retirement of fossil fuel generators, and lower emissions over a much longer time horizon. This approach should look more closely at the lead times for large-scale projects, such as pumped energy storage, since investors need reliable signals earlier so that projects are ready when they are needed. This research should include attention to how changes in the federal policy environment may benefit investment in pumped storage in California. Policymakers should evaluate various cost recovery models and mechanisms, including transmission charges, tariff structures, direct load-serving entity contracting, federal energy rate opportunities, and other reasonable cost recovery approaches. Technical analysis should be complemented by analysis of the technical needs for the California grid and how they interact with market and business incentives. The studies will need to evaluate the impact to investors and operators of electric market assets and how they will respond and behave to market and business incentives.

- **Understanding the value of pumped energy storage and other forms of large-scale energy storage in a grid that is rapidly evolving in unpredictable ways.** The effort to study the future must pay very close attention to how the California grid will evolve under "real world" conditions where some of the many ways that are imagined to help integrate massive amounts of renewables don't come to fruition on the imagined schedule. Regional integration of the grid, massive optimal charging of electric vehicles, other forms of "demand response" and advanced new power electronics could all help with integration of renewables. But the scale of the effort needed and the challenges of making those options work in reality must be understood along with the risks of these options faltering. In this light, early investment in large-scale energy storage should be seen and evaluated financially and technically as central to a strategy of ensuring that California can shift to renewables and cut emissions as promised.

**Not only is pumped energy storage a proven technology that is used around the world, it also provides many additional advantages with very low risk.**

- **Identifying early projects.** As noted above, specific incentives are needed to jump-start investment in this area so that a few projects are constructed. The business models that emerge from this fresh investment in new projects will lead to a set of playbooks for how to develop and implement pumped storage projects in California. In time, normal market forces can create the right incentives for fully private sector projects to emerge, but that future won't happen automatically without some earlier projects to demonstrate how private sector participants can manage market and other risks. Some attention is needed to the attributes of the best projects to help make this jump-starting happen. Those are likely to be projects that: a) have low environmental footprints, such as projects that can utilize existing lower reservoirs; b) are close to renewable generation, transmission, and load so they can reduce or offset the need for additional investment in transmission; and c) have the involvement of public agencies that can help steward the necessary relationships between private investors and local interest groups, including land owners, environmentalists, Native American groups, and labor groups so that the projects contribute to responsible, inclusive growth.

With incentives, practical experience, and real projects moving ahead in the 2020s, the private market will follow along and build more projects as needed. That practical experience can also guide additional reforms in policy that will be needed as the California grid continues to move toward increased renewables.

## Conclusion

As a world leader in energy solutions, California is faced with an opportunity to make the shift to renewables at a cost that is acceptable to Californians. Legislative mandates are pushing that shift quickly, and failure to invest in the needed infrastructure to keep the grid reliable will undermine the economic potential and political support vital to California's grid.

While the state has begun the implementation of energy storage at a relatively small scale, the critical need for large-scale storage with long duration deployment is outpacing actual energy storage procurement. The state is relying heavily on other options such as demand response, grid integration, and flexible charging for electric vehicles, which are proving difficult to implement in the real world. Planning for real futures is essential.

Pumped storage is a proven technology that is used around the world, and provides certain advantages over other energy storage technologies including:

1. Long duration energy deployment
2. Spinning inertia that provides grid voltage and frequency regulation
3. Long lasting assets (more than 40 years)

4. Lower long-term costs
5. Lower risk

This storage is essential to enable California to meet its renewable energy and emissions goals in a cost-effective way, while maintaining reliability of the State's vital electric grid. Pumped storage projects are essential for inclusive growth and creating and keeping good jobs in the State. Legislative and regulatory support is needed to ensure the investments California has made in renewable and carbon-free energy actually deliver the benefits that Californians expect.

# Glossary of Terms

**Alternating Current (AC):** An electric current that reverses its direction many times a second at regular intervals. An example is a standard wall socket in a house. .

**Ancillary Services:** 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.

**Arbitrage:** The simultaneous buying and selling of products in a market. Applied to electricity it involves buying power at times when it is cheap, storing and reselling it when prices are higher.

**Automatic Voltage Regulator (AVR's):** Regulates the voltage output of a generator to ensure generators provide reactive support and voltage control, within generating facility capabilities, in order to protect equipment and maintain reliable operation of the interconnection.

**Batteries:** A device that converts chemical energy into electrical energy to provide a source of power and also electrical energy into chemical energy to provide energy storage.

**Battery Energy Storage Systems (BESS):** A compilation of batteries and auxiliary facilities, including air conditioning units to keep the batteries from overheating and inverters, needed to create a functioning system for energy storage using an array of batteries.

**Black Start:** The ability of a generator to start and interconnect with the electrical grid with no source of external power from the electric grid.

**California Energy Commission (CEC):** The CEC, established in 1974 by the Warren-Alquist Act, is the primary energy policy and planning agency for California.

**California Public Utilities Commission (CPUC):** The CPUC regulates services and utilities, protects consumers, safeguards the environment, and assures Californians' access to safe and reliable utility infrastructure and services. The essential services regulated include electric, natural gas, telecommunications, water, railroad, rail transit, and passenger transportation companies.

**California Independent System Operator (CAISO):** CAISO oversees the operation of California's bulk electric power system, transmission lines, and electricity market generated and transmitted by its member utilities.

**Carbon-Free Renewable Energy:** Energy from a source that does not cause emissions of carbon dioxide. With most known technologies, this means energy sources that do not use fossil fuels. This category includes wind, geothermal, hydroelectric, nuclear or solar power.

**Control Area:** The electrical system under the operational control of an Independent System Operator or a Regional Transmission Operator.

**Curtail/Curtailment:** The reduction or removal of renewable energy resources when they are not needed or they are unable to be exported.

**Direct Current (DC):** An electric current flowing in one direction only, such as a battery cell in a flashlight.

**Deep Decarbonization:** The removal of nearly all emissions of greenhouse gases from all sectors of the economy including energy, transportation, and energy efficiency.

**Demand Response:** The ability of an electric load to respond to price or reliability signals.

**Direct Load-Serving Entity Contracting:** A form of contractual electric supply that is dedicated to a specific load.

**Electrical Grid:** A system of generators, transmission and distribution infrastructure that matches and supplies generation with load.

**Electric Power Research Institute (EPRI):** EPRI is a nonprofit organization that conducts research and development related to the generation, delivery, and use of electricity to help address challenges in electricity, including reliability, efficiency, affordability, health, safety, and the environment.

**Energy Storage:** The ability to store energy either through a chemical process like a battery or through potential energy like water pumped uphill (pumped storage), compressed air, or flywheels.

**Federal Energy Regulatory Commission (FERC):** FERC is a United States government agency, established in 1977 to oversee the country's interstate transmission and pricing of a variety of energy resources, including electricity, natural gas and oil.

**Flywheels:** A method of energy storage and rotating speed control using a spinning mass.

**Frequency:** The time parameter of a periodically (cyclically) varying electric current, expressed by the ratio of the number of complete cycles of current variation to unit of time. The number of cycles per second is expressed as Hertz (Hz). In the United States the frequency of the AC electric system is 60 Hz.

**Governors:** A device designed to maintain a constant speed of an electric generator.

**Industrial Combustion:** The process where fuel is burned within an engine converting the chemical energy of the fuel into mechanical energy such as in a combustion engine to power an electric generator.

**Interconnecting Grids:** Independently operated grids that come together allowing coordination of power flows, frequency, reactive power and voltage.

**Lazard:** A financial advisory and asset management firm that engages in investment banking, asset management, and other financial services, primarily with institutional clients.

**Megawatts (MW):** A unit of power equal to one million watts

**Megawatt Hours (MWh):** A volume of power equal to one million watts over the period of one hour

**National Renewable Energy Laboratory (NREL):** The National Renewable Energy Laboratory (NREL), located in Golden, Colorado, specializes in renewable energy and energy efficiency research and development. NREL is a government-owned, contractor-operated facility, and is funded through the United States Department of Energy.

**Net Qualifying Capacity (NQC):** Means an estimate of the amount of Net Qualifying Capacity deliverability a project may receive in accordance with an interconnection agreement.

**Power System Stabilizers (PSS):** A control system applied at a generator that monitors variables such as current, voltage, and shaft speed and sends the appropriate control signals to the voltage regulator to dampen sudden changes in system frequency.

**Price Signals:** A price signal is a message sent to consumers and producers in the form of a price charged for a commodity. This is seen as indicating a signal for producers to increase supplies and/or consumers to reduce demand.

**Primary Frequency Control (PFC):** Ability to regulate short period, random variations of frequency during normal operation conditions and rapid response to an emergency.

**Pumped Energy Storage or Pumped Storage:** A type of hydroelectric energy storage that stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation.

**Renewable Energy:** Energy from a source that does not use depletable fuels (e.g., fossil fuels); the category includes wind, geothermal, hydroelectric or solar power.

**Resource Adequacy (RA):** Sufficient power resources available to reliably serve electricity demands across a range of reasonably foreseeable conditions.

**Superconducting Magnetic Energy Storage (SMES):** Systems that store energy in the magnetic field created by the flow of direct current in a wire coil that has been cooled to a point where resistance to the flow of electricity is eliminated. superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature.

**Supercapacitors:** Type of electrical device that can store a large amount of energy.

**T&D:** Transmission and Distribution. Transmission systems are typically defined as those systems that operate at a voltage of 100 kv or higher.

**Tariff Structures:** The regulated structure that defines the cost of electricity paid by consumers for consuming electric power. The tariff covers the total cost of producing and supplying electric energy plus a reasonable rate of return for the provider.

**Transmission Charges:** The cost of moving electric energy over the transmission system.

**Ultra-High Voltage:** Refers to power transmission lines operating at greater than 800,000 volts (800 kV).

**Uninterruptable Power Supply (UPS):**

**An electrical apparatus that provides emergency power to a load when the input power source fails.**

**Voltage:** Voltage is the electric potential difference between two points.

**Voltage Support:** The ability of an electric generator to adjust output voltage to raise or lower grid voltage.

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## Reviewers

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# References

[1] California Public Utilities Commission, *Renewables Portfolio Standard Annual Report*, November 2017: http://www.cpuc.ca.gov/General.aspx?id=6442455328
[2] California Legislature. Senate. *SB 100, De León. California Renewables Portfolio Standard Program: emissions of greenhouse gases, Chapter 312*, 10 September 2018.
[3] California Independent System Operator (CAISO), Wind and Solar Curtailment, December 31, 2018. (For more on Managing Oversupply see: http://www.caiso.com/informed/Pages/ManagingOversupply.aspx )
[4] Based on 6.7MWh average residential household consumption for the 13.5million households in California as reported for 2017 (most recent year) at: U.S. Energy Information Administration, *Electric Sales, Revenue, and Average Price, Tables T1 and T5a*, October 12, 2018 (corr Jan 15, 2019): https://www.eia.gov/electricity/sales_revenue_price/
[5] Assumes 150-megawatt solar project at 30 percent capacity factor and $1 dollar per watt assumed cost.
[6] This calculation comes from dividing the 460,000 MWh of curtailment in 2018 into the approx. 206,146,000 MWh of net generation in the state (see 2017 data, which are about the same for 2018, reported at Table 10 of the California Electricity Profile at: https://www.eia.gov/electricity/state/california/ )
[7] The exact share was 32% for 2017. California Energy Commission, *Tracking Progress* (July 2018)
[8] For renewable investment planning see, for example, Mark Rothleder "Renewable Integration" Presentation to the California Energy Commission IEPR Workshop, May 12, 2017. http://www.caiso.com/Documents/RenewableIntegrationUnlockingDividends.pdf
[9] This calculation divides the daily curtailment into the estimated daily net generation for April 2018. Daily generation is from net monthly generation for utility scale facility net generation (table 1.3.A of the EIA Report Electric Power Monthly with data for April 2018, (June 2018) https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_03_a
[10] California Independent System Operator, *Impacts of Renewable Energy on Grid Operations*, May 2017: https://www.caiso.com/documents/curtailmentfastfacts.pdf
[11] Nelson, J. and Wisland, L, *Achieving 50 Percent Renewable Electricity in California: The Role of Non-Fossil Flexibility in a Cleaner Electricity Grid*, Table 3, Union of Concerned Scientists, August 1, 2015: https://www.jstor.org/stable/resrep17224
[12] Fundamentally this "minimum" requires an assessment of both the technical characteristics of the grid and the economics of avoiding curtailment. All grids with large amounts are renewables are likely to have some curtailment, but excessively high levels of curtailment are a sign of poor management or constraints on investment and operations that can be extremely costly. This scenario has been playing out on the Chinese grid, for example. Davidson, M. R. Technology Integration in China's Electricity System: Central Targets and Local Challenges. In T. G. Rawski & L. Brandt (Eds.), *Policy, Regulation and Innovation in China's Electricity and Telecom Industries*, (in press).
[13] California Energy Commission, *Final 2017 Integrated Energy Policy Report*, Chapter 1, April 16, 2018: https://efiling.energy.ca.gov/getdocument.aspx?tn=223205
[14] Working Group III Technical Support Unit, *Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.
[15] California Energy Commission, *Deep Decarbonization in a High Renewables Future*, June 2018 https://efiling.energy.ca.gov/GetDocument.aspx?tn=223785
[16] California Air Resources Board, *1990-2004 Inventory Data*, June 6, 2017: https://www.arb.ca.gov/cc/inventory/1990level/1990data.htm
[17] Executive Order B-55-18 (10 September 2018). https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf
[18] Computed from U.S. Environmental Protection Agency Greenhouse Gas Equivalencies Calculator: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator , accessed January 26, 2019.
[19] California Legislature. Senate. SB 100, *De León. California Renewables Portfolio Standard Program: emissions of greenhouse gases, Chapter 312*, Section 454.53, 10 September 2018
[20] CPUC is aware of these challenges, as are other energy-related agencies in the State, but the process of developing new scenarios and IRPs is a slow one and must also address the many deep uncertainties

about the rapid shift to renewables and lower emissions. For example, CPUC has looked at some lower emission scenarios but not done fine-grained analysis of how much the power sector will need to cut as other sectors struggle to make reductions. Also, the reference case does not reflect this environment of rapid change in the California policy. See, for example, CPUC "Proposed References System Plan," September 18, 2017, http://cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/AttachmentA.CPUC_IRP_Proposed_Ref_System_Plan_2017_09_18.pdf

[21] See Portland General, "Integrated Resource Planning," Roundtable 19-1, February 27, 2019. https://www.portlandgeneral.com/-/media/public/our-company/energy-strategy/documents/2019-02-27-irp-roundtable-19-1.pdf?la=en

[22] Baker, David R. *California's power grid is changing fast, and 'we don't have a plan'*, San Francisco Chronicle, May 2018. https://www.sfchronicle.com/business/article/California-s-electricity-grid-is-changing-fast-12885084.php

[23] U.S. Energy Information Administration, *Electricity Browser Data-California, Alaska, Connecticut, Hawaii, Massachusetts, New Hampshire, and Rhode Island*, https://www.eia.gov/electricity/data/browser/ accessed December 3, 2018.

[24] California Legislature. Senate. *SB 100, De León. California Renewables Portfolio Standard Program: emissions of greenhouse gases, Chapter 312*, Section 454.53, 10 September 2018.

[25] CAISO "Solutions" at http://www.caiso.com/informed/Pages/ManagingOversupply.aspx. See also: https://www.utilitydive.com/news/getting-to-100-zero-emissions-in-california-beyond-caisos-eight solution/544467/

[26] Holland, S. and Mansur, E., *Is Real-Time Pricing Green? The Environmental Impacts of Electricity Demand Variance*, The Review of Economics and Statistics, MIT Press, vol. 90(3), pages 550-561, 04, April 2008.

[27] Alcott, H., *Evaluating Energy Efficiency Policies*, NBER Reporter 2017 Number 2: https://www.nber.org/reporter/2017number2/allcott.html, accessed December 3, 2018.

[28] Starn, J., *Power Worth Less Than Zero Spreads as Green Energy Floods the Grid: Wind and solar farms are glutting networks more frequently, prompting a market signal for coal plants to shut off*, August 5, 2018: https://www.bloomberg.com/news/articles/2018-08-06/negative-prices-in-power-market-as-wind-solar-cut-electricity

[29] Davis, L., *Is solar really the reason for negative electricity prices?*, August 28, 2017: http://blogs.berkeley.edu/2017/08/28/is-solar-really-the-reason-for-negative-electricity-prices/

[30] Los Angeles Times, *California invested heavily in solar power. Now there's so much that other states are sometimes paid to take it*, June 22, 2017: https://www.latimes.com/projects/la-fi-electricity-solar/

[31] Pérez-Arriaga, I.J., et al., *Utility of the Future: An MIT Energy Initiative response to an industry in transition*, Cambridge, MA: MIT Energy Initiative, December 2016.

[32] Wei Peng, et al, *Air Quality and Climate Benefits of Long-Distance Electricity Transmission in China, Environmental Research Letters*, June 2017. http://iopscience.iop.org/article/10.1088/1748-9326/aa67ba/pdf

[33] E.g., Christian M. Grams, Remo Beerli, Stefan Pfenninger, Iain Staffell, and Heini Wernli, "Balancing Europe's wind-power output through spatial deployment informed by weather regimes" *Nature Climate Change* vol 7 (August 2017).

[34] Sepulveda, N., Jenkins, J. et. al, *The Role of Firm Low-Carbon Electricity Resources in Deep Carbonization of Power Generation*, Joule Volume 2, Issue 11, p. 2403-2420, November 21, 2018.

[35] For example, these difficult-to-police problems of co-mingling of "cleaner" and "dirtier" electrons on a fungible grid were raised in the context of passage of SB100 in 2018, which requires the state to get 100% of its electricity from clean sources. California Legislature. Senate. *SB 100, De León. California Renewables Portfolio Standard Program: emissions of greenhouse gases, Chapter 312, Section 454.3, subsection (a)*, 10 September 2018.

[36] Jorgenson, Jennie, et al, *Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future, National Renewable Energy Laboratory*, January 2017. https://www.nrel.gov/docs/fy17osti/67240.pdf

[37] Jimmy Nelson, Saamrat Kasina, John Stevens, Jack Moore, Arne Olson, Mahesh Morjaria, John Smolenski and Jose Aponte, 2018, "Investigating the Economic Value of Flexible Solar Power Plant Operation," Energy & Environmental Economics, https://www.ethree.com/wp-content/uploads/2018/10/Investigating-the-Economic-Value-of-Flexible-Solar-Power-Plant-Operation.pdf

[38] Jenkins, J.D., Zhou, Z., Ponciroli, et. al, "*The benefits of nuclear flexibility in power systems operations with renewable energy*," Applied Energy 222: 872-884. doi:10.1016/j.apenergy.2018.03.002

[39] The long-term modeling work by E3 identifies the need to understand the investment and availability of long-duration energy storage technologies as pivotal for 'resource adequacy and energy sufficiency during periods of low renewable energy availability (p.68). See: A. Mahone et al, 2018, "Deep Decarbonization in a High Renewables Future," Final Project report CEC-500-2018-012. https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf

[40] Zach Ming et al., "Resource Adequacy in the Pacific Northwest," Environment and Energy Economics, March 2019. https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf

[41] California Independent System Operator, *Storage as a Transmission Asset: Enabling storage assets providing regulated cost-of-service based transmission service to access market revenues-Straw Proposal*, p. 32, May 18, 2018.

[42] Federal Energy Regulatory Commission, *Utilization of Electric Storage Resources for Multiple Services When Receiving Cost-Based Rate Recovery*, Policy Statement, 158 FERC ¶61,051 at p. 9. January 19, 2017.

[43] Among the initiatives is one that might generate additional revenues for storage projects that provide transmission services, although whether such transmission-anchored projects could be of sufficient scale to serve the State's bulk energy storage needs and the business models for developing such projects are among the many open questions. California Independent System Operator, *Storage as a Transmission Asset: Enabling storage assets providing regulated cost-of-service based transmission service to access market revenues-Issue Paper*, March 30, 2018.

[44] The Guardian, *India blackouts Leave 700 million without power: Power cuts plunge 20 of India's 28 states into darkness as energy suppliers fail to meet growing demand*, July 31, 2012: https://www.theguardian.com/world/2012/jul/31/india-blackout-electricity-power-cuts

[45] See "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California Event October 9, 2017" Joint NERC and WECC Staff Report (February 2018) https://curent.utk.edu/files/6715/1924/9100/NERC_Report_October_9_2017_Canyon_2_Fire_Disturbance_Report_900_MW_Solar_Photovoltaic_Resource_Interruption_Disturbance_Report.pdf
Steve Ashbaker (WECC) and Rich Bauer (NERC), "Inverter Task Force/Blue Cut Fire" Western Electricity Coordinating Council.
https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf

[46] The exact amount is still a question of intense and important debate. The PJM market, which faces a much smaller rise in renewables, looked in detail at this question and found that the need for ancillary services did in fact increase, but only modestly. The exact rise needed for a smaller and less interconnected grid (California) with a more rapid shift to renewables is a topic urgently needing attention. For more see: ERCOT Concept Paper, September 2013 http://www.ferc.gov/CalendarFiles/20140421084800-ERCOT-ConceptPaper.pdf; Ela, E, et al, *Active Power Controls from Wind Power: Bridging the Gaps*, NREL, January 2014 http://www.nrel.gov/docs/fy14osti/60574.pdf; and Trabish, Herman K., *California solar pilot shows how renewables can provide grid services*, Utility Dive, October 2017 https://www.utilitydive.com/news/california-solar-pilot-shows-how-renewables-can-provide-grid-services/506762/.

[47] Most research on curtailment and the value of storage has focused on shorter term variability and value of storage, but at renewables rise the value for longer term storage rises as well. See generally Clack, C., Qvist, S. et. al, *Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar*, Proceedings of the National Academy of Sciences of the United States, 114 (26) 6722-6727, June 19, 2017.

[48] Clack, C., Qvist, S. et. al, *Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar*, Proceedings of the National Academy of Sciences of the United States, 114 (26) 6722-6727, June 19, 2017.

[49] Moreno, J., Bhattarai, M. et. al, *Pumped Storage in Spain*, International Water Power and Dam Construction, July 11, 2013: http://www.waterpowermagazine.com/features/featurepumped-storage-in-spain/.

[50] For detailed power output through 2017 for wind (19.2%) and solar (5.4%) see: https://renewablesnow.com/news/renewables-produce-337-of-spains-power-in-2017-596136/

[51] Sandia National Laboratories, DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, September 2014: https://prod.sandia.gov/techlib-noauth/access-control.cgi/2015/151002.pdf

[52] Denholm, P. and Margolis, R., *Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California*, U.S. Department of Energy National Renewable Energy Laboratory, August 2016: http://www.nrel.gov/docs/fy16osti/66595.pdf

[53] For example: https://www.utilitydive.com/news/getting-to-100-zero-emissions-in-california-beyond-caisos-eight-solution/544467/

[54] For more detail about all the financial key assumptions, see Appendix A-1. Capital costs depend partly on the particulars of the individual sites, and some of the attributes of the more financially attractive sites are discussed below. As an illustration of the capital cost of a project that has been recently explored with cost estimates reported publicly, the Iowa Hills Pumped Storage project has a cost per MWh of $453,000/MWh in 2019 dollars. The estimates we use for our analysis are our best assessment of capital costs for a high-quality site extended to the year 2026.

[55] For a detailed summary of the assumptions see Table A1 in the Appendix.

[56] The extra upgrades at year 50 we estimate, based on industry experience and projected with civil works inflation, at about $90 per MWh in 2026 dollars, or about one-fifth the cost of building a new pumped storage facility. For the full assumptions see table A3 in the Appendix.

[57] We are mindful that all comparisons of the types presented here depend critically on assumptions and thus in the appendix we have included some detailed sensitivity analysis. And in the main text, below, we focus on the impact of uncertainties in the most important variable: capital cost. Other important uncertainties in this analysis include the future cost of electricity for pumping. We assume $24 per MWh, which rises at 1.25% per year for the first fifty years, consistent with today's energy markets. These power prices, however, may be flat or even declining in the future with massive over-building of solar systems that could supply electricity at much lower prices, even zero, mid-day. If so, the cost of pumping and storing energy will decline as a portion of the overall LCOS. We note, below, that the Lazard analysis uses charging costs that are higher than our 24 $/MWh, and we present the Lazard numbers exactly as they are so that the data we offer here for comparison are identical to what is already in the established literature. And there are good reasons why Lazard—which looks across the market for battery systems, not just in California where the buildout of solar is proceeding especially rapidly (and thus mid-day overgeneration and lower prices are more likely)—uses higher charging costs. While Lazard's BESS 2018 basis charging energy cost is slightly higher than PS pumping energy cost basis, it is escalated at a lower rate. The 20-year BESS model was sensitized using the PS basis. This would reduce the BESS LCOS by about 3%. It did not change the comparative results. It was decided to use the Lazard rates for the BESS in order to maintain compatible results with Lazard.

[58] For more detail on this 100-year extension see the Appendix.

[59] For the Lazard analysis see table A4 in the Appendix and see LAZARD, LAZARD's Levelized Cost of Storage Analysis - Version 4.0, November 2018: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjE_Ie3zO7gAhUwHTQIHSHzCiEQFjAAegQIAhAC&url=https%3A%2F%2Fwww.lazard.com%2Fmedia%2F450774%2Flazards-levelized-cost-of-storage-version-40-vfinal.pdf&usg=AOvVaw1SFyUmw4QB65U_5pEDrr82

[60] Other differences include variation in charging costs and in inflation of those costs. (Lazard starts with higher charging costs but lower rates of inflation, compared with our analysis of pumped storage. We have left the assumptions "as is" to allow ready comparison with published literature.) See earlier note for more discussion of this topic and the Appendix for sensitivity analysis.

[61] In theory it is possible to estimate the costs for a Li project of 8 hours duration, but in practice doing that requires so many assumptions that it would not be useful for the present purposes. Among the

assumptions required are the charging/discharging cycles. Today's battery systems mostly operate over short charge cycles because most of the financial value comes from brief storage services—for example, rapid ramping that previously was provided by a natural gas peaker plant or an over-built transmission system. Those values are important and an area where batteries provide excellent grid services, but the experience from those short duration projects is not comparable in any way to the larger-scale long-duration bulk grid storage services we are focused on in this White Paper.

[62] For the EPRI analysis we use their computed full capital costs for their maximum size 8-hour projects (50MW) for providing what EPRI calls "bulk services". This allows a comparison of capital costs with Lazard without needing to complexify the analysis by stacking other services beyond bulk storage—such as frequency regulation and grid support. Scaling to larger battery systems of this type will lead to some modest economies of scale, most likely, since some transformer, engineering and other costs can be amortized over a larger project. See EPRI, Energy Storage Technology and Cost Assessment: Executive Summary, December 2018, https://www.epri.com/#/pages/product/3002013958/?lang=en-US. We note that EPRI's analysis also includes flow batteries of various types, which have attracted considerable attention as an alternative means of battery-based bulk energy storage. It is important to note, as well, that EPRI's assessment is that flow batteries remain immature and largely untested for these functions—and thus by their analysis flow batteries are much more expensive than lithium (with today's knowledge) and even more expensive than our analysis of pumped storage.

[63] Among the other reputable studies on battery costs. All of these studies see a wide range of costs and are roughly comparable with Lazard and EPRI.

[64] California Public Utilities Commission, *Decision on Track 2 Energy Storage Issues*, Rulemaking 15-03-011, April 27, 2017: http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M184/K630/184630306.PDF

[65] Malashenko, E., O'Donnell, A. et. al, *Energy Storage Phase 2 Interim Staff Report*, California Public Utilities Commission, Energy Storage Proceeding R.10-12-007, January 4, 2013.

[66] California Public Utilities Commission, Decision Adopting Energy Storage Procurement Framework and Decision Program, Rulemaking 10-12-007, September 3, 2013: http://docs.cpuc.ca.gov/publisheddocs/published/g000/m079/k533/79533378.docx

[67] California Public Utilities Commission. *Draft Energy Storage Use Case Analysis-Transmission Connected Energy Storage*, Energy Storage Proceeding R.10-12-007

# Appendix

## METHODOLGY AND KEY ASSUMPTIONS USED IN THE LCOS ESTIMATES FOR BESS AND PS ALTERNATIVES

### METHODOLOGY

1. An electric industry standard Levelized Cost of Storage (LCOS) economic analysis process was used. A simplified spreadsheet model was developed.
2. The key assumptions, presented below, are representative of generic Pumped Storage Projects (PS) and Battery Energy Storage Systems (BESS) that would be operated for wholesale daily storage in a regional electrical grid.
3. Data taken from Lazard's Levelized Cost of Storage Analysis 00 Version 4.0 (Lazard) was used as model input for BESS alternatives. As a baseline, the study model was correlate with the results of Lazard's Lithium ion, wholesale market, 20-year life, 100MW/400 MWh alternative. The results correlate well with Lazard's LCOS of $204/MWh for the low capital cost range. For the high range cost, the model LCOS of $275/ MWh did not exactly match Lazard $298/ MWh LCOS but is deemed within an acceptable range.
4. For PS, the base model was a 40-year life, 500MW/4,000MWh project using input data from planned or recently evaluated pumped storage projects in California. The key assumptions were discussed with Black & Veatch along with investors and equipment suppliers and contractors to confirm they were within industry norms.
5. Once the BESS and PS baseline models were established, the following sensitivities were performed, as discussed in the report and as summarized in the table found at the end of this Appendix:
    a. The baseline 20-year life BESS project using low-range cost factors. (Column A)
    b. A 20-year life BESS project using high-range cost factors. (Column B)
    c. To provide a comparison of LCOS between PS and BESS for both high and low range costs, 40-year BESS life-extended projects were developed. (Columns C and D)
    d. The baseline 40-year PS project. (Column E)
    e. A 50-year life PS project. (Column F)
    f. To reflect the potential 100-year life of PS, an estimate of the LCOS for an additional 50-year PS life. (Column G)

### KEY ASSUMPTIONS

1. The commercial operation year was selected as 2026 and is the earliest reasonable year that a pumped storage project would be operational. Adjustment of Lazard's 2018 cost basis was considered and discussed below.
2. The modeled plant capacity (MW) is the net power supplied at the point of interconnection (POI) to the grid. To match Lazard assumptions, the plant capacity does not include the additional plant capacity required to offset power loss due to step-up transformer efficiency and transmission line to the POI. If this were to be included an additional 10%-15% would need to be added to both alternatives.

3. The energy storage (MWh) is calculated as the product of the capacity times the hours of plant operation in the generating or discharge mode.
    a. For BESS it was selected based on the Lazard report as four hours. This is acknowledged as being non-conservative as BESS has not been demonstrated that the batteries can be fully discharged. Allowable discharge duration of 2-3 hours would be more realistic and conservative. For purposes of this analysis and to compare more directly to Lazard, the full discharge depth / full capacity is assumed.
    b. For PS, in order to achieve minimum economics of scale and support daily storage operation eight hours at full generating capacity is selected. This a significant difference between the two technologies.
4. With respect to plant availability and capacity factor:
    a. Lazard, page 28, reports a BESS project would be available 350 days a year, each day operating for 4 hours at full capacity. This works out to a capacity factor of about 16%.
    b. For the pumped storage, it was assumed that there will be slightly more downtime for mechanical maintenance outages and that the plant would operate 329 days a year, each day operating for 8 hours at full capacity or a capacity factor of 30%.
    c. Depending on the actual CAISO dispatch needs, the differences in capacity factor indicate a PS could provide additional energy storage and grid support services.
5. With respect to assumed capital costs:
    a. Lazard reports cost factors that are dependent on the project utilization. Extrapolating data on pages 6 and 28 and using their wholesale market parameters, the following range of 2018$ capital cost factors were assumed:
        i. BESS Equipment Cost. Lazard, page 28, range of $232/MWh - $398/MWh of storage capacity (400MWh).
        ii. Inverter Cost. Lazard, page 28, range of $49 /MW -$61 / MW of plant capacity (100MW).
        iii. Balance of System Cost. Lazard, page 6, footnote 6, $27.00/kWh of storage capacity. This was kept constant.
        iv. EPC Cost. Lazard, page 6, applied a 16.7% mark-up to the sum of the BESS, Inverter and Balance of System Costs.
        v. BESS Cost Escalation to COD. As noted above the Lazard costs are in 2018 dollars. For purposes of this analysis, capital costs were assumed to remain constant to a 2026 COD.
    b. PS capital costs are dependent partly on the particulars of the individual sites. A project was configured to reflect the following:
        i. An existing lower reservoir.
        ii. An underground powerhouse with four x 125 MW pump turbine units.
        iii. An upper reservoir using a ring dike.
        iv. After reviewing a number of available alternative cost estimates, the Iowa Hills Pumped Storage project was judged as the most recent and a reasonable basis. It has a reported $2016 cost per MWh of $453,000/MWh. Adjusting for differences in scope and timing, a $2026 cost of $477,000 was selected.
    c. Capital costs for BESS and PS did not include land costs, development costs, or transmission cost.

6. The energy required to charge the BESS or pump-back to an upper reservoir is equal to the total annual generation divided by the applicable cycle efficiency.
    i. Lazard, page 6, calculates annual charging energy based on 140,000 MWh of annual generation and an 87% cycle efficiency.
    ii. PS pump-back energy was based on annual generation energy of 1,314 GWh. Typical cycle efficiencies range from 75%-85% depending on equipment selected and project configuration. A 77% mid-range efficiency was selected.
  b. Given California's recent history of negative pricing, curtailment of off-peak energy generation and the changing of the utility rate structures to time-of-use basis, predicting the future 2026 energy rates is challenging. Lazard used a generic US energy purchase rate of ($2018) $33 per MWh escalated at 0.55% per year. Reviewing CPUC and EIA data for 2018 indicated a range of $15 to $25 per MWh. $22/MWh was selected and escalated at 1.25% to $24/MWh ($2026) for PS pumping energy.
  c. While Lazard's BESS 2018 basis charging energy cost is slightly higher than PS pumping energy cost basis, it is escalated at a lower rate. The 20-year BESS model was sensitized using the PS basis. This would reduce the BESS LCOS by about 3%. It did not change the comparative results. It was decided to use the Lazard rates for the BESS in order to maintain compatible results with Lazard.
7. With respect to annual O&M costs:
    a. BESS was modeled using Lazard data, page 6, which indicated a year 1 cost of $5.7 million escalated at 2.5%.
    b. For PS a line item estimate was developed that resulted in a year 1 cost of $8.8 million, also escalated at 2.5%.
8. To analyze the impact to the BESS LCOS to extend the life from 20-years to 40-years, the following model adjustments were performed:
    a. Lazard acknowledges that BESS equipment performance will degrade over time and provides an O&M allowance of 4.2% of original BESS installed cost for what they call "augmentation". This is understood to be an addition of BESS modules to make up for degraded storage over time. This however does not reflect the cost to extend the life of the full project for another 20 years.
    b. Starting in year 15 the BESS equipment will be modernized and upgraded to industry standards in place at that time. Since actual scope and cost for life extension is unknown, it was assumed as follows:
        i. The life-extension cost would be 75% of the Lazard BESS equipment module cost of $205/MWh (page 6, footnote 4) or $154/MWh.
        ii. All other costs would have been covered by the Lazard augmentation cost included in their base O&M cost.
        iii. The life-extension would occur over a five-year period.
        iv. To provide funding a reserve account would be set-up and funded using an additional O&M cost of $2.75 Million per year (constant). The reserve fund would earn interest at 5%.
9. To analyze the impact to the PS LCOS to extend the life from 50-years to 100-years, the following model adjustments were performed:

    a. A separate 50-year LCOS analysis was performed to reflect a significantly different cost structure since debt and equity return will be drastically reduced.
    b. A new debt of $360 million was added and amortized for 50 years to pay for refurbishing the pump-turbines, and other project features.
    c. The Year 1 pumping and O&M costs were carried over from the original 50-year analysis. Both were escalated at 1.25% from that point.
    d. The LCOS for this analysis used a starting year of 2076. For presentation purposes the 2076 LCOS value was brought back to a 2026 starting year using a deflation rate of 1.25%.

10. Financial model parameters are significantly different for BESS and PS projects due to their historic financial performance and project specific risk profiles. The following parameters were used:
    a. The internal rate of return (IRR) for each alternative was set constant at 12% and is equal to what was used in the Lazard report (Version 4.0).
    b. Debt / Equity Ratio
        i. Lazard uses 20% debt / 80% equity (page 6). This was adopted for this study.
        ii. Pumped storage was evaluated at 66% debt / 34% equity.
    c. Financing Terms. Both BESS and PS assume financing by private developers.
        i. Lazard assumed an 8%, 20-year debt service (page 6). No further back-up data is available on this rate selection but is assumed for this study based on Lazard's knowledge of the BESS industry.
        ii. Based on discussions with pumped storage developers, an interest rate range of 5% to 6% for a 40-year debt service. A separate calculation arrived at a rate of 5.52% based on recent 30-year forward Treasury rate of 3.27% plus a 2.25% spread was used.
    d. Taxes. Both BESS and PS assume a combined federal and state income tax rate of 28% on net taxable income. Lazard did not include a cost allowance for property taxes so both models do not include property taxes.

# Levelized Cost of Storage Analysis
## Summary Tables

| CRITERIA | UNIT | BESS --20 YR (LOW) | BESS --20 YR (HIGH) | BESS --40 YR (LOW) | BESS --40 YR (HIGH) |
|---|---|---|---|---|---|
| | | A | B | C | D |
| **Financial Results** | | | | | |
| Developer IRR | | 12% | 12% | 12% | 12% |
| LCOS | $/MWh | $ 204.00 | $ 275.00 | $ 218.00 | $ 285.00 |
| Levelizing Starting Year | | 2026 | 2026 | 2026 | 2026 |
| | | | | | |
| **Investment** | | | | | |
| Project Capacity at POI (MW) | | 100 | 100 | 100 | 100 |
| Storage (MWh) per day | MWh | 400 | 400 | 400 | 400 |
| BESS Initial Unit Cost | $/MWh | $ 232.00 | $ 398.00 | $ 232.00 | $ 398.00 |
| BESS Initial Cost | x1000 | $ 92,800 | $ 159,200 | $ 92,800 | $ 159,200 |
| Inverter Unit Cost | $/kW | $ 49.00 | $ 61.00 | $ 49.00 | $ 61.00 |
| Inverter Cost | x1000 | $ 4,900 | $ 6,100 | $ 4,900 | $ 6,100 |
| BOP System Unit Cost | $kwh | $ 27.00 | $ 27.00 | $ 27.00 | $ 27.00 |
| BOP System Cost | x1000 | $ 10,800 | $ 10,800 | $ 10,800 | $ 10,800 |
| Subtotal | x1000 | $ 108,500 | $ 176,100 | $ 108,500 | $ 176,100 |
| EPC Mark-up | 16.7% | $ 18,120 | $ 18,120 | $ 18,120 | $ 18,120 |
| Total Capital Cost | x1000 | $ 126,620 | $ 194,220 | $ 126,620 | $ 194,220 |
| | | | | | |
| **Operating Parameters** | | | | | |
| Operating Days per year | | 350 | 350 | 350 | 350 |
| Generating Hours Per Day | | 4 | 4 | 4 | 4 |
| Annual Generation | MWh | 140,000 | 140,000 | 140,000 | 140,000 |
| | | | | | |
| **Charging Cost** | | | | | |
| Annual Generation | MWh | 140,000 | 140,000 | 140,000 | 140,000 |
| Daily Storage Hours | Hours | 4 | 4 | 4 | 4 |
| Cycle Efficiency | | 87% | 87% | 87% | 87% |
| Pumping Energy | MWh | 160,920 | 160,920 | 160,920 | 160,920 |
| Charging Rate | | $ 0.033 | $ 0.033 | $ 0.033 | $ 0.033 |
| Year 1 Charging Cost | x1000 | $ 5,310 | $ 5,310 | $ 5,310 | $ 5,310 |
| Charging Rate Escalator | | 0.55% | 0.55% | 0.55% | 0.55% |
| | | | | | |
| O&M Cost | | | | | |
| Year 1 O&M Cost | x1000 | $ 5,700 | $ 5,700 | $ 5,700 | $ 5,700 |
| O&M Escalator | | 2.50% | 2.50% | 2.50% | 2.50% |
| | | | | | |
| **Financial Inputs** | | | | | |
| Tax rate on net income | | 28% | 28% | 28% | 28% |
| Interest rate on loan | | 8% | 8% | 8% | 8% |
| Time period for loan (years) | | 20 | 20 | 20 | 20 |
| Reserve Account Contribution | | 0 | 0 | $ 2,575 | $ 2,575 |
| Debt | 20% | $ 25,324 | $ 38,844 | $ 25,324 | $ 38,844 |
| Equity | 80% | $ 101,296 | $ 155,376 | $ 101,296 | $ 155,376 |
| Reserve Interest | | NA | NA | 5% | 5% |

# Levelized Cost of Storage Analysis
## Summary Tables

| CRITERIA | UNIT | PS -- 40 YR | PS--50 YR | PS--YR 51-100* |
|---|---|---|---|---|
| | | E | F | G |
| **Financial Results** | | | | |
| Developer IRR | | 12% | 12% | 12% |
| LCOS | $/MWh | $ 186.00 | $ 177.00 | $ 108.00 |
| Levelizing Starting Year | | 2026 | 2026 | 2076 |
| **Investment** | | | | |
| Project Capacity at POI (MW) | | 500 | 500 | 500 |
| Storage (MWh) per day | MWh | 4,000 | 4,000 | 4,000 |
| Unit Capital Cost | $/MWh | $ 477 | $ 477 | $ 90 |
| Capital Cost | x1000 | $ 1,906,000 | $ 1,906,000 | $ 360,000 |
| Subtotal | x1000 | $ 1,906,000 | $ 1,906,000 | $ 360,000 |
| Total Capital Cost | x1000 | $ 1,906,000 | $ 1,906,000 | $ 360,000 |
| * Levelized cost using a start date of 2026 is $58.00 using a 1.0125% de-escalator. | | | | |
| **Operating Parameters** | | | | |
| Operating Days per year | | 329 | 329 | 329 |
| Generating Hours Per Day | | 8 | 8 | 8 |
| Annual Generation | MWh | 1,314,000 | 1,314,000 | 1,314,000 |
| **Charging Cost** | | | | |
| Annual Generation | MWh | 1,314,000 | 1,314,000 | 1,314,000 |
| Daily Storage Hours | Hours | 4 | 4 | 4 |
| Cycle Efficiency | | 77% | 77% | 77% |
| Pumping Energy | MWh | 1,706,494 | 1,706,494 | 1,706,494 |
| Charging Rate | | $ 0.024 | $ 0.024 | $ 0.024 |
| Year 1 Charging Cost | x1000 | $ 40,956 | $ 40,956 | $ 75,279 |
| Charging Escalation | | 1.25% | 1.25% | 1.25% |
| **O&M Cost** | | | | |
| Year 1 O&M Cost | x1000 | $ 8,781 | $ 8,781 | $ 23,000 |
| O&M Escalator | | 2.50% | 2.50% | 2.5 |
| **Financial Inputs** | | | | |
| Tax rate on net income | | 28.00% | 28.00% | 28.00% |
| Interest rate on loan | | 5.52% | 5.52% | 5.52% |
| Time period for loan (years) | | 40 | 50 | 50 |
| Reserve Account Contribution | x1000 | $ 1,888 | $ 1,888 | $ 1,888 |
| Debt x1000 | 66% | $1,255,482 | $1,255,482 | $ 216,000 |
| Equity x1000 | 34% | $ 650,518 | $ 650,518 | $ 144,000 |
| Reserve Interest | | 5% | 5% | 5% |