DOCKETED

Docket Number:	20-MISC-01
Project Title:	2020 Miscellaneous Proceedings.
TN #:	240545
Document Title:	Draft Storage Technology Summary
Description:	Draft Storage Technology Summary report submitted for public review.
Filer:	Jeffrey Sunquist
Organization:	California Energy Commission
Submitter Role:	Commission Staff
Submission Date:	11/10/2021 9:40:50 AM
Docketed Date:	11/10/2021

DRAFT STORAGE TECHNOLOGY SUMMARY

November 2021

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

This summary is posted for requested public comment

ACKNOWLEDGMENTS

The authors of this report thank the California Energy Commission for its financial support and guidance on this project. The project benefited from the inputs of many individuals. The project team is listed here.

NAME	ORGANIZATION
Prof. Sarah Kurtz	University of California Merced
Prof. Daniel Kammen	University of California Berkeley
Asst. Prof. Noah Kittner	University of North Carolina
Asst. Prof. Patricia Hidalgo-Gonzalez	University of California San Diego
Asst. Prof. Sergio Castellanos	University of Texas at Austin
Kenji Shiraishi	University of California Berkeley
Julia Szinai	University of California Berkeley
Pedro Andrés Sánchez Pérez	University of California Merced
Jeremiah Reagan	University of California Merced
Zabir Mahmud	University of California Merced
Mahmoud Abido	University of California Merced
Rui Shan	University of North Carolina
Martin Staadecker	University of California San Diego

Additionally, the following individuals have contributed comments and suggestions

NAME	ORGANIZATION
Julia Prochnik	Long-Duration Energy Storage Association of California
Ron Sinton	Sinton Instruments
Richard Brody	Quidnet Energy

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

This Storage Technology Summary reviews the storage technologies that may be useful to California in meeting the SB100 goals in the context of providing long-duration storage. Multiple technologies are poised to contribute. An overview of these is presented in Table Exec 1, which serves as a summary of the primary conclusions of the report.

This report complements a second report "Generation Technologies," which elucidates how the choice of electricity-generating technologies affects the need for energy storage.

Section 1 of this report gives an overview of what long-duration storage is and how it has the potential to support a decarbonized grid. Section 2 reviews many of the developed or developing technologies that may be used for storage. Section 3 describes an approach to modeling that is meant to identify the cost target that a specific storage technology (defined by efficiency and duration) must achieve to be able to be successful in the market.

This version is provided for public comment. Please use the website where this was posted.

Table Exec 1 Summary of energy storage technologies

Technology	Strengths	Opportunities (technical and market)	Policy needs
Lithium batteries	High efficiency; ease of use	Continued growth – is currently expanding very rapidly	Modify market structure to enable more effective use (of all storage) Support expanded market; include in ITC and other incentives even without solar
Pumped hydropower	High-efficiency; least cost over 100-year lifetime; well established	Can provide long-term benefit to the community including water and jobs once completed. Closed-loop implementation may open many new sites	Support to implement large projects through permitting and financing
Gravity	High efficiency and the land footprint can be minimal and or flexible	Can have negligible idle loss even over months of time	Support permitting, deployment to reduce risk
Flow batteries Metal-air and exfoliated-metal batteries	Potential to be lower cost than Li batteries for higher energy-to-power ratios	May enter market by providing resilience via microgrids during power outages.	Support R&D and deployment to prevent being locked out by Li batteries
Compressed air storage	Decades of experience; Advanced technology has higher efficiency and more flexibility in siting	Has potential for large scale, low-cost deployment once it demonstrates performance	Support deployment of advanced compressed air technology; facilitate permitting
Liquid air	Leverages existing supply chain to be scalable; May achieve high efficiency; ready to scale	Is ready to scale deployment for > 4-h systems	Support deployment and permitting
Thermal – CSP	Recent cost reductions combined with synergy of CSP + storage	Could combine generation with storage as costs come down	Support deployment and cost-reduction strategies
Thermal – without solar	Combined with decarbonization of industrial heating. May use very inexpensive storage media like sand or rocks to increase energy capacity at low cost	Could play primary role of decarbonizing industrial heating, then that success could be leveraged to give inexpensive storage; may be incorporated in existing fossil fuel power plants	Support decarbonization projects that also provide storage; support retrofits
Geomechanical	Leverages oil & gas; could scale rapidly to GWs; relatively high efficiency	Leverages oil & gas expertise & workforce. Once de-risked could scale very rapidly	Support deployment; facilitate permitting
Hydrogen	Can be used as a fuel to replace hydrocarbons	Could provide backbone of decarbonized energy system to drive transportation, heating, and chemical synthesis	Support infrastructure development as well as R&D

1. Introduction

This Storage Technology Summary describes storage technology options California might consider in reaching SB100 goals. Storage technologies are rapidly evolving. The costs and applications are changing, which will necessitate frequent adjustment during a transition to much higher-penetration variable renewable electricity sources. This summary is intended to help us prepare for defining our scenario analysis for evaluation of the evolution of the energy system to 2045, which will be the next phase of our project.

1.1 Background

A summary written in 2011 and commissioned by the California Energy Commission *"2020 Strategic Analysis of Energy Storage in California"*[1] had a similar goal, but a nearer-term focus (2020). It placed substantial emphasis on short-duration storage technologies, including capacitors and flywheels, as was most relevant to the grid's needs in 2020. By 2045, we expect that storage will play much broader roles, including covering a larger fraction of the energy needed during peak demand times as well as being able to provide power for extended periods.

After lagging behind other countries, the U.S. took the lead in adopting energy storage in 2020. IHS Markit reports "The US will account for half of the energy storage installations in 2021, roughly tripling its pace of capacity growth a year earlier."[2] Wood Mackenzie notes that the U.S. energy storage market passed $1.5 billion for the year 2020 and agrees with the IHS Markit assessment that the U.S. energy storage market will more than double or maybe triple in 2021 with most of that growth being "front-of-the-meter" (connected to the grid on the utility side of the meter) applications.[3]

The EIA reported 152 MW batteries installed in the U.S. during 2019 and 301 MW added in the first half of 2020. Wood Mackenzie has already reported full numbers for the U.S. for 2020, with 1464 MW and 3487 MWh.[4] Based on July 2020 data, EIA expects installations of almost 7 GW of batteries in the U.S. in the next few years, with many of those paired with wind and/or solar.[5]

As countries, companies, and utilities set targets to decarbonize the grid, energy storage will play multiple roles in balancing electricity supply and demand. The need for energy storage is anticipated to increase as dispatchable sources of electricity like natural gas are replaced with variable sources like solar and wind. Most agree that long-duration storage will be a critical requirement of a decarbonized grid, but questions often arise about what is meant by "long-duration storage." Here we suggest clarification of terminology to help us communicate better; we propose a broad definition that may help reach a zero-carbon grid sooner by encouraging development and implementation of diverse strategies.

Today's grid balances supply and demand mostly by maintaining power-generating assets that are dispatched as needed, with some generators operating at full capacity most of the time and others operating only during high demand. A decarbonized grid may continue to use fossil-fuel-powered

---

[1] Andris Abele, Ethan Elkind, Jessica Intrator, Byron Washom, et al (University of California, Berkeley School of Law; University of California, Los Angeles; and University of California, San Diego) 2011, ***2020 Strategic Analysis of Energy Storage in California***, California Energy Commission. Publication Number: CEC-500-2011-047.

[2] https://ihsmarkit.com/research-analysis/global-energy-storage-market-to-more-than-double-in-2021-ihs.html

[3] https://www.woodmac.com/research/products/power-and-renewables/us-energy-storage-monitor/

[4] https://www.woodmac.com/press-releases/us-energy-storage-market-shatters-quarterly-deployment-record/

[5] https://www.eia.gov/todayinenergy/detail.php?id=45596

generators coupled with carbon sequestration, but solar and wind generators coupled with low-cost storage may be able to deliver reliable electricity at a lower cost. The California Energy Commission (CEC) recently awarded more than $2 million to study long-duration storage to better understand the roles that long-duration storage may play and the related cost targets as a basis for future technology development and implementation. This understanding will guide the CEC in its efforts toward a zero-carbon-emissions grid in 2045.

1.2 Types of energy storage opportunities

Multiple opportunities for storage to help balance the electrical grid are shown by the green boxes in Fig. 1.1, representing the electricity flows to and from various types of energy storage reservoirs. Demand management may be used to facilitate storage at the customer's site, as indicated by the Fig. 1.1 green box "Load – Stored energy." Some customer-sited forms of energy storage are relatively low in cost. For example, many large buildings chill water for air conditioning at times when electricity rates are low, storing the chilled water in a relatively low-cost tank for later use. Such demand management strategies have the potential to both reduce total cost and shift the capital investment cost away from the utility. Understanding customer-sited storage in more detail is a prerequisite to developing effective policy. Such policy would expand today's demand management programs into comprehensive programs that can effectively provide large storage assets such as Tesla's aggregation of batteries in many customers' homes into a virtual power plant.

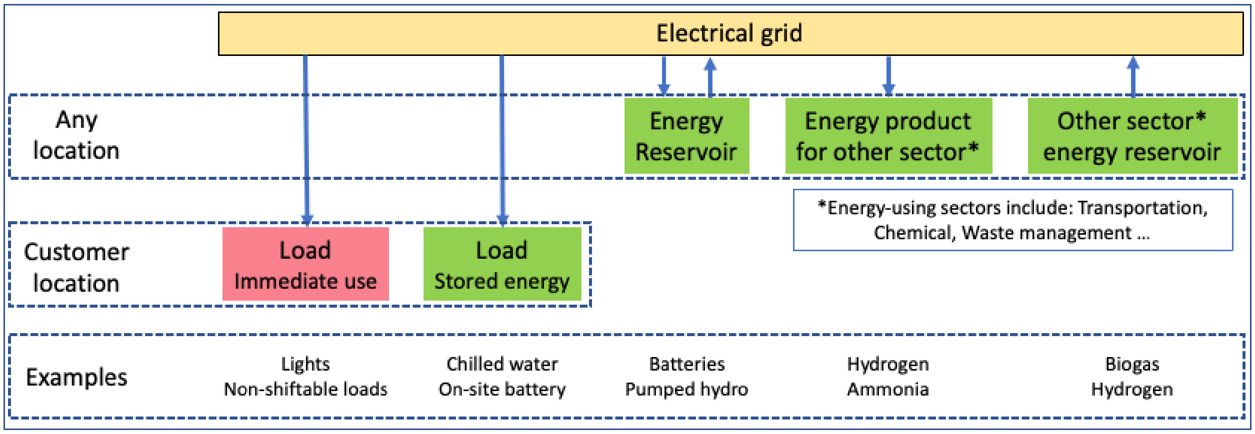


Fig. 1. 1 Opportunities for energy storage (green boxes) to help balance electricity supply and demand

More generally, surplus electricity may be stored for later electricity generation (green box labeled "energy reservoir") or for creation of an energy product like hydrogen (green box labeled "energy product for other sector") that may be stored at low cost until the energy is needed later. Also, when electricity is in short supply, energy that is stored for use in other sectors may be used to generate electricity (green box labeled "other sector energy reservoir"). A decarbonized grid may benefit from using all of these strategies.

Capacity-expansion models commonly include batteries and pumped hydro storage, keeping track of their state-of-charge as they are charged or discharged (Fig. 1 green box "Energy reservoir"). Modeling the value of cross-sector storage opportunities is less common. For example, some capacity-expansion models increase the input load profile to include hydrogen production, requiring more electricity generation. A more complete model would optimize the hydrogen production by considering the capital costs and operating costs of the electrolyzers offset by the value of the hydrogen that is generated, potentially turning curtailed electricity into a revenue stream. Similarly, a more complete model would calculate the cost of using hydrogen (that is being stored for transportation or chemical use) to generate electricity when electricity is in short supply.

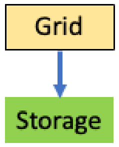
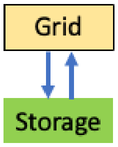
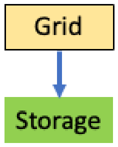
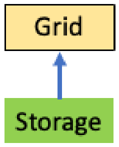
While there is no general agreement that all four green boxes in Fig. 1.1 should be called "long-duration storage" we assert that a full understanding of the roles of long-duration storage will require understanding the opportunities described by all four green boxes and that understanding the relative benefits of all of these will help policy makers identify the most effective actions to take.

1.3 Taxonomy for storage

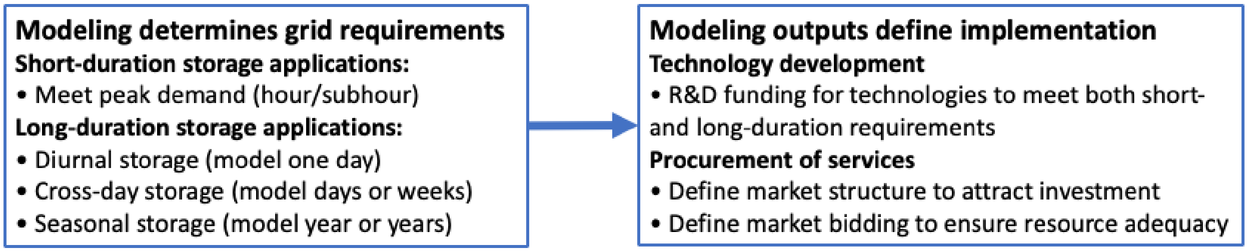
As we work to envision the roles of storage in supporting tomorrow's grid, it is useful to develop a taxonomy for improved communication. For the purposes of modeling, it is useful to differentiate types of storage according to how they are modeled. We highlight here two aspects that are critical to the model implementation: a) the electricity flows (with associated costs) and b) the temporal resolution.

In Table 1.1 we propose a taxonomy for the four storage opportunities outlined in Fig. 1.1. We suggest that "customer-sited storage" describe storage assets that are purchased and operated by the electricity customer (or business partner) at the customer's location. "Self-contained storage" assets are connected to the grid, charged with surplus electricity, and discharged when electricity demand is high. Finally, "cross-sector storage" created to serve the transportation or other sector may be charged or discharged to help balance the grid. While it is clear that all of these energy flows need to be modeled to fully understand the roles storage plays in balancing the grid, it is less clear that all of the opportunities should be called "storage." Table 1.1 gives examples of how to implement each storage opportunity and also suggests opportunities that need to be included in the modeling, but that are usually not labeled as "storage." We emphasize that in our study of "long-duration storage," we intend to model the potential of all of these, but recognize that, for example, biogas is usually viewed as a generation technology even though biogas represents a form of energy storage that may be useful for balancing the grid. We feel that it is less important to decide whether biogas is called a generation technology or storage technology and more important to agree that biogas has the potential to help balance the grid by providing a reservoir of energy.

Table 1. 1 Proposed taxonomy for differentiating storage opportunities

Figure 1.1 label	Load – stored energy	Energy reservoir	Energy product for other sector	Other-sector energy reservoir
Modeled electricity flow				
Proposed taxonomy	**Customer-sited storage**	**Self-contained storage**	**Cross-sector storage**	
Examples modeled and included in taxonomy	Hot and chilled water On-site batteries Thermal mass of building Water pumping	Batteries Gravity storage Hydrogen stored on-site for electricity generation	Hydrogen for transportation, etc. Power-to-X	Hydrogen brought from underground storage Ammonia or other fuel made from electricity
Examples included in electrical modeling, but not called "storage"	Energy efficiency Demand management not involving energy storage		Thermal energy used for industrial process	Biogas Natural gas plant with carbon sequestration

We propose a second piece of the taxonomy (Fig. 1.2) related to the relative amount of energy stored. When modeling the roles of storage, a short-time-resolution (hourly or even subhourly) model aids in understanding how storage may help meet the peak load of the year or of the day. Reducing the peak demand is a "short-duration storage" application. We propose that long-duration storage applications include 1) diurnal storage, 2) cross-day storage, and 3) seasonal storage. The modeled contiguous timesteps need to span the time from when energy is added to a storage reservoir to when the energy is withdrawn from the reservoir, as indicated in Fig. 1.2, left side. For a given grid design and weather, a model can identify the cycling frequency of the short-duration and long-duration (diurnal, cross-day and seasonal) storage reservoirs. These define the storage applications that need to be met to achieve a stable grid, providing the foundation for taking actions to create a stable zero-carbon-emissions grid.



Modeling determines grid requirements
Short-duration storage applications:
- Meet peak demand (hour/subhour)

Long-duration storage applications:
- Diurnal storage (model one day)
- Cross-day storage (model days or weeks)
- Seasonal storage (model year or years)

Modeling outputs define implementation
Technology development
- R&D funding for technologies to meet both short- and long-duration requirements

Procurement of services
- Define market structure to attract investment
- Define market bidding to ensure resource adequacy

Fig. 1. 2 Taxonomy for modeling of storage (left) and implications for implementation (right)

Once the grid's requirements for short-duration and the various long-duration storage applications/requirements have been identified, the next step is to develop technologies that can meet those needs (right side of Fig. 1.2). We anticipate that it will be useful to the grid to have access to many storage technologies and that many of those technologies may address multiple storage applications. It is tempting to label a technology as a "short-duration" or "long-duration" storage technology, but it could be possible for any storage technology to address all storage requirements. On the other hand, some storage technologies may be better suited to address short-duration applications while others may be better suited for long-duration storage applications.

1.4 Competition between types of storage

The schematic in Fig. 1.3 suggests how different types of storage may compete to meet the range of storage requirements. Technologies built into self-contained storage systems with large energy reservoirs have the potential to meet all of our storage needs. However, short-duration storage applications may be addressed at lower cost by storage systems that have small energy storage reservoirs. Conversely, seasonal storage applications may be met at lower cost by cross-sector storage that can leverage huge energy reservoirs used on a daily basis by the transportation, chemical and/or other sectors. Technology development efforts should consider the storage applications and what other technologies will be competing to meet those needs.

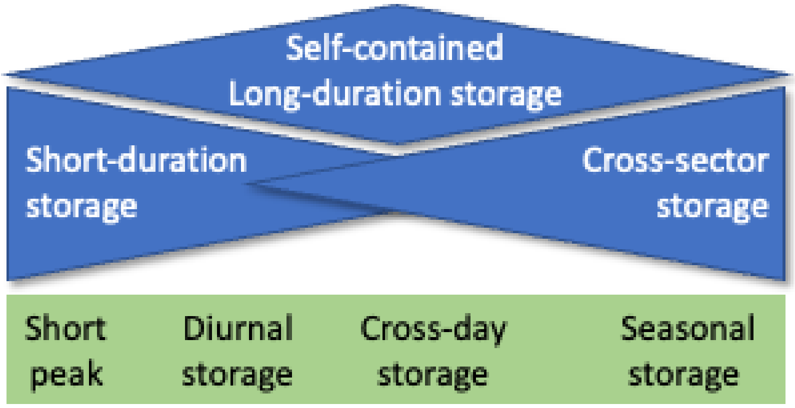


Fig. 1. 3 How types of storage systems (blue shapes) may compete to meet storage needs (green)

1.5 Large-scale energy storage

Energy storage is an essential part of energy security. As shown in Fig. 1.4, currently, the United States maintains energy storage mostly to supply the transportation sector (jet fuel, motor fuels, and oil to make these) and heating sector (oil and natural gas). The chemical industry and power sector also rely on storage described in Fig. 1.4, with their chemicals/fuels sometimes mixed with those of the other sectors. Maintaining energy storage to simultaneously serve many sectors increases flexibility and reduces costs. If the energy represented in Fig. 1.4 were converted to electricity, it could yield more than four months of electricity for the U.S. In a decarbonized world, it is useful to consider the energy storage needed for other sectors as we plan for long-duration storage for the power sector.

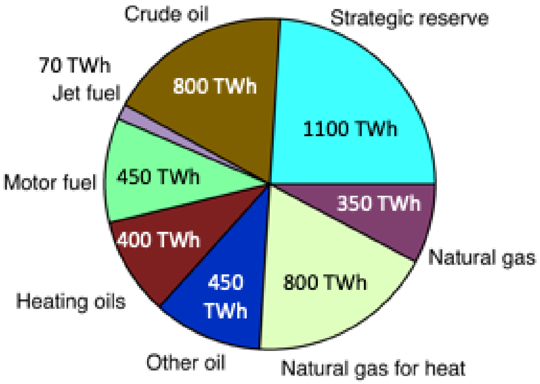


Fig. 1. 4 Energy storage used to supply the transportation, heating, power, and chemical sectors [6]

1.6 Seasonal storage requires many TWh of energy motivating cross-sector energy storage

The long-duration storage needed for seasonal storage applications may require many TWh. Just as a peaker plant today is idle much of the year, some long-duration storage assets of a decarbonized grid will be used infrequently. Thus, the storage cost for such applications will need to be low. We suggest that inclusion of attractive cross-sector storage opportunities (such as shown on the right side of Fig. 1.1) will be helpful in keeping storage costs low while being prepared for extreme conditions. Today, natural gas is used both for heating and for electricity generation, so the cost of maintaining the natural gas storage and distribution infrastructure is shared by both the power and heating sectors. In a decarbonized world, hydrogen (or other fuel) storage and distribution infrastructure may be established to support the transportation, chemical, and heating sectors. The power sector may be able to ensure resource adequacy at lower cost by leveraging such infrastructure rather than creating its own large energy storage that is infrequently used.

Thus, the study of long-duration storage should consider how the different types of storage will compete for different storage applications as described in Figs. 1.2 and 1.3, and should also consider how cross-sector storage approaches may reduce cost by leveraging infrastructure developed for other sectors. Policy development should be technology agnostic so that the markets will be able to choose the lowest cost path to keeping the lights on even in the most challenging times.

---

[6] The natural gas stored for heating applications was estimated from the depletion of the stored natural gas during the heating season. The 350 TWh "Natural gas" may be used for power generation, heating, or other uses. The strategic petroleum reserve is the largest single category of storage on this pie chart.

1.7 Data resources

Storage data are constantly changing. In particular, the following are quite useful for staying up to date on storage data resources.

- 2021 Annual Technology Baseline published by NREL[7]
- Wood Mackenzie U.S. Energy Storage Monitor
- Lazard Cost of Energy and Storage[8]
- IHS Markit report[9]
- DOE OE Global Energy Storage Database[10]
- ISO interconnection queues, especially CAISO[11]
- Energy Information Agency (EIA)[12]
- Berkeley National Lab Energy Technologies Area – Energy Storage Group[13]
- Pacific Northwest National Laboratory – Energy Storage[14]

1.8 What we've learned from other technologies

Photovoltaic technologies

The photovoltaic industry explored many photovoltaic (PV) materials starting in the 1970s. It could be said that the PV industry has been divided in two camps: those who have pursued silicon as the obvious winning technology and those who predicted that silicon could not reach low enough costs and that a different material system would be needed based on a direct-gap semiconductor that could be applied as a thin film to glass or another inexpensive substrate.

Today, silicon modules dominate global sales of solar panels (> 90%) with low module prices that are reported to enable solar electricity prices as low as one cent/kWh (in Saudi Arabia). The thin-film vision has also been realized: First Solar has achieved both high efficiency (19% at the full module level) and low manufacturing costs and has increased their manufacturing volume, representing by far the strongest U.S. PV company. Their initial success was a direct result of a shortage of purified silicon. Their continued success required them to reach efficiencies approaching 20%. Thus, so far, history shows that efficiency is very important and that, once technologies have scaled production to large volumes, they can reduce their costs by more than is often projected. The conclusion is NOT that efficiency is all important: Alta Devices attempted to launch GaAs (a more efficient PV technology) as a terrestrial PV technology and was not successful because of their high costs, though GaAs could be successful if given the opportunity to expand. The conclusion is that a product with lower efficiency will need to be lower in cost than the high-efficiency product to be competitive.

---

[7] https://atb.nrel.gov/electricity/2020/index.php?t=in
[8] https://www.lazard.com/media/451418/lazards-levelized-cost-of-storage-version-60.pdf
[9] https://ihsmarkit.com/research-analysis/global-energy-storage-market-to-more-than-double-in-2021-ihs.html
[10] https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/
[11] http://www.caiso.com/PublishedDocuments/PublicQueueReport.xlsx
[12] www.eia.gov
[13] https://eta.lbl.gov/about-us/organization/groups/esg
[14] https://www.pnnl.gov/energy-storage

Initial development of solar technology focused mostly on reducing the cost of the panels. Later, as the panels became less expensive it was found that balance-of-system and "soft costs" (permitting, etc.) became a larger fraction of the system cost.

For storage technologies, will the conclusions be similar? While the efficiency of solar panels is directly quantified, the efficiency of batteries is much more difficult to quantify and depends on how the battery is used (rate and depth of discharge, operating conditions, etc.). Nevertheless, the success of storage in the end is likely to be highly dependent on the performance, with the expectation that costs can be decreased significantly. Not only is it costly to operate an inefficient battery (because of needing to purchase more electricity for charging), but the system-wide cost will require installation of more electricity-generating systems. Also, we may expect to see that the system-level costs will become more important as the battery costs are decreased.

Centralized versus distributed

Wind and solar are fundamentally different with regard to size. The taller the wind turbines are, the better able they are to reach the stronger winds that are high in the air. The technology trends for wind have been consistently toward larger turbines and toward larger capacity factors. Although solar panels do not inherently gain resource by being larger, they have also evolved toward larger sizes, which tends to reduce cost.

Many solar advocates have promoted rooftop installation so that the electricity can be used directly where it is generated. However, worldwide deployments (in terms of power installed) are dominated by utility-scale systems, where economies of scale provide lower electricity costs. (Note: the number of residential systems is much bigger than the number of utility-scale systems, even though the power ratings are dominated by utility-scale systems).

In considering whether storage follows more the centralized or distributed models, we note that there is a strong drive toward utility scale because of the lower associated costs, but that distributed systems provide better resilience. Both have their benefits.

We also note that storage is fundamentally different from solar and wind in that the storage always has the potential of performing. Distributing solar means that the electricity is sometimes delivered where it is needed, but when the sun isn't shining, the electricity will still need to be brought in from elsewhere. Thus, distributed solar may not be successful in reducing the needed transmission/distribution capability. In contrast, if there is adequate storage paired with local generation, it may be possible to reduce the sizes of the transmission and distribution systems.

Our studies place more emphasis on utility-scale systems because all analyses show that they are less expensive than distributed systems. The addition of customer-sited PV is handled in the modeling by estimating the amount that will be installed and then telling the model to build the planned amount. The installation of distributed solar is driven largely by policy.

1.9 Report structure

Section 2 of this report discusses the status of each storage technology. Section 3 provides a summary of all of the inputs that we will use in RESOLVE for the baseline modeling and for various scenarios.

2. Storage technology descriptions

Public releases of RESOLVE have typically included resources for:

- Pumped hydropower storage
- Lithium batteries
- Flow batteries

These reflect the storage that is installed today in California, with the omission of sodium batteries that represent 0.2% of installations. The current trend for installations in California can be seen in Fig. 2.1, showing that pumped hydropower is the largest source of storage, but Li batteries are growing quickly. Flow batteries are currently reported at < 0.1% of the total. The doubling of the Li batteries from 2019 to 2020 is quite spectacular, especially because an additional 300 MW were installed in January 2021, with CAISO interconnection queue suggesting that in total, 2021 will bring an additional 1.1 GW of storage-only and an additional 1.8 GW of storage coupled with PV systems online. Together with what is already installed, this would bring non-pumped hydro storage to approach what is available from pumped hydro at the end of 2021. Even more spectacular are the interconnections being planned in 2022: another 3 GW of stand-alone storage and 3 GW of storage coupled with solar plants. In all, this could bring the storage in California to about 12 GW by the end of 2022 (or about 25% of peak demand), though note that the CAISO queue includes storage outside of California.

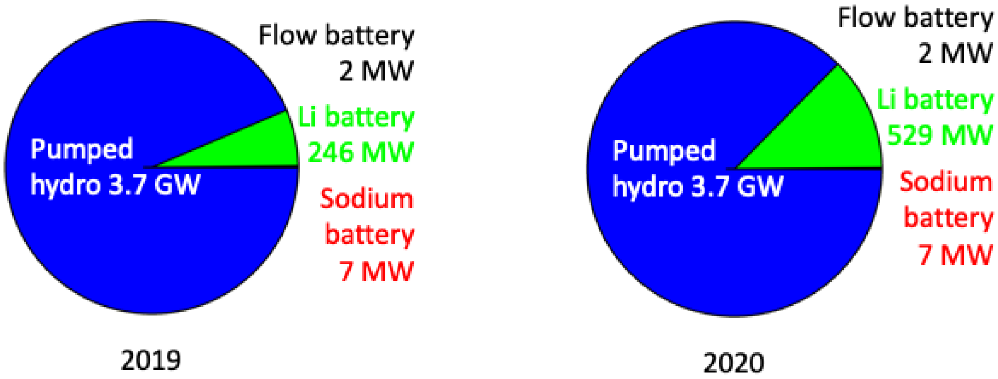


Fig. 2. 1 Installed California storage identified by EIA 860 by technology type

Here we will discuss pumped hydro, Lithium-ion battery and flow battery storage technologies as well as some newer technologies that have not yet been deployed at a utility scale in California, but that might be deployed on a large scale by 2045. These include:

- Compressed air storage
- Liquid-air storage
- Gravity storage other than conventional pumped hydropower storage
- Geomechanical storage
- Thermal storage
- Electrochemical batteries (in addition to lithium-ion and flow batteries) including metal-air and exfoliated-metal batteries”
- Hydrogen and other cross-sector storage

Solar thermal systems using concentrated solar power (CSP) combined with storage provides an option for storage that is qualitatively different from the others because it skips the initial electricity generation, using only the storage-generation part of the cycle rather than the generation-storage-generation cycle that would be used for a more conventional storage type.

We also discuss carbon sequestration using natural gas plants, because storage technologies will compete with these to deliver dispatchable power that is zero-carbon or close to zero-carbon.

2.1 Lithium batteries

Lithium battery prices have been dropping quickly and installations have been skyrocketing. The sizes of the markets for lithium batteries have now grown large enough that we can see some market differentiation of the optimal chemistries. In particular, while EV applications continue to use chemical formulations including nickel, cobalt, and manganese, there is increasing evidence that stationary storage markets are shifting to lithium iron phosphate batteries. The lithium iron phosphate batteries are heavier, making them unattractive for mobile applications, but they currently appear to be slightly lower in cost, have reduced flammability issues, and use more abundant materials.[15] As an example of this trend, Tesla recently announced use of the lithium iron phosphate chemistry for its Megapack utility-scale battery.[16] A consensus of the shift in chemistry for stationary applications has been growing through 2020 and 2021. Technology diversity is very useful to the energy system, enabling flexibility if one supply chain becomes limited.

Batteries are becoming an essential element of CAISO's grid and are now routinely discharged for about four hours during peak demand (Fig. 2.2), which aligns with the 4 hours of capacity that CAISO requires. As the need for storage extends into the night, we anticipate that storage will require even more hours of discharge.

Fig. 2. 2 CAISO's use of batteries on August 18, 2021.[17]

Both RESOLVE and SWITCH assume that the cost and operation of a storage resource have factors that scale with the energy and with the power. In our previous reports, we showed that the segmentation of the costs into \$/kWh and \$/kW has a significant effect on the model's selections. This raises the question of how to divide the cost between \$/kWh and \$/kW. Fig. 2.3 shows an analysis done by NREL breaking out individual costs for 60-MW utility-scale lithium-ion storage systems. The 0.5-h battery system is dominated by non-battery costs, while the 4-h battery system

---

[15] In particular, cobalt is difficult to obtain and comes with environmental as well as societal issues

[16] https://www.utilitydive.com/news/tesla-shifts-battery-chemistry-for-utility-scale-storage-megawall/600315/

[17] http://www.caiso.com/TodaysOutlook/Pages/supply.html

has more than half of the cost in the batteries themselves. The costs for the inverter and the charge controller are expected to scale with the power more than with the energy. The "Installation Labor and Equipment" (see Fig. 2.3) costs may scale with the relative volumes of the batteries and the electronics. The size of the electronics has been decreasing, but currently the volume of the electronics for a MW and the volume of the batteries for a MWh are within a factor of two of each other suggesting that the installation labor and equipment scale with both MW and MWh. The "Developer Cost" (see Fig. 2.3) differentiation between power and energy may change as the market structures change.

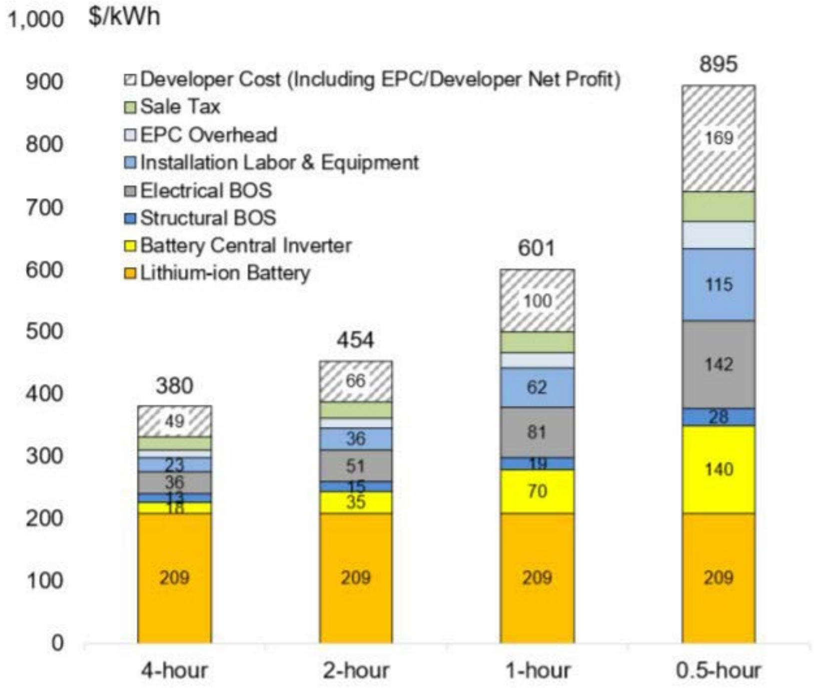


Fig. 2. 3 Cost breakdown of 2018 U.S. utility-scale lithium-ion battery standalone storage costs (60 $\mathrm{MW_{DC}}$) [18]

In Table 2.1, we summarize the costs per kW, costs per kWh and the ratio of the two from different sources. There is some substantial variation on both the absolute costs (reflecting the rapid rate of change in the cost) and in the ratio. We see two trends toward lower cost associated with energy: 1) Each research group is tending toward a lower ratio (E3 decreased from 1.9 for 2030 for the 2018 RSP to 1.38 for 2030 for the SB100 study and then to 0.96 in the 2021 PSP, while NREL ATB decreased from 1.15 to 1.08 or 0.75) and 2) NREL projects that the cost associated with the energy will decrease faster than the cost associated with the power and commercial batteries pay an additional per project cost.

Another key issue with modeling battery systems is the extent to which the degradation of the batteries is accounted for by overbuilding the system at beginning of life to account for the fade in performance by the stated end of life, or whether a plan is made to supplement the battery resources with additional battery packs to compensate the loss of capacity as was proposed in NREL's 2020 ATB. It may make a lot of sense to add more capacity as needed and at lower cost rather than overbuilding at the start, given the decreasing price trends. On the other hand, procuring batteries

---

[18] R. Fu, T. Remo, and R. Margolis, "2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark," NREL technical report #NREL/TP-6A20-71714, 2018. https://www.nrel.gov/docs/fy19osti/71714.pdf

each year will be associated with increased installation costs, which might be more than the decrease in price over time. It could also be possible to change the capacity rating with time, but that is not currently included in the RESOLVE code.

Table 2. 1 Costs reported for Li battery systems

Source	Year	Power cost (upfront in $/kW or annualized in $/kW/y)	Energy cost (upfront or annualized)	Ratio of $/kWh to $/kW
R. Fu, et al (see Fig. 2.3)	2018	294 $/kW	307 $/kWh	1.04
NREL 2020 ATB	2018	292 $/kW	317 $/kWh	1.15
NREL 2020 ATB	2020	260 $/kW	299 $/kWh	1.15
NREL 2020 ATB	2030	146 $/kW	168 $/kWh	1.15
RESOLVE 2018 RSP	2020	23 $/kW/y	42 $/kWh/y	1.8
RESOLVE 2018 RSP	2030	10.3 $/kW/y	20 $/kWh/y	1.9
SB100 study	2030	162 $/kW	224 $/kWh	1.38
NREL 2021 ATB (utility scale)	2020	257 $/kW	277 $/kWh	1.08
NREL 2021 ATB (utility scale - moderate)	2030	197 $/kW	147 $/kWh	0.75
NREL 2021 ATB (commercial- moderate)	2020	444 $/kW*	$236 $/kWh*	0.53
NREL 2021 ATB (commercial- moderate)	2030	324 $/kW**	$108 $/kWh**	0.33
2021 PSP	2022	19.8 $/kW/y	24.5 $/kWh/y	1.23
2021 PSP [19]	2030	14.2 $/kW/y	13.7 $/kWh/y	0.96

* Additional cost of $276,846 is added for each project regardless of size

** Additional cost of $213,492 is added for each project regardless of size

In Fig. 2.4 we copy an NREL graph to show how reported values for battery O&M maintenance costs vary by as much as an order of magnitude. NREL's 2020 ATB chose to associate these high O&M costs solely on the power rating. If the high costs are associated with reduced energy capacity of the batteries, then it would make more sense to associate these costs with the energy rating. The figure shows the $/kW-yr for 4-hour batteries. Given that the duration is fixed, we could also divide these numbers by 4 and report them as O&M costs in units of $/kWh-yr, associated with the rated energy of the batteries rather than associating them with the rated power of the batteries.

Li batteries have a fairly low energy idle loss rate but require air-conditioned operating conditions in many climates. Running an air conditioner has the same net effect as a loss rate. On a cool night, the operation of an air conditioner may be negligible, but if a Li battery is not being actively used and is sitting in a very hot location, the energy used by the air conditioning may decrease the effective efficiency of the battery. This might be dealt with by favoring the siting of batteries in more moderate weather locations in California, and fewer batteries in hotter areas. We could consider adding a higher operational cost depending on the average temperature at the given location.

---

[19] ftp://ftp.cpuc.ca.gov/energy/modeling/2021%20PSP%20RESOLVE%20Package_09072021.zip

We summarize the input data for modeling in Section 3.

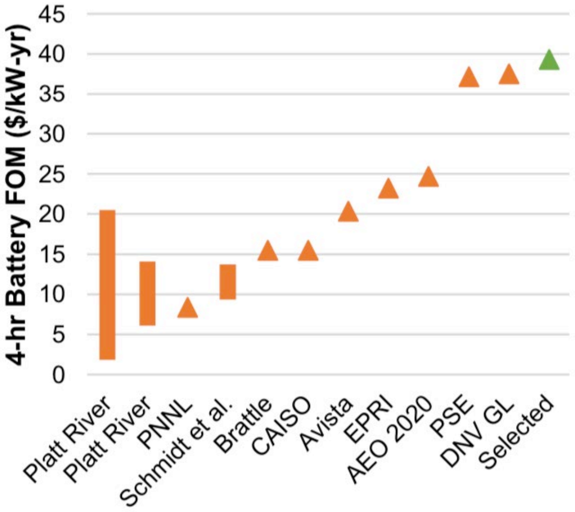


Fig. 2. 4 Battery fixed O&M cost as reported by different sources (Source: NREL) [20]

2.2 Pumped hydropower storage

Pumped hydropower storage (referred to here as “pumped hydro”) is the world’s most mature and widely deployed electricity storage technology at over 150GW deployed internationally. It is demonstrated to be low in cost when the primary items for determining feasibility – siting, water availability, geology, topography (available head and ease of creating reservoirs), and ease of interconnection create the necessary environment for permitting. The description of pumped hydro given in the 2011 report for the CEC by Oglesby, et al, is still relevant today. While there is an increased interest in pumped hydro projects worldwide, as well as within California, the rate at which these are being completed is overshadowed by the rapid deployment of lithium batteries, though there are a number of large projects that are being discussed or implemented.

As shown in Fig. 2.1, pumped hydro storage is the dominant storage resource in California, as well, with almost 4 GW installed. CAISO currently has 1.6 GW of pumped hydro storage capacity with a total of 253 GWh of energy storage capacity. These numbers represent 5 existing systems the largest of which is Helms with roughly 75% of the total (power) capacity.

New pumped hydro plants have been proposed that could be useful to California. These are detailed in Table 2.2, and, together, could total almost 5 GW. These projects are at a development stage that could enable them to come online during a time when investment in storage is greatly needed to enable higher penetration of renewable electricity. The motivation for these is increased significantly as we plan for a zero-carbon grid. Pumped hydro also provides the substantial long-term benefit that its lifetime is very long (typically much longer than the financing period), so if the investment can be made, once the initial capital investment is paid, pumped hydro can provide storage for a lower cost than any other technology. Our modeling to 2045 does not capture this value because we include annual costs to pay for the capital investment for the 30 years after the initial investment and don’t capture the benefit of having paid off the initial capital investment until after the simulation is over. Ideally, the government will provide support for these large

---

[20] https://www.nrel.gov/docs/fy20osti/75385.pdf

projects that will be in the public interest in the long term, especially given the difficulty of moving these projects forward through private investment. Government support of the existing private efforts could make the difference for their success, especially with regards to permitting and including them in incentive programs.

Table 2. 2 Proposed pumped hydropower storage projects in or near California

Project name	Company	Location & RESOLVE label	Capacity (MW)	Planned start	Notes
Cat Creek Energy and Water Storage	Cat Creek Energy	Idaho	720	2027	110 MW wind; 150 MW solar
Eagle Mountain	Eagle Crest Energy	Desert Center (Southern California)	1300	2028	Closed loop
Mokelumne Water Battery	GreenGenStorage	Amador County (Northern California)	250-800	2028	Uses existing reservoirs
Swan Lake	Rye Development	Oregon	393	2026	Closed loop
Goldendale	Rye Development	Washington	1200	2028	Closed loop
San Vicente	San Diego County Water Authority	San Diego	500	2030	Closed loop

Pumped hydro technology is well established, but it is still improving. Today's projects, like the one at Cat Creek, may include solar and/or wind, enabling better use of the transmission lines and improving operation, especially when coupled with floating PV, which reduces evaporation from the reservoir while enabling dual use of the space (for both PV and the reservoir). A broader scope of needed transitional services is now designed into most new pumped hydro projects and some projects go far beyond even those expanded set of services. Government investment in such projects could accelerate the advancement of the technology and would help to quantify the potential that can be gained. As noted above, without some government support, large pumped-hydro projects are unlikely to reach completion. Government support may be defined by local jobs, community benefits, and local opposition. A project's impact assessment imposes a longer and more cautious permitting process, which could address many local concerns, yet could also extend the project development timeline which already involves more time-consuming civil construction compared with many other storage technologies.

As part of the SB100 analysis,[21] the cost inputs for pumped hydro were revisited and the results are shown in the rightmost column of Table 2.3. The minimum duration for the new pumped hydro is specified to be 12 hours. The "Total for 12 h duration" column enables direct comparison with the SB100 total.

The following assumptions were made in the SB100 Joint Agency Report.

- Financing lifetime of 50 years. (35 years is recommended by Cat Creek, while NREL ATB suggests 100 years to reflect the technology life)
- Fixed O&M of $25/kW-yr with an annual escalation of 2% - an increase from the 2018 RSP. (We question this: Cat Creek described to us how new designs have reduced maintenance costs, and suggest $9.4/kW-yr as more reflective of the modern technology)
- No variable O&M costs
- After-tax WACC of 7.24% (in 2030).

---

[21] https://efiling.energy.ca.gov/getdocument.aspx?tn=234532

Table 2. 3 Summary of inputs for new pumped hydro resources in 2018 RESOLVE RSP and SB100

Period	Annualized Power Capex ($/kW-y)	Annual Power O&M ($/kW-y)	Annualized Energy Capex ($/kWh-y)	Annual Energy O&M ($/kWh-y)	Total for 12 h duration ($/kW-y)	SB100 total ($/kW-y)
2020	117.22	13.89	10.78	0	260.47	
2021	109.84	13.83	10.1	0	244.87	
2022	104.26	13.81	9.59	0	233.15	
2023	92.46	13.71	8.5	0	208.17	
2024	92.48	13.76	8.5	0	208.24	
2026	93.37	13.87	8.59	0	210.32	
2027						190
2030	95.02	14.03	8.74	0	213.93	192
2035			8.96			197
2040			9.09			199
2045	99.69	14.06	12.15	0	259.55	200

While multiple groups are working on new pumped hydro plants, many of these projects (Eagle Mountain and Cat Creek) have taken years. There can be opposition and construction barriers to overcome. Pumped hydro is the largest storage technology available today and it has been proposed[22] that pumped hydro could meet all of our storage needs by executing projects that are off river. Although this vision is quite attractive, we have found little evidence that it is on the verge of becoming a reality, though a number of projects have been proposed around the world like those shown in Table 2.2. As these are implemented, they may be the first steps toward the vision of pumped hydro being able to meet our storage needs. Changes in policy could rapidly make a big difference in realizing the vision of pumped hydro being a large contributor to the storage required by the state.

The 2021 Preferred System Portfolio[23] includes "Riverside_East_Pumped_Storage" that can be built to 1400 MW starting in 2028. It also includes the "Tehachapi_Pumped_Storage" which can be bult to 500 MW starting in 2026, as well as "Riverside_West_Pumped_Storage" and "San_Diego_Pumped_Storage" each of which can be built to 500 MW starting in 2030.

2.3 Other gravity storage technologies

In addition to pumped hydropower storage, gravity storage may be used in many ways. Energy Vault is developing an energy storage concept that lifts blocks as shown in Fig. 2.5. Such systems have the benefits of zero idle losses and high operating efficiencies. One approach to estimating the scalability of systems is to consider the possibility of diverting waste concrete away from landfills to be used in these systems. Based on 3 X 10^{11} kg/year of waste[24] aggregate concrete that could be available, we find we could install 3 X 10^{13} joule/year or 10 GWh/yr for a 10 m height or 100 GWh/y for a 100 m height.

---

[22] Lu, Bin, et al. "Geographic information system algorithms to locate prospective sites for pumped hydro energy storage." *Applied energy* 222 (2018): 300-312.

[23] ftp://ftp.cpuc.ca.gov/energy/modeling/2021%20PSP%20RESOLVE%20Package_09072021.zip

[24] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100SSJP.PDF?Dockey=P100SSJP.PDF

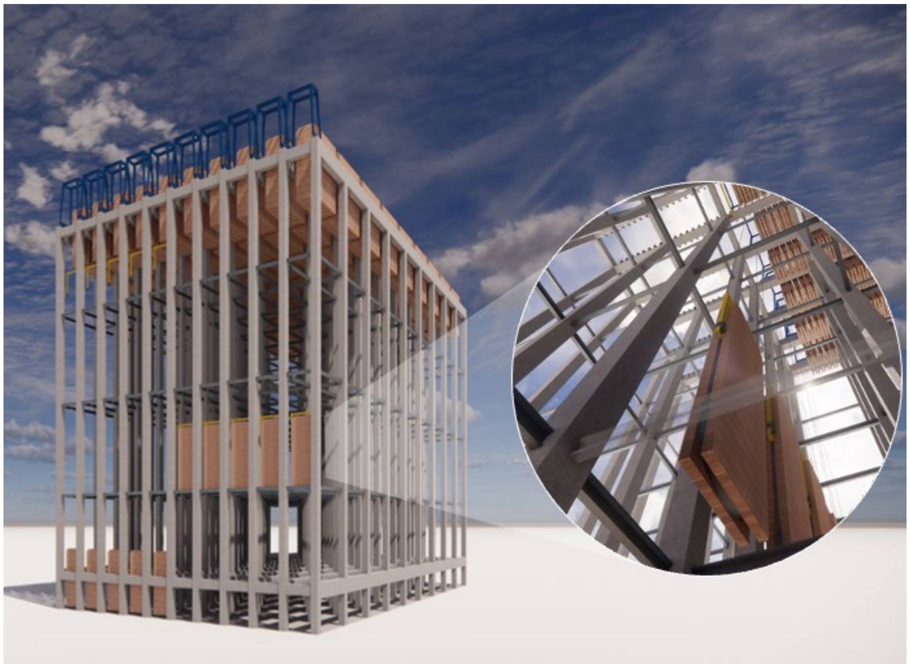


Fig. 2. 5 Gravity storage concept being implemented by Energy Vault

Strengths of gravity storage include:

High efficiency: Like hydropower, most gravity storage technologies can have efficiencies > 80%.

Low idle losses: Once the weights are lifted into place, there is no need for energy loss with time.

Flexible siting: Compared with hydropower, many gravity storage technologies can be sited most anywhere and can be built with variable size.

2.4 Flow and other scalable batteries

Flow batteries have the potential to provide flexible long-duration storage as they can be configured in different arrangements based on power and energy needs. Flow batteries have been under development for decades, but investment has increased in recent years. Flow batteries separate power density from energy capacity and duration by adjusting the electrolytic tank volume. The ability to substitute different electrolytic, membrane, and electrode materials provides multiple options. The number of chemistries being pursued toward commercialization is quite impressive. The list below represents only a fraction of the chemistries and companies pursuing new types of batteries today. This discussion focuses on utility-scale batteries because the capacity expansion models select the lowest cost (utility-scale) products. Distributed applications bring resilience and other benefits, but these are not captured directly in the modeling. which are almost always utility scale.

Flow batteries

In general, flow batteries are quite safe without risk of fire (though any device that generates electricity has the possibility of causing fire).

- Vanadium-redox flow batteries have been most widely deployed and have demonstrated recent cost reductions and commercialization through companies such as Invinity Energy Systems.

- Zinc-bromine flow batteries have been commercialized by RedFlow. These can be used with 100% discharge without damaging the battery and come with a 10-year limited warranty for both commercial and residential products.

- Iron flow batteries convert between ferrous (Fe+2) and ferric (Fe+3) ions using a flow battery configuration. Energy Storage Systems (ESS) is commercializing a packaged "Energy Warehouse" with 400 kWh that comes in a shipping container and has a 10-year extended warranty that is backed by Munich RE.

- Metal-free flow batteries can be made from organic redox couples as is being researched by Harvard University and as commercialized by Jena Batteries. These are not as far advanced in their commercialization path but would have reduced requirements for vanadium or other metals.

Metal-air batteries

- Zinc-air (commercialized by Zinc8) batteries are typically lower efficiency compared to vanadium-redox flow batteries, but they may be lower in cost.

- Aqueous-air-iron batteries cycle iron between its metallic state and oxidized state using air as the oxidized. The technology is being commercialized by Form Energy, which has announced deployment in 2023 of a 1 MW, 100 MWh aqueous-air battery in Minnesota.

- Aqueous-air/aqueous-sulfur batteries are anticipated to be lower in cost, though to our knowledge, now that Form Energy has switched to iron batteries, it is not clear that these batteries are being actively commercialized.

Exfoliated-metal batteries

- Exfoliated-zinc batteries can reduce zinc to cover the electrode, then wipe the zinc off of the electrode to enable additional zinc to be reduced. This exfoliation process enables the reduced zinc to be collected in relatively large quantities for later oxidation allowing these to have a higher energy density and reducing the footprint of the plant. Exfoliated-zinc batteries are being developed by Ezinc.

Vanadium flow batteries potentially can charge more than 10,000 cycles, making it an attractive option due to its extended lifetime (20+ years) compared to other flow batteries – and roundtrip efficiencies are reported up to 85%.

Some of these technologies offer portability and transportability as key advantages for projects that require mobility such as temporary micro-grids or other portable long-duration applications.

Flow batteries may have lower total cost of ownership than Li batteries for 8+ hour applications. Durability and the ability to locate flow batteries in most geographic locations also make these batteries a promising long-duration storage candidate.

In California, a 2 MW (8 MWh) vanadium flow battery was deployed in 2017 in San Diego. In 2020, the CEC chose to fund 4 vanadium flow battery projects comprising 7.8 MWh of batteries made by Invinity.[25]

The 2018 RSP calculated by RESOLVE does not select flow batteries. The reason for this can be easily seen by plotting the modeled costs, as shown in Fig. 2.6. Under no condition (year of

---

[25] https://www.smart-energy.com/industry-sectors/storage/california-energy-commission-opts-to-fund-vanadium-flow-batteries/

installation or selected duration) is the flow battery lowest in cost and its efficiency is assumed to be inferior to the others. The SB100 modeling revised the costs substantially, but not in a way that would provide a benefit to flow batteries in 2030. However, the SB100 inputs provide lower cost for flow batteries with > 13 h duration when built in 2045. Nevertheless, this cost advantage is not enough to overcome the lower efficiency assumed for the flow batteries and the modeling of individual days does not lead to build out of > 13 h duration. There are many uncertainties about the costs, lifetime, and other performance characteristics of flow batteries because of their early commercialization phases. We will model these with variable costs to understand what cost target they must hit to be adopted more broadly. Flow batteries may be more disruptive for mini-grid or off-grid building back-up solutions. This would tangentially affect grid operations and the energy sector, but if further cost reductions were achieved you might see more flow batteries as part of a shift from centralized to decentralized energy blocks.

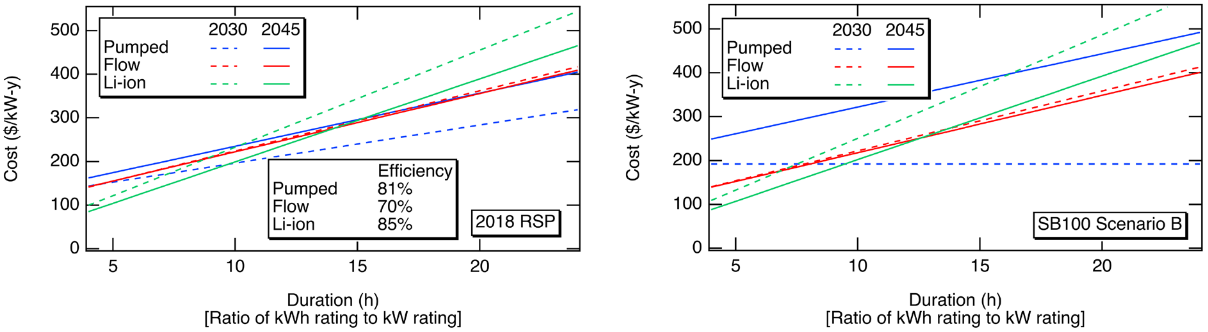


Fig. 2. 6 Annualized costs used by RESOLVE for modeling storage resources

Strengths of these batteries include:
Technology diversity: There are many chemistries being explored for flow and other batteries, increasing the chances of success.
Lower cost of increasing energy capacity: Many of these battery designs can increase the energy rating of the battery at relatively low cost. Flow batteries can add an extra liquid tank, while the exfoliated-metal batteries can collect the reduced metal within the battery.
Market entry: May enter market by providing resilience for relatively small-scale application in microgrids.

2.4 Compressed air storage

Worldwide, compressed air storage was the second largest technology until newer technologies have surpassed it in recent years. Installations of 290 MW (480 MWh) and 110 MW (2000-3370 MWh) have been operated for decades. These used salt caverns for the compressed air storage, limiting the locations where more installations can be deployed.

Newer technology differs from the older technology in multiple ways. In particular, we highlight here advancements by a company that is developing a project for California, Hydrostor. A schematic of their approach is shown in Fig. 2.7. The advantages of the technology they are developing (relative to conventional compressed-air storage technology) include:

• **Higher efficiency** (they are using an adiabatic process that stores thermal energy for later use, enabling higher efficiencies than the diabatic conventional technology. They guarantee 60% efficiency, but anticipate reaching 65%.)

- **More flexible siting** (they create a cavern in solid rock rather than using a salt dome, increasing the number of locations where systems may be installed)
- **Greater depth of discharge** (they propose to use a water bladder, enabling the system to operate at constant pressure even when most of the air is withdrawn)

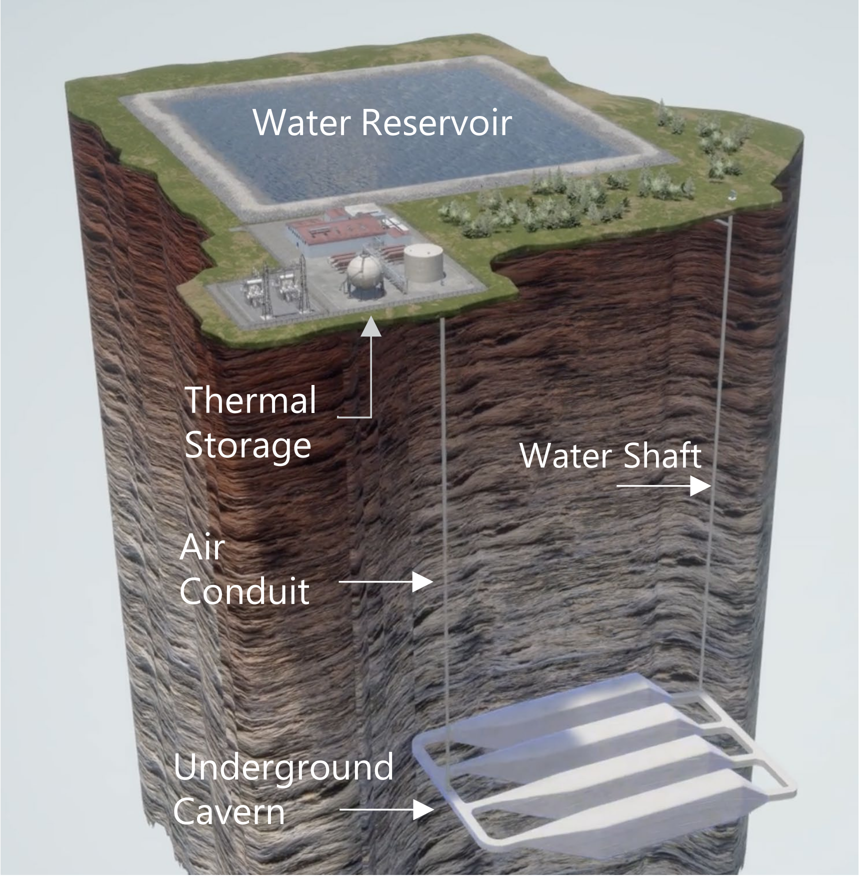


Fig. 2. 7 Schematic of Hydrostor's advanced compressed air storage approach

These advanced, adiabatic systems only reached commercial production recently. After completion of their Toronto Island Demonstration Facility in 2015, Hydrostor opened their Goderich site (1.75 MW and 10 MWh) to commercial service in 2019 in Ontario. Though early system sizes are small compared to diabatic systems, Hydrostor has a 500 MW, 6 GWh project under development in Rosamond that could start by 2024.

In summary, Hydrostor brings the following strengths:

Scalable: The equipment needed (drilling, mining, turbines) is already available for large-scale deployment, positioning them to scale up quickly.

Leverages established technology: Hydrostor leverages well established processes (with new innovations to overcome previous weaknesses) and supply chains.

The Advanced Compressed Air Storage efficiency is expected to be similar to that of many of the other technologies.

A related, but distinctly different concept has been developed by Augwind (Fig. 2.8). Their system uses electricity from the grid or nearby renewable sources to run water pumps in a modular pumping station. The water compresses the air in the AirX (see Fig. 2.8) chambers up to about 900 psi, and the compressed air is stored in buried AirX storage tanks. When electricity is needed, the compressed air is discharged according to Augwind's proprietary technology, generating electric power via a hydro-turbine. The system's roundtrip efficiency is 70%-80% AC to AC. The AirX tanks are installed underground, generally to a depth of about 12 feet, covered with concrete, and have a manhole access. The system may be sited in most locations, terrains, and geology as long as the needed space is available, as tabulated in Table 2.4, showing how the above ground space scales with the power rating and the below-ground space scales with the energy rating. Augwind began development of the technology 10 years ago. The compression system (Augwind's AirSmart technology that optimizes energy use of air compressors rather than being designed for storage) has been installed and operated for more than 5 years in dozens of large factories across Israel. A similar installation is planned for Pepsi-Co in Fresno.

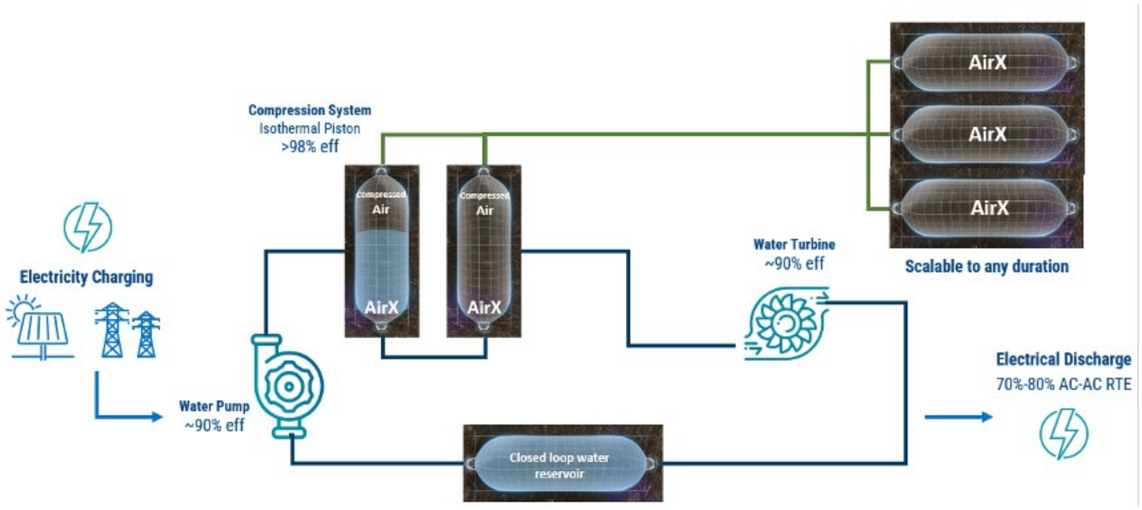


Fig. 2. 8 Schematic of the working process for Augwind's AirBattery

In summary, Augwind brings the following strengths (similar to Hydrostor):

Scalable: The equipment needed (water pumps/turbines, excavation equipment, piping, concrete) is already available for large-scale deployment, positioning them to scale up quickly.

Leverages established technology: Augwind leverages well established processes (water pumps) and supply chains.

Table 2. 4 Space requirements for Augwind's AirBattery

MW	MWh	Above Ground (m^2)	Below Ground (m^2)
1	4	300	1,000
1	8	300	2,000
5	20	800	4,500
5	40	800	9,000
10	40	1,300	9,000
10	80	1,300	18,000

2.5 Liquid air energy storage

Liquid air energy storage has been developed by Highview Power with projects in the UK and Europe. Air is cooled to cryogenic temperature using alternate compression and expansion cycles with associated hot and cold storage tanks. Round trip efficiency is 55%, though it could climb to 70% with integration of waste heat recovery if built into existing power plants.

Highview Power tested a 350 kW, 2.5 MWh pilot between 2011 and 2014. The 5 MW, 15MWh Pillsworth Demonstration Plant in Bury, Greater Manchester began operation in April 2018. Two more plants are under development in Vermont and Carrington, at 50 MW, 400 MWh and 50 MW, 250 MWh respectively. Highview Power reports that they have 400 MW with 4 GWh of storage of projects in the pipeline. The concept is illustrated in Fig. 2.9.

Fig. 2. 9 Liquid air storage as envisioned by Highview Power

Successful completion of these projects could position Highview Power for an even larger wave of deployments, including some in California. Their own modeling suggests that they can compete with Li batteries for applications requiring more than 4 h of storage.

The strengths of Highview Power's liquid air storage may be summarized as:

Scalable: The equipment needed (liquification, cryogenic storage, heat exchangers, turbines) is already available for large-scale deployment, positioning them to scale up quickly.

Demonstrated: Multiple demonstration plants have been completed, positioning Highview to undertake a rapid scale up (4 GWh of projects in the pipeline).

2.6 Thermal storage – combined with concentrated solar power

After analyzing the Global Energy Storage Database hosted at Sandia National Laboratory, we found that most thermal storage systems in that database store thermal energy for later generation of electricity rather than converting electricity to heat and back to electricity.[26] These are almost entirely implemented as Concentrated Solar Power (CSP), with typical duration of 4 – 10 hours, though there is increasing discussion of designing CSP plants to provide power through the night. CSP originally led solar electricity production in California, but the CSP industry stalled as PV prices dropped precipitously and deployment of PV skyrocketed. However, CSP has succeeded in reducing prices substantially as shown in Fig. 2.10.

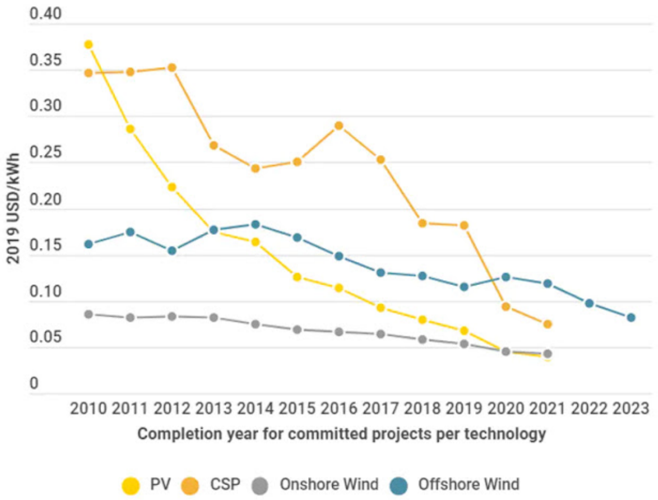


Fig. 2. 10 Cost evolution showing how CSP has recently been reducing cost[27]

Deployment of CSP systems may continue to lag those of PV (global electricity generation from CSP is less than 1% of that from PV), but CSP's ability to store heat and generate electricity after the sun sets provides it an advantage in a place like California, where the generation for solar already meets much of the load during the day at some times of year. Investment in CSP has increased recently. For example, Heliogen just announced $83 million in new funding, providing them with a total of $108 million for their power tower approach.[28] Although Heliogen is focusing on industrial processes rather than electricity generation, such an investment provides a pathway to reduced costs that could also be applied to CSP for electricity generation.

2.7 Thermal storage – without solar

AC-to-AC thermal storage systems are relatively new. Systems in which a working gas/fluid is circulated between hot and cold tanks are referred to as Pumped Heat Electrical Storage (PHES). Isentropic finished their 600 kWh, 150 kW Newcastle University demonstrator facility in 2019. It pumps argon between two tanks of mineral gravel and achieved an AC-to-AC roundtrip efficiency of 60-65% (with theoretical 75-80%). Analysis and cost estimates for a theoretical commercial system of 16 MWh and 1.6 MW, based on data from the project then in progress,[29] and using an

---

[26] https://www.sandia.gov/ess-ssl/global-energy-storage-database/

[27] https://www.evwind.es/2020/07/29/the-cost-of-concentrated-solar-power-fell-by-47-between-2010-and-2019/76120

[28] https://www.forbes.com/sites/erikkobayashisolomon/2021/06/15/activity-at-bill-grosss-heliogen-is-heating-up/?sh=7d9ad1ea23c4

[29] Smallbone A, Jülch V, Wardle R, Roskilly AP. Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. Energy Conversion and Management 2017;152:221–8.

assumed efficiency of 67% (with 52% and 72% as end case scenarios), predicted storage costs of \$17/kWh (\$13 – \$21/kWh).

The National Renewable Energy Laboratory (NREL) is developing the ENDURING storage technology under ARPA-E funding. This storage approach uses sand as the storage medium, circulating it between tanks, using a fluidized bed heat exchanger. They plan a 405 MW plant with 50% roundtrip efficiency. Their plants are designed to have between 10 and 100 hours of duration with energy ranges between 100 MWh – 76 GWh. The storage cost, including the power system, is \$10/kWh when based on 100-hour of storage and \$40/kWh for 10-hour storage designs. The cost estimates were based on basic equipment cost of materials and manufacturing. Costs may be lower if built into a pre-existing thermal plant. The modular nature of heating elements allows for broad scalability of their charge time.

Malta is constructing a 100 MW prototype of a molten salt based PHES system (See Fig. 2.11) with 4- to 24-hour duration, with 10 hours as an initial design target. It will have a similar modularity of heating elements and variable charge rates.

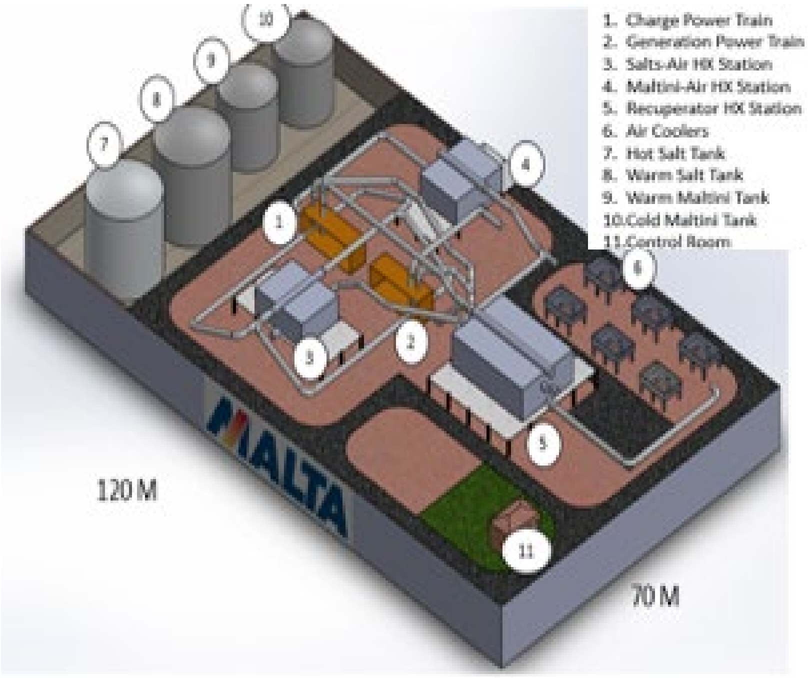


Fig. 2. 11. Thermal storage system being developed by Malta

Siemens developed an Electric Thermal Energy Storage (ETES) system using volcanic rocks for both heat-to-heat storage and heat-to-electricity via steam generation, see Fig. 2.12. Having completed a 130 MWh demonstrator in Hamburg in 2019, they are currently working on the first series of commercial pilots.

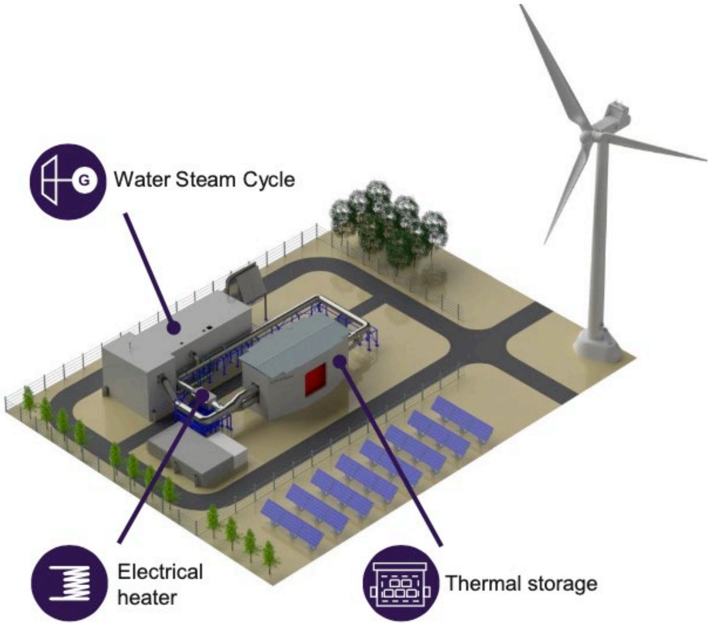


Fig. 2. 12 Schematic of Electrical Thermal Energy Storage (ETES) system

A product trademarked HeatStorE by 247Solar converts electricity to heat for storage at temperatures up to 1200°C for up to 20 hours or more. The low-cost storage medium (silica sand) enables < $100/kWh costs with more than 20 years operation without degradation. Super-heated air is used to turn a proprietary turbine to regenerate electricity without burning fuel. (Fig. 2.13) The system can also burn fuel, including hydrogen, for 24/7 dispatchability.

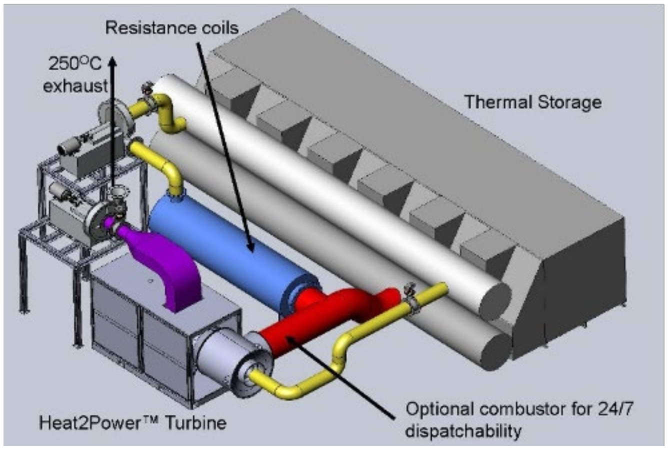


Fig. 2. 13 Schematic of 247Solar's Standard Heat2Power Turbine configuration

Another sensible heat, but non-PHES system is being developed by Antora Energy (Fig. 2.14). Their thermophotovoltaic (TPV) system allows the thermal energy to be emitted as light in the infrared and near-infrared frequencies to be absorbed by a photovoltaic cell. Energy not absorbed by the photovoltaic cell is reflected back toward the emitter. The 5 – 50,000 MWh, 0.5 – 200 MW system would have 50% roundtrip efficiency and ~$10/kWh storage cost.

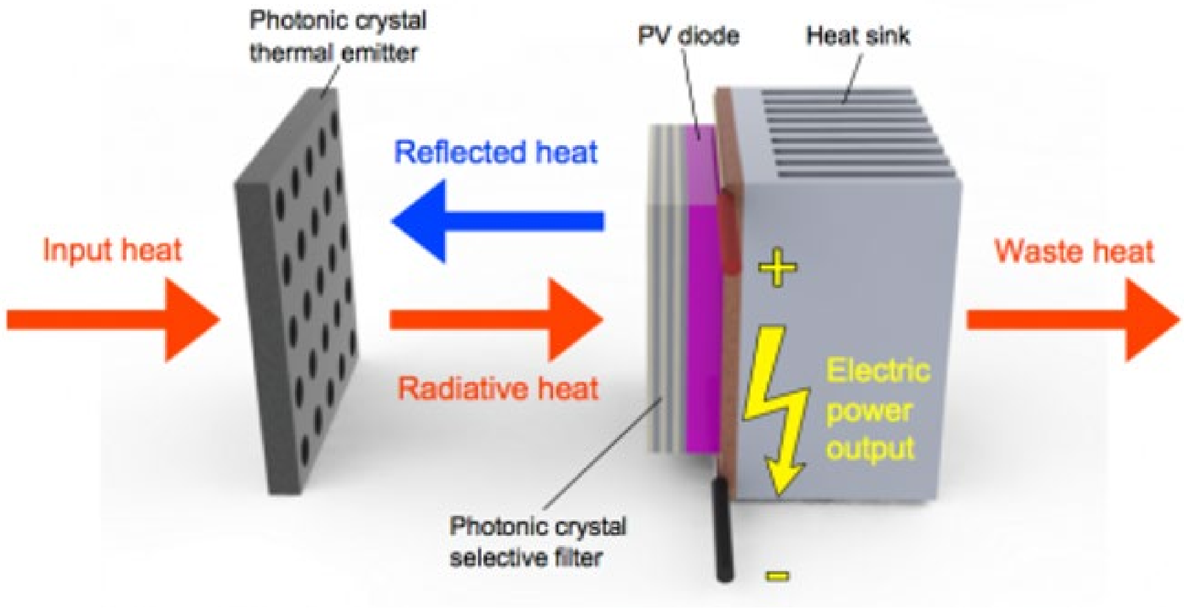


Fig. 2. 14 Conceptual schematic of electrical thermal storage system being developed by Antora Energy

A phase-changing-material system is being pursued by Swedish company, Azelio. Their Thermal Energy Storage Pod uses phase changing aluminum and a Sterling engine to run a turbine. The first commercial installation of their system has started in Dubai as of February 2021.

Idle energy loss is a major challenge when discussing thermal storage. The loss rate depends on the effectiveness and cost of insulation technology. CSP systems rarely discuss heat loss, as they are typically built for duration times of 10 hours or less. Smallbone et al[30] use a daily value of 1% in their projected estimate of a PHES system, as does Siemens for their ETES. Malta predicts <0.5% loss daily for their 100-MW system. NREL's ENDURING project claims weekly loss of 3-5%. Antora Energy gives ~5-10% weekly.

Thermal storage can be most effective when partnered with an industrial process that requires process heat. If a thermal reservoir can be used either to regenerate or to use as local heat for an industrial process, the effective efficiencies can be very high, and the cost of the storage may be greatly reduced. To be more specific, envision an industry that needs heat to drive a process. Replacing natural gas with a heat pump enables delivering multiple kWh of heat for every kWh of electricity used, depending on the coefficient of performance of the heat pump. If that heat is then stored in a well-insulated reservoir, the heat can be extracted to drive the process 24/7. Such a system is attractive for electrification of an industrial thermal process. Once the investment is made in the thermal storage system, adding an electricity generator is an incremental cost. Furthermore, the use of the system may be optimized: on days when there is forecast to be a shortage of electricity after sunset, daytime electricity may be used to charge the thermal reservoir more than

---

[30] Smallbone A, Jülch V, Wardle R, Roskilly AP. Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. Energy Conversion and Management 2017;152:221–8.

needed by the industrial process. On days when the grid looks capable (*e.g*. a windy night), the reservoir would only be charged enough to drive the industrial process through the night.

Strengths of thermal storage include:

Technology diversity: There are many approaches being explored for the energy conversion and energy storage technologies.
Lower cost of increasing energy capacity: The cost of adding sand or rocks for extended storage can be quite low.

Cross-sector opportunities: The thermal energy many be monetized for industrial or other applications, providing a way to leverage the cost of installing the thermal storage and supporting the very important and broader problem of decarbonizing energy use in the industrial sector.

2.8 Geomechanical and related mechanical storage

Geomechanical storage is a new storage technology, being pioneered by Quidnet Energy, that uses compressed rock for storing the energy while using water to transmit the energy and convert it from electricity to stored energy to electricity (Fig. 2.15). The technique requires identifying suitable subterranean rock (Quidnet is starting with shale, then expanding to other rock types) and drilling a well that can inject pressurized water. The rock is initially cracked with pressurized water to form a horizontal fracture, or a storage lens. The lens is then sealed from further horizontal propagation using a proprietary technique. Subsequently, water is injected under pressure to increase lens width to form a water pocket. The lens must be managed to stay sealed because any leakage would be a loss mechanism; this differentiates the method from fracking, which intentionally injects water into nearby rock. Initial trials have verified that the storage lens can be made and used consistently in this way. As of July 2021, with over $35 million in funding, they have four projects under development. They have completed a mapping of potential for geomechanical storage identifying the potential for hundreds of TWh, with enough in California to meet most of California's storage needs.

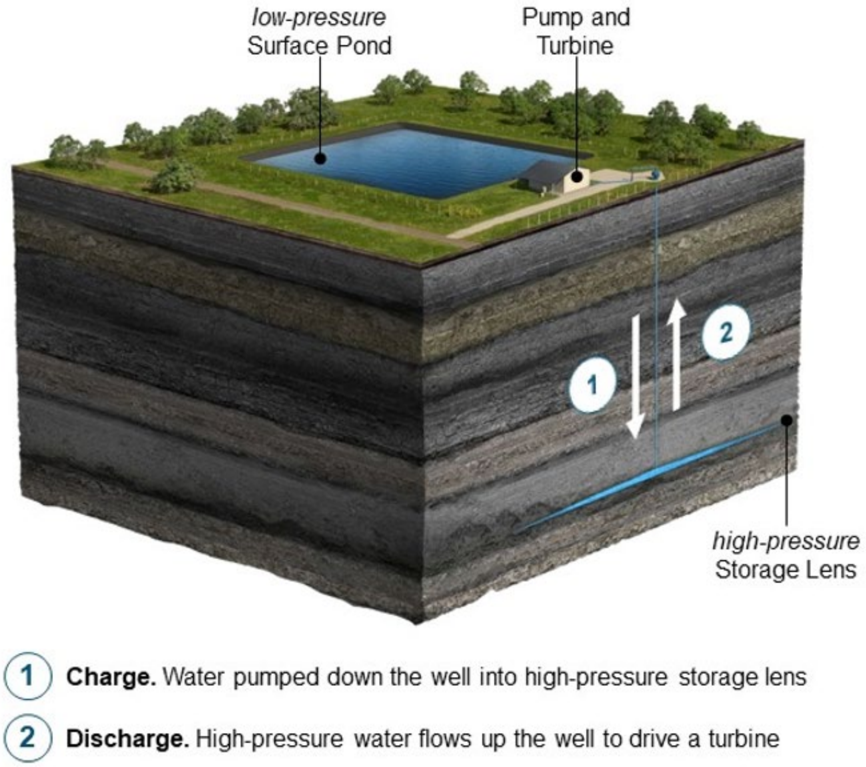


Fig. 2. 15 Schematic of geomechanical storage approach developed by Quidnet

They estimate costs of $500-$1000/kW for systems that can deliver 10 hours of storage, estimating that their systems will typically have a discharge power of 160-320 MW, with costs that are about half of those of Li batteries. The marginal cost of additional kWh is low – below $10/kWh – which means Quidnet can deliver 20-30 hour or even longer duration systems at extremely low $/kWh installed costs.

Geomechanical storage has some important advantages. Its efficiency has the potential to be close to that of pumped hydropower while it leverages existing expertise to position it to be able to scale rapidly. These advantages include:

• **Efficiency**: Quidnet is currently suggesting efficiencies between 65% and 75%, which is lower than usually assumed for Li batteries, but higher than is likely to be achieved by some of the other technologies.

• **Leverages oil and gas**: the approach may use equipment, expertise, and workforce that will be idled as the oil and gas industry scales back in response to electrification of the transportation and industrial energy sectors.

• **Leverages hydropower**: as the best-established storage technology, though the details of the geomechanical storage differ from conventional pumped hydropower, there is some overlap in technology and workforce.

Quidnet appears to be uniquely positioned to use existing capabilities to rapidly scale this storage technology once they have fully developed the geomechanical storage lens. Their cost estimate should be relatively accurate given that the costs of well drilling and hydropower turbines are fairly well known. However, there are risk factors associated with the largely unknown geomechanical technology that need to be addressed before large scale deployment. Thus, their choice of pursuing 4 projects to gain experience appears to be wise.

2.9 Hydrogen and other cross-sector storage

The use of hydrogen as a carbon-free fuel to replace hydrocarbons has captured attention around the world, especially in Australia, Europe and in the Middle East. The investment in both green hydrogen (solar plus hydrogen or offshore wind plus hydrogen) as well as in hydrogen infrastructure development (including production, storage, and transportation) is likely to quickly drive down the costs associated with hydrogen.

The U.S. Energy Department recently announced a target of \$1/kg for green hydrogen, which would enable green hydrogen to successfully compete with gray hydrogen (made by steam reformation of natural gas) and blue hydrogen (from natural gas using carbon capture and sequestration).

This low-cost green hydrogen is expected to be the key carbon-free fuel that can be used for parts of the energy system that cannot be easily electrified. The world already uses large quantities of hydrogen for applications for industrial processes like making ammonia and making steel. Currently, electrolysis is used to make only a few per cent of the supply of hydrogen. The key reason electrolysis is expensive is because of the electricity cost. California currently curtails large quantities of electricity, essentially providing a zero-cost electricity sources. However, if curtailed electricity is used during the few times a year when it is available, the cost of the electrolyzer becomes important. Reaching the U.S. Energy Department's goal of \$1/kg will benefit from reduced costs of both electrolyzers and electricity. If electrolyzer costs can be substantially reduced, it may be beneficial to use electrolysis as a variable load that can help to make the grid be more flexible. Thus, we assert that hydrogen is not only a key zero-carbon fuel for a decarbonized energy system, but that low-cost green hydrogen enables a decarbonized electricity grid by

1. providing a very large flexible load
2. providing electricity when solar and wind electricity aren't available and other storage reservoirs are depleted

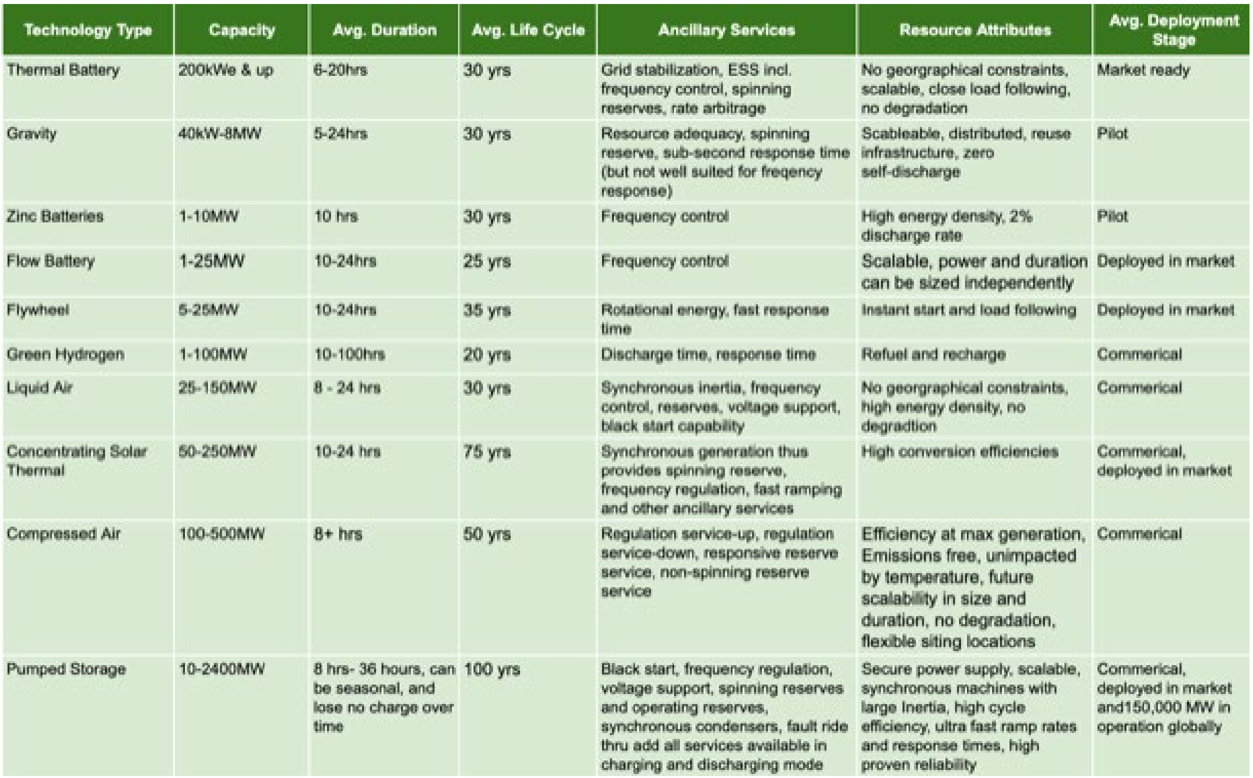
Our goal for the modeling will be to identify the extent to which each of these mechanisms will be important. In section 3.9 below we discuss strategies for modeling both of these mechanisms without needing to model the entire energy system.

Understanding the role of hydrogen is complicated by the additional costs of storage and transportation. Underground storage can be relatively inexpensive, but it is not readily available in many locations. Liquid hydrogen is a low-volume approach to storing hydrogen, but the liquefication process requires energy and long-term storage is compromised by boil off. GKN is launching a set of products that use metal hydride storage claiming storage densities that approach those of liquid hydrogen, but that store at temperatures and pressures close to common ambient conditions. Of course, high pressure storage in gas cylinders is always an option, but these are cumbersome. Liquid hydrogen is preferred by some experts because of the high rate at which the hydrogen can be transferred for refueling of vehicles. Liquid hydrogen may also be attractive approach for transportation on the ocean using technology that is similar to that used for liquified natural gas. These options for storage and the various options for transporting hydrogen must be considered to fully understand how hydrogen will interact with a decarbonized electrical grid.

2.11 Summary of attributes of storage technologies

Direct comparison of the storage technologies is desirable to better understand their strengths and weaknesses, but direct comparison is difficult because of the different attributes. In this section of the report, we present several different summaries with the goal of identifying how each of the technologies may fit into a restructuring of California's grid. We envision the possibility of all of these technologies contributing, so it will be the purpose of the next phase of our study to quantify the cost and performance targets that each will need to meet to be able to be a significant contributor.

The Long-Duration Storage Association of California shared their overview of storage technologies as shown in Table 2.5. They identify ancillary services that each technology can provide. We have not attempted to discuss ancillary services in this report because the ancillary services are not directly relevant to providing the state's needed long-duration storage. However, indirectly, the ancillary services are quite important because these provide entry markets for the technologies to enable them to reduce costs. Market entry is critical to success and some technologies might provide substantial value to the market but be "locked out" by a more mature product with which it is unable to compete. Thus, being able to provide an ancillary service may contribute to which technologies are able to meet the grid's longer-timeframe needs by providing a market entry strategy.



Technology Type	Capacity	Avg. Duration	Avg. Life Cycle	Ancillary Services	Resource Attributes	Avg. Deployment Stage
Thermal Battery	200kWe & up	6-20hrs	30 yrs	Grid stabilization, ESS incl. frequency control, spinning reserves, rate arbitrage	No georgraphical constraints, scalable, close load following, no degradation	Market ready
Gravity	40kW-8MW	5-24hrs	30 yrs	Resource adequacy, spinning reserve, sub-second response time (but not well suited for freqency response)	Scableable, distributed, reuse infrastructure, zero self-discharge	Pilot
Zinc Batteries	1-10MW	10 hrs	30 yrs	Frequency control	High energy density, 2% discharge rate	Pilot
Flow Battery	1-25MW	10-24hrs	25 yrs	Frequency control	Scalable, power and duration can be sized independently	Deployed in market
Flywheel	5-25MW	10-24hrs	35 yrs	Rotational energy, fast response time	Instant start and load following	Deployed in market
Green Hydrogen	1-100MW	10-100hrs	20 yrs	Discharge time, response time	Refuel and recharge	Commerical
Liquid Air	25-150MW	8 - 24 hrs	30 yrs	Synchronous inertia, frequency control, reserves, voltage support, black start capability	No georgraphical constraints, high energy density, no degradtion	Commerical
Concentrating Solar Thermal	50-250MW	10-24 hrs	75 yrs	Synchronous generation thus provides spinning reserve, frequency regulation, fast ramping and other ancillary services	High conversion efficiencies	Commerical, deployed in market
Compressed Air	100-500MW	8+ hrs	50 yrs	Regulation service-up, regulation service-down, responsive reserve service, non-spinning reserve service	Efficiency at max generation, Emissions free, unimpacted by temperature, future scalability in size and duration, no degradation, flexible siting locations	Commerical
Pumped Storage	10-2400MW	8 hrs- 36 hours, can be seasonal, and lose no charge over time	100 yrs	Black start, frequency regulation, voltage support, spinning reserves and operating reserves, synchronous condensers, fault ride thru add all services available in charging and discharging mode	Secure power supply, scalable, synchronous machines with large Inertia, high cycle efficiency, ultra fast ramp rates and response times, high proven reliability	Commerical, deployed in market and150,000 MW in operation globally

Table 2. 5 Summary of storage technologies [31]

As storage technologies begin to replace the role that peaker plants play today – providing resilience rather than frequent delivery of electricity – market structures may be revised to encourage the needed investment. Attributes that will contribute to a technology being competitive for such applications are well differentiated from the attributes needed for diurnal storage. For example, the replacements of the peaker plants don't need to have high round-trip efficiency, but do need to have low idle losses. Similarly, low capital costs associated with the size of the energy storage are essential, while the capital costs for the power conversion equipment are less critical. A technology that stores energy for multiple purposes may have an advantage if the reservoir that is used for the other purpose (*e.g.* energy for transportation) uses the reservoir on a regular basis, enabling the cost to be shared between multiple enterprises. In particular, storage of hydrogen for use in fuel cells could provide a special opportunity to leverage the investment in both the hydrogen storage and the fuel cell. The opportunity for the use of cross-sector storage has not been consistently included in capacity expansion models, but such use could provide one of the best solutions for seasonal storage.

Additional statistics compiled as part of this study are summarized in Table 2.6. Most of these statistics are highly variable depending on the situation, so in most cases a range is given. More mature technologies may have a smaller range specified, but a large range may be retained for even the most mature technologies because of variation of that statistic with the situation. The differences between Tables 2.5 and 2.6 reflect both the uncertainty in the numbers and the methodologies used for defining them. Table 2.7 summarizes similar information that was

---

[31] Courtesy of the Long-Duration Energy Storage Association of California

collected directly from the companies. Again, ranges are used to indicate the breadth of projects that each company anticipates.

Table 2. 6 Summary of typical technical statistics for storage technologies

Type of storage	Power capacity (MW)	Energy capacity (MWh)	Discharge duration (h)	Self-discharge rate (%/day)	Roundtrip efficiency (%)
AirBattery	5-500	20-5,000	4-24	0.1	70-80
Advanced compressed air	200-500+	800-12,000+	4-24	1	60-65
Liquid air	10-200	40-1000	4-24	0.5-1	55-60
Vanadium-based flow battery	0.01-10	0.1-100	4-24	0-1	65-85
Zinc-based battery	0.02-10	0.1-100	4-24	0.5-1	55-75
Flywheels	0.008-25	0.032-100	4	5-10	>86
Gravity using blocks	1-1000	4-10,000	4-24	0	80-85
Pumped storage hydropower	10-3000	100-20,000	10-100	0-0.02	70-85
Geomechanical	10-500	100-5,000	~10	0.5	55-75
Concentrated solar power with thermal storage	10-300	40-2,000	4-24	0.5-1	N/A*
Thermal	0.5-200	5-50,000	4-24	0.5-1	50-65
Lithium iron phosphate	0.001-300	0.002-2000	0.5-8	0.1-0.3	85-90

*Concentrated solar power has a unique opportunity to delay the original generation of electricity instead of converting electricity to thermal energy followed by regeneration of the electricity. Thus, although we label this as "not applicable", the effective efficiency of the storage could be equated to the idle losses of the thermal storage for the number of hours the generation is delayed, resulting in an effective efficiency over 95%.

In Tables 2.6 and 2.7, the power and energy capacity ranges were selected to reflect the range of probable products that may be offered. We avoided reporting plant sizes that reflected demonstration projects. Business models for most of the companies are still evolving, so all numbers are subject to change. The ranges on the power and energy capacities generally vary by a factor of at least ten and can vary as much as a factor of 1000. The discharge duration time is taken as the ratio of the Energy capacity rating to the Power capacity rating. In most cases the discharge duration time is targeted at the minimum 4 hours that is currently useful in California's markets. We anticipate that companies will begin to target products with longer discharge durations as the need for longer duration storage becomes more acute. Response times for some of the technologies depend on whether you are changing from charging to discharging or ramping from a low discharge rate to a high discharge rate. The self-discharge rate is especially important for products that are intended to retain the charge over multiple days or even months. In some cases, the self-discharge rate may depend on the temperature, the state of charge and other factors. The roundtrip efficiency is intended to be a system level efficiency, including losses in the charge controllers and inverters. For technologies that are already installed, it is possible to obtain data from the EIA, but for the newer technologies, the data need to be estimated. In all cases, we expect that improvements in technology will enable increased efficiencies in the future. More frequent use of storage may also improve the observed performance.

Table 2. 7 Summary of technical statistics provided by the companies

Company	Type	Power capacity (MW)	Energy capacity (MWh)	Discharge duration (h)	Self-discharge rate (%/day)	Roundtrip efficiency (%)
Invinity	Flow battery	0.08-10	0.2-100	2-12		78
Zinc8	Flow battery	0.02-10	0.16-240	8-100+	0.5-0.7	65
Renewell	Gravity	1-100	1-100	1-200	0	74
Energy Vault	Gravity	1-1000	4-10,000	4-10	0	83
Hydrostor	Advanced compressed air	200-500+	800-12,000+	4-24+	1	60-65
Augwind	AirBattery	5-500	20-5,000	4-24	0.1	70-80
Quidnet	Geomechanical	160-320	160-3200	~10	0.5	65-75
Cat Creek	Pumped hydropower	120-720	1,000,000	121-726	N/A	83
ETES	Thermal	30-100	240-1,600	6-48	1	39
Antora Energy	Thermal	0.5-200	5-50,000	10-250	0.5-2	50
Malta	Thermal	100-200	800+	4-24	0.6	53-65
Highview Power	Liquid air	10-200	10-1,000	4-24	0.5-1	55*

* This is without capturing waste heat, so higher efficiencies are expected to be achieved.

Additional statistics for the technologies shared by the companies are shown in Tables 2.8 and 2.9, respectively. The average costs are calculated by dividing the cost of a plant by its rating in kW or in kWh. In cases where additional energy capacity may be added, a marginal price may also be specified. Some companies refrained from sharing some of the data.

Table 2. 8 Summary of typical market related statistics for storage technologies

Type of storage technology	Average capital cost ($/kW).	Average capital cost ($/kWh)
Advanced compressed air	1500-2500	125-250
Liquid air		
Vanadium-based flow battery	600~1500	150~1050
Zinc-based battery	700~2500	150~1680
Flywheels		
Gravity using blocks	1000-1300	250-300
Pumped storage hydropower	1700~3200	5~200
Geomechanical	500-1000	50-100

Concentrated solar power with thermal storage		40~6250
Thermal		
Lithium iron phosphate		

Table 2. 9 Summary of market-related statistics obtained from the companies

Company	Type	Average capital cost ($/kW)	Average capital cost ($/kWh)	Marginal energy capital cost ($/kWh)	Fixed O&M ($/kW-yr)	Land usage (m2/MW)	Land usage (m2/MWh)
Invinity	Flow battery					292-568	97-189
Zinc8	Flow battery					150-200	20-25
Renewell	Gravity		50-75		50	900*	900
Energy Vault	Gravity	1130	280	85	20	90	175*
Quidnet	Geomechanical	500-1000	50-100	5-10	10-20		
Augwind	AirBattery					130-300	220-250
Hydrostor	Advanced compressed air	1500-2500	125-360	80	17-19	400-950	50-120
Cat Creek	Pumped hydropower	2200	0.05	7	9	10,600	90*
ETES	Thermal		126-154	1-2.3		NA	7*
Antora Energy	Thermal	400-750	10	<5	10	50-100*	
Malta	Thermal	1000	100	25-30	TBD	150	15
Highview Power	Liquid air						

*Land usage scales more naturally with this metric.

The land usage compared with the rating of a plant is a critical statistic when siting the plant. Data for the land usage were estimated by some of the companies as shown in Table 2.9.

The strengths of each storage technology and what policy steps might best help advance that technology are summarized in Table 2.10.

Table 2. 10 Summary of strengths and policy needs for each storage technology

Technology	Strengths	Opportunities (technical and market)	Policy needs
Lithium batteries	High efficiency; ease of use	Continued growth – is currently expanding very rapidly	Modify market structure to enable more effective use (of all storage) Support expanded market; include in ITC and other incentives even without solar
Pumped hydropower	High-efficiency; least cost over 100-year lifetime; well established	Can provide long-term benefit to the community including water and jobs once completed. Closed-loop implementation may open many new sites	Support to implement large projects through permitting and financing
Gravity	High efficiency and the land footprint can be minimal and or flexible	Can have negligible idle loss even over months of time	Support permitting, deployment to reduce risk
Flow batteries Metal-air and exfoliated-metal batteries	Potential to be lower cost than Li batteries for higher energy-to-power ratios	May enter market by providing resilience via microgrids during power outages.	Support R&D and deployment to prevent being locked out by Li batteries
Compressed air storage	Decades of experience; Advanced technology has higher efficiency and more flexibility in siting	Has potential for large scale, low-cost deployment once it demonstrates performance	Support deployment of advanced compressed air technology; facilitate permitting
Liquid air	Leverages existing supply chain to be scalable; May achieve high efficiency; ready to scale	Is ready to scale deployment for > 4-h systems	Support deployment and permitting
Thermal – CSP	Recent cost reductions combined with synergy of CSP + storage	Could combine generation with storage as costs come down	Support deployment and cost-reduction strategies
Thermal – without solar	Combined with decarbonization of industrial heating. May use very inexpensive storage media like sand or rocks to increase energy capacity at low cost	Could play primary role of decarbonizing industrial heating, then that success could be leveraged to give inexpensive storage; may be incorporated in existing fossil fuel power plants	Support decarbonization projects that also provide storage; support retrofits
Geomechanical	Leverages oil & gas; could scale rapidly to GWs; relatively high efficiency	Leverages oil & gas expertise & workforce. Once de-risked could scale very rapidly	Support deployment; facilitate permitting
Hydrogen	Can be used as a fuel to replace hydrocarbons	Could provide backbone of decarbonized energy system to drive transportation, heating, and chemical synthesis	Support infrastructure development as well as R&D

3. Modeling of storage technologies

This study's objective is to identify the role long-duration storage may play in decarbonizing a renewable-energy-powered grid for California. While non-renewable electricity sources could be used, [32] there is value in achieving a clean-energy system that uses only renewable energy sources. If new storage technologies can duplicate the successes that wind and solar have experienced in the last decades, there is a vision of creating an energy system that meets all of our needs at a cost that is lower than today's energy. However, the pathway is not clear, and success will rely on understanding how multiple technologies can work together to achieve the desired goal.

When the storage companies were asked what information would be useful to them, a key answer was to identify the cost target that a storage product would need to achieve to successfully enter the market. This is a key question that is also relevant to the California Energy Commission as it identifies cost targets and timelines for development of new storage technologies. To answer this question, we propose to use the strategy described in Fig. 3.1 with the goal of creating a time-dependent cost curve. as shown in Fig. 3.2.

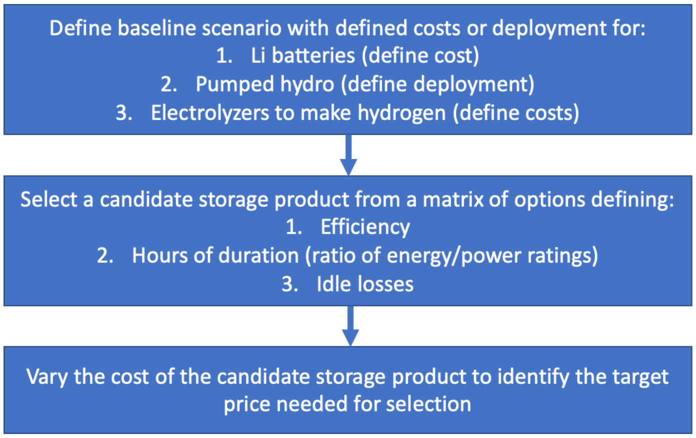


Fig. 3. 1 Modeling strategy for determining the cost target for candidate storage technologies

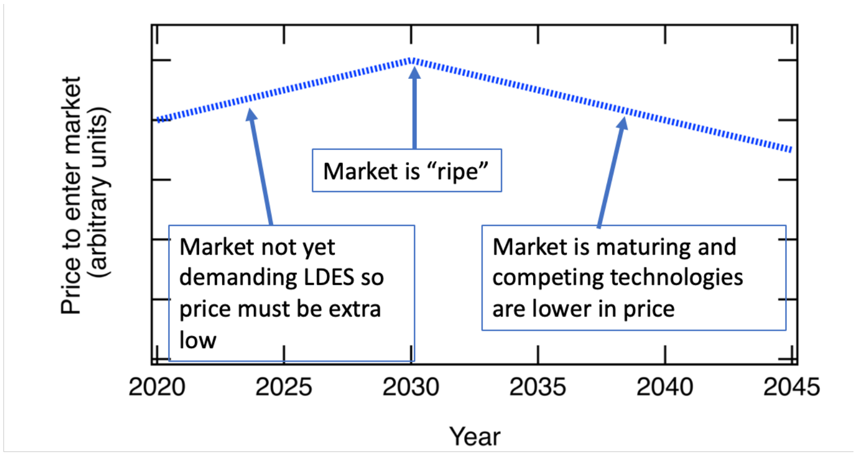


Fig. 3. 2 Example anticipated output of modeling strategy shown in Fig. 3.1.

---

[32] Baik, Ejeong, et al. "What is different about different net-zero carbon electricity systems?." *Energy and Climate Change* 2 (2021): 100046. https://doi.org/10.1016/j.egycc.2021.100046

The modeling strategy described in Fig. 3.1 anticipates that adoption of a new technology will depend both on its cost relative to Li batteries and the system's requirement for storage. The cost model for Li batteries is described in Section 3.1. Our baseline scenario will assume that today's planned pumped hydro projects are completed by 2030 (the first period we will model). A second scenario will evaluate the impact if the pumped hydro projects are not completed, with the expectation that the demand for new storage technology will increase. We plan to model seasonal storage and associated large-scale storage needed for grid reliability by including electrolyzers that can generate hydrogen for use by the transportation, industrial, and other energy sectors. It is very difficult to model all energy sectors simultaneously, so we propose to include hydrogen production as a manageable way to capture the opportunity that cross-sector storage will provide.

The output from the modeling, when displayed as shown in Fig. 3.2, will enable companies and the CEC to select products that can be launched in the appropriate time frame. Modeling of a storage product with a specific duration enables optimization of a single cost rather than considering reduction of both energy-associated costs and power-associated costs. However, to understand the potential for longer duration products, we will need to study products with a range of durations. As a starting point, we plan to model storage technologies with the parameters shown in Table 3.1. These may be revised to meet the needs of our stakeholders.

Table 3. 1 Candidate long-duration storage technology matrix to be studied

Efficiency	Duration (h)	Idle loss	Relevant technologies
80%	8, 16, 32, sometimes 128	About 0	pumped hydro, gravity, flow battery
70%	8, 16, 32, sometimes 128	About 0	geomechanical, flow battery, metal-air, exfoliated-metal, gravity
60%	8, 16, 32, sometimes 128	1%/day*	flow battery, metal-air, exfoliated-metal, compressed air, liquid air, thermal
50%	8, 16, 32, sometimes 128	1%/day*	thermal

*For thermal storage, we will also attempt to monetize the waste heat as discussed in section 3.4. In addition to plotting results as shown in Fig. 3.2 for each of the candidate long-duration storage technologies noted in Table 3.1, the modeling will enable analysis of the lowest cost approaches to decarbonizing a renewables-powered grid for California, including analysis of how frequently the storage is cycled, how much curtailment of solar and wind can be expected, etc.

For a subset of the candidate storage technology matrix, we plan to execute sensitivity analysis using the scenario modifications listed in Table 3.2.

Table 3. 2 Sensitivity analysis topics for understanding the role of long-duration storage

Parameter	Change
Weather	Use a number of years (*e.g.* 2015-2020) varying the generation and load profiles as well as the hydropower budgets
Hydrogen	Vary cost of electrolyzer
EV charging	Compare daytime charging to full-day/night charging
Loads	Enhanced electricity demand scenario
Transmission	Variable availability of new transmission
Offshore wind	Lower cost offshore wind
Geothermal	Lower cost geothermal
Pumped hydro	Assume none of the proposed pumped hydro plants is built

In the remainder of Section 3, we provide the relevant inputs for lithium batteries, pumped hydro, and hydrogen electrolysis that we propose to use in the baseline scenario.

3.1 Lithium batteries

Modeling inputs for Li batteries are summarized in Table 3.3 for RESOLVE. These costs reflect the NREL 2021 ATB, which is representative of Li battery storage for 60 MW power capacity with 240 MWh energy capacity (4 h duration). The capital costs for the moderate case were used and range from $190/kWh and $198/kW in 2025 to $113/kWh and $185/kW in 2045. The annualized costs have assumed a 15-year life with 4% interest. The O&M costs are in units of $/kW/year.

The charging and discharging efficiencies of 92.2% translate into an efficiency of 85% for the round-trip efficiency.

Table 3. 3 RESOLVE inputs for Li batteries

Timestamp	Attribute	Value
1/1/25	new_storage_capacity_fixed_om_by_vintage*	24
1/1/30	new_storage_capacity_fixed_om_by_vintage*	19
1/1/35	new_storage_capacity_fixed_om_by_vintage*	18
1/1/40	new_storage_capacity_fixed_om_by_vintage*	17
1/1/45	new_storage_capacity_fixed_om_by_vintage*	16
1/1/25	new_capacity_annualized_all_in_fixed_cost_by_vintage	17.8
1/1/30	new_capacity_annualized_all_in_fixed_cost_by_vintage	17.7
1/1/35	new_capacity_annualized_all_in_fixed_cost_by_vintage	17.4
1/1/40	new_capacity_annualized_all_in_fixed_cost_by_vintage	17.0
1/1/45	new_capacity_annualized_all_in_fixed_cost_by_vintage	16.6
1/1/25	new_storage_annual_fixed_cost_dollars_per_kwh_yr_by_vintage	15.3
1/1/30	new_storage_annual_fixed_cost_dollars_per_kwh_yr_by_vintage	13.2
1/1/35	new_storage_annual_fixed_cost_dollars_per_kwh_yr_by_vintage	12.2
1/1/40	new_storage_annual_fixed_cost_dollars_per_kwh_yr_by_vintage	11.2
1/1/45	new_storage_annual_fixed_cost_dollars_per_kwh_yr_by_vintage	10.2
None	can_build_new	1
None	can_retire	0
None	charging_efficiency	0.922
None	discharging_efficiency	0.922
None	parasitic_loss	0.01

*If the RESOLVE software allows, we would replace this with a value that scales with the energy rating rather than the power rating.

SWITCH parses the information about the storage resources in three main input files: “generation_projects_info.csv”, “gen_build_cost.csv” and “gen_build_predetermined.csv”. The general technical information of each project such as the location, energy source, round-trip efficiency, among others is listed on the “generation_projects_info.csv” file as shown in Table 3.4. The pre-existing or legacy installations are listed on “gen_buil_preditermined.csv” and the overnight cost for future years is listed in “gen_build_cost.csv” both shown in Table 3.5 and 3.6 respectively. such as the large Table 3.45 and smaller tables 3.5 & 3.6. These files give example data. The SWITCH modeling of WECC will include too many zones to include here.

Table 3. 4 Example of generation_projects_info.csv file format

GENERATION_PROJECT	1191209739
gen_tech	Battery_Storage
gen_energy_source	Electricity
gen_load_zone	CA_SDGE
gen_max_age	10
gen_is_variable	FALSE
gen_is_baseload	FALSE
gen_variable_om	0
gen_connect_cost_per_mw	82822
gen_scheduled_outage_rate	0.0055
gen_forced_outage_rate	0.02
gen_capacity_limit_mw	
gen_min_build_capacity	.
gen_is_cogen	FALSE
gen_storage_efficiency	0.85
gen_store_to_release_ratio	1
gen_can_provide_cap_reserves	1

Table 3. 5 SWITCH gen_build_costs file format

GENERATION_PROJECT	1191209739	1191209739	1191209739
build_year	2030	2040	2050
gen_overnight_cost	150026.3	126912	113216.2
gen_fixed_om	20981.9	17749.3	15834
gen_storage_energy_overnight_cost	172312.8	145764.7	130034.6

Table 3. 6 SWITCH gen_build_predetermined file format

GENERATION_PROJECT	**build_year**	**gen_predetermined_cap**
158014	1993	69

The very high fixed O&M costs included in the NREL ATB arise because of assuming capacity additions will be used to counter degradation (4 hr batteries).[33] The graph in Fig. 7 top right in NREL Report #75385 shows how the reported O&M costs may vary by a full order of magnitude. Some of the highest values are taken from 2017 and imply that the batteries must effectively be replaced something like every 3-4 years, inconsistent with the concept of a 15-year battery. For SWITCH, consistent with the above, we will follow the NREL ATB.

3.2 Pumped hydropower storage

We propose to model all pumped hydropower storage as planned builds rather than candidate resources that would be selected by the model. For the baseline, we propose to include the projects included in Table 2.2 in 2030 and subsequent years. The costs can be highly variable depending on the details of the project so will be modeled based on the total project cost rather than assigning a \$/kW or \$/kWh cost. The project cost will be annualized over 30-40 years using a 4% interest rate. As part of our sensitivity analysis, we will remove the pumped hydro projects to better understand their effect on adoption of other long-duration storage technology. The modeling parameters for these plants are listed in Table 3.7. The NREL ATB suggests 80% for the roundtrip efficiency. To duplicate the 80% roundtrip efficiency, we will use 89.4% efficiency for both charging and discharging.

---

[33] https://www.nrel.gov/docs/fy20osti/75385.pdf

Table 3. 7 Parameters for modeling pumped hydropower storage projects in or near California

Project name	Transmission zone	Capacity (MW)	Capacity (MWh)	Cost (million $)	Notes
Cat Creek Energy and Water Storage	RattleCat substation*	720	87,000	1700 for storage; 2457 with wind/solar	110 MW wind; 150 MW solar
Eagle Mountain	Southern California	1,300	23,400		Closed loop
Mokelumne Water Battery	Salt Springs Substation**	800	8,000	1100	Existing reservoir
Swan Lake	Oregon	393		882	Closed loop
Goldendale	Washington	1,200		2,400	Closed loop
San Vicente	San Diego	500			Closed loop

* Will use connection to the Idaho Power 230-kV grid system collecting at Rattlesnake substation [5 – 230-kV lines] and stepping up in the RattleCat substation from 230 kV to 500 kV. Two 500-kV lines then connect to the existing 500-kV PacifiCorp Midpoint to Hemingway HV line and is designed to also connect to the future Segment 8 Gateway West 500-kV line that will run parallel to the existing 500-kV line. The Midpoint substation is intended to move power to and from California via the Great Basin 500-kV line.

** The project will be connected at PG&E's Salt Springs substation and upgrade/reconductor the current line to a 230-V line to Tiger Creek Substation (17 miles), and potentially down to the Belota Substation (70 miles)

3.3 Hydrogen and other cross-sector storage

RESOLVE has included modeling of hydrogen as an added electrolyzer load and as a fuel for fuel cells. We propose to model hydrogen in a slightly different way by capturing the cost of building electrolyzers and then selling the hydrogen. For RESOLVE this is a new approach to modeling cross-sector hydrogen. So, we may vary these inputs after gaining some experience. For example, the selling price of hydrogen may be $2/kg if one needs to transport it elsewhere, but if it can be used on site, then it may be of much higher value. It may take some time to evaluate the feasibility of selling the hydrogen for a higher price. The inputs for hydrogen in RESOLVE are based on an analysis[34] of anticipated proton exchange membrane (PEM) electrolyzer costs. These are currently expected to be somewhat higher than alkaline electrolyzers, but lower than solid oxide electrolyzers. The PEM CapEx costs range from 900 Euro/kW in 2025 to 430 Euros/kW in 2045. The annualized CapEx costs were calculated based on $1.16/Euro, 15-year life and 4% interest as summarized in Table 3.8. The O&M costs were taken to be 2.5% of the CapEx cost. The hydrogen price is adjusted to meet the U.S. Department of Energy's goal to reduce to $1/kg, though not in the same timeframe.

---

[34] https://h2.pik-potsdam.de/H2Dash/

Table 3. 8 RESOLVE inputs for electrolyzers to generate hydrogen

Timestamp	Attribute	Value
1/1/25	new_provide_power_capacity_annualized_fixed_cost	94
1/1/30	new_provide_power_capacity_annualized_fixed_cost	72.5
1/1/35	new_provide_power_capacity_annualized_fixed_cost	60
1/1/40	new_provide_power_capacity_annualized_fixed_cost	51
1/1/45	new_provide_power_capacity_annualized_fixed_cost	45
1/1/25	planned_provide_power_capacity_fixed_om	26
1/1/30	planned_provide_power_capacity_fixed_om	20
1/1/35	planned_provide_power_capacity_fixed_om	17
1/1/40	planned_provide_power_capacity_fixed_om	14
1/1/45	planned_provide_power_capacity_fixed_om	12.5
1/1/25	Price_hydrogen_$_per_kg	2
1/1/30	Price_hydrogen_$_per_kg	1.8
1/1/35	Price_hydrogen_$_per_kg	1.6
1/1/40	Price_hydrogen_$_per_kg	1.3
1/1/45	Price_hydrogen_$_per_kg	1
None	can_build_new	1
None	can_retire	0
None	Electricity_to_hydrogen_kWh_kg	50

The implementation of the monetization of hydrogen generation will require modification of the RESOLVE software. The hydrogen price will be adjusted according to the model's output. If the price of the hydrogen is set high, the model will build solar to the limit and make money by selling the hydrogen. If this were to happen in the real world, the price of the hydrogen would drop. We anticipate that the hydrogen price will settle at a level where the added investment provides a balance between the value of the hydrogen and the value of having a very large flexible load.

3.4 Monetizing value of thermal waste heat from thermal storage

Some of the thermal storage technologies may be co-located with industries needing process heat. Such industries can benefit from waste heat from the discharge cycle, thereby reducing usage of natural gas or other source of heat. Table 3.9 summarizes examples of applications that operate processes with relatively low temperatures, potentially benefiting from the waste heat.[35]

To assess the value that can be gained by monetizing such heat, we will adjust the RESOLVE objective function to provide income based on the value of heat delivered. In general, we know that not all waste heat will be able to be used by the local application. We assume the discharge heat utilization factor is 20%. In practice, the availability of waste heat may be highly variable and

---

[35] We thank Mert Geveci of Malta, Inc for sharing this table who compiled it from the following references:

- https://www.epa.gov/rhc/renewable-industrial-process-heat
- https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf
- http://www.calmac.org/publications/California%20Ind%20EE%20Mkt%20Characterization.pdf
- https://www.nrel.gov/docs/fy15osti/64503.pdf
- https://www.nrel.gov/docs/fy16osti/64709.pdf

will benefit from innovative siting of the thermal storage system to be able to locally share the waste heat.

The amount of waste heat available depends on the process used to convert the heat back to electricity. The available heat may be up to two times the delivered electricity. From Table 3.9, the value of the heat may range from \$31/MWh to \$143/MWh. Note that Table 3.9 was constructed before the recent increase in natural gas prices. When modeling the 50% and 60% efficient candidate storage products, we will add the value of \$31/MWh or \$143/MWh (adjusted by the 20% discharge heat utilization factor) to see the effect it might have on the price target for the thermal storage technology. The \$143/MWh will represent both the displacement of processes run by electricity and the displacement of natural gas when natural gas prices are higher.

We anticipate that the implementation of the monetization of the waste heat will require modification of the RESOLVE software.

Table 3. 9 Summary of possible applications for waste heat

Industry	Application	Temperature (°C)	Medium	Process	Fuel source replaced	Efficiency	Price	Normalized Price/MWh
Paper & Pulp	Pulping paper	120-180	Hot water		Natural gas	82%	$25.47	$31.06
Lumber & wood	Kiln drying of lumber	110-180	Hot air		Wood pellets	78%	$48.76	$62.51
Fabricated metals	Metal galvanizing	130-180	Electrical coils	Batch	Electricity	98%	$140.10	$142.96
Food processing	Storage of vegetable oils	120			Electricity	98%	$140.10	$142.96
Food processing	Beer pasteurization	145	Steam		Natural gas	82%	$25.47	$31.06
	Meat scalding, washing, and cleanup	140	Hot water		Natural gas	82%	$25.47	$31.06
	Meat smoking/cooking	155	Hot air		Wood pellets	78%	$48.76	$62.51
	Milk pasteurization	162-185	Steam		Natural gas	82%	$25.47	$31.06
	Vegetable blanching/peeling	180-212	Hot water/steam		Natural gas	82%	$25.47	$31.06
	Canned sauce concentration	212	Steam		Natural gas	82%	$25.47	$31.06
	Food – pellet conditioning	180-190	Steam	Batch	Natural gas	82%	$25.47	$31.06
	Cooking oil storage	100-120	Steam		Natural gas	82%	$25.47	$31.06
	Fatty acid removal	180	Steam		Natural gas	82%	$25.47	$31.06
	Can/Bottle washing	140-190	Hot water		Natural gas	82%	$25.47	$31.06
	Fructose storage (soft drinks)	90	Steam		Natural gas	82%	$25.47	$31.06
	Starch and corn steam/steeping	122	Steam		Natural gas	82%	$25.47	$31.06
Chemicals	Soap fatty acid preheat	130	Steam jacket	Continuous	Natural gas	82%	$25.47	$31.06
	Soap mixing tank	180	Steam jacket	Continuous	Natural gas	82%	$25.47	$31.06
	Detergent mixing	180	Steam jacket	Continuous	Natural gas	82%	$25.47	$31.06
Agriculture	Greenhouses	80-85		Continuous	Electricity	98%	$140.10	$142.96
	Poultry brooding	87-92		Continuous	Electricity	98%	$140.10	$142.96
	Crop drying	130-150	Hot air	Batch	Electricity	98%	$140.10	$142.96
Sewage	Wastewater mesophyllic digesters	95	Steam		Natural gas	82%	$25.47	$31.06
	Wastewater thermophyllic digesters	120	Steam		Natural gas	82%	$25.47	$31.06

4. Bibliography

References referred to directly in the text are included as footnotes above. We also found the following references to be useful:

- Black and Veatch, 2012, Cost and performance data for power generation technologies. Overland Park, KS, 2012; [http://bv.com/docs/reports-studies/nrel-cost-report.pdf]
- Bloomberg NEF, March 2020, Hydrogen Economy Outlook [https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf]
- California Energy Commission, June 2020, Input & Assumptions - CEC SB 100 Joint Agency Report [https://efiling.energy.ca.gov/GetDocument.aspx?tn=234532&DocumentContentId=67359]
- California Energy Commission, 2021, Draft 2020 Integrated Energy Policy Report (IEPR) Update, Volume I [https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2020-integrated-energy-policy-report-update-0]
- California Public Utility Commission, March 2020, 2019-2020 Electric Resource Portfolios to Inform Integrated Resource Plans and Transmission Planning [https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M331/K772/331772681.PDF]
- Center for Climate Energy and Solutions, State Climate Policy Maps [https://www.c2es.org/content/state-climate-policy/]
- Clean Energy States Alliance (CESA), 2020, 100% Clean Energy Collaborative - Table of 100% Clean Energy States [https://www.cesa.org/projects/100-clean-energy-collaborative/table-of-100-clean-energy-states/]
- Cole, W. and A.W. Frazier, June 2020, Cost Projections for Utility-Scale Battery Storage: 2020 Update
- Cole, Wesley, and A. Will Frazier, June 2019, Cost Projections for Utility-Scale Battery Storage
- Eichman, Josh, Mariya Koleva, Omar J. Guerra, and Brady McLaughlin, March 2020, Optimizing an Integrated Renewable Electrolysis System [https://www.nrel.gov/docs/fy20osti/75635.pdf]
- Energy and Environmental Economics, June 2020, “Hydrogen Opportunities in a Low-Carbon Future” [https://www.ethree.com/wp-content/uploads/2020/07/E3_MHPS_Hydrogen-in-the-West-Report_Final_June2020.pdf]
- European Commission, March 2020, Commercialisation of Energy Storage in Europe [https://www.fch.europa.eu/sites/default/files/CommercializationofEnergyStorageFinal_3.pdf]
- Fu, Ran, Timothy Remo, and Robert Margolis, November 2018, 2018 U.S. Utility-Scale Photovoltaics Plus-Energy Storage System Costs Benchmark
- Fuel Cell and Hydrogen Energy Association (FCHEA), “Road Map to a US Hydrogen Economy” [http://www.fchea.org/us-hydrogen-study]
- Klein, J., 2007, Comparative costs of California central station electricity generation technologies: cost of generation model. California Energy Commission, Sacramento, CA,

2007; [http://www.energy.ca.gov/2007publications/CEC-200-2007-011/CEC-200-2007-011-SD.PDF]

- Lazard, November 2019, Lazard's Levelized Cost of Storage Analysis - version 5.0
- McGowin, C., 2007, Renewable Energy Technical Assessment Guide. TAG-RE:2007. Palo Alto, CA: Electric Power Research Institute.
- Mileva, A., et al. 2016, Power system balancing for deep decarbonization of the electric power sector. Applied Energy, 162, 1001-1009
- National Renewable Energy Laboratory (NREL), 2018 Annual Technology Baseline (ATB) [https://data.nrel.gov/system/files/89/2018-ATB-data-interim-geo.xlsm]
- National Renewable Energy Laboratory (NREL), 2019 Annual Technology Baseline (ATB) [https://data.nrel.gov/system/files/115/2019-ATB-data.xlsm]
- National Renewable Energy Laboratory (NREL), 2020 Annual Technology Baseline (ATB) [https://atb.nrel.gov/electricity/2020/files/2020-ATB-Data.xlsm]
- pv magazine, August 2020, Power-to-gas facility in Canada could pay back in just under three years [https://www.pv-magazine.com/2020/08/11/power-to-gas-facility-in-canada-could-pay-back-in-just-under-three-years/]
- pv magazine, December 2020, PV trends of 2020: Part 5 [https://www.pv-magazine.com/2020/12/30/pv-trends-of-2020-part-5/]
- RESOLVE Scenario Tool for creating the input files for RESOLVE [ftp://ftp.cpuc.ca.gov/energy/modeling/RESOLVE_Scenario Tool 2020-05-27_inputs_for_pyomo_5-6-9.xlsb]
- Strategen, December 2020, Long Duration Energy Storage for California's Clean, Reliable Grid [https://www.strategen.com/strategen-blog/long-duration-energy-storage-for-californias-clean-reliable-grid]
- United States Energy Information Administration, 2007a, Form EIA-860 database annual electric generator report. Washington, DC, 2007.
- United States Department of Labor, 2009, Occupational pay comparisons among metropolitan areas. Bureau of Labor Statistics, Washington, DC, 2009.
- United States Energy Information Administration, 2012, Annual energy outlook 2012. Washington, DC, 2012.
- U.S. Department of Energy, July 2020, Battery Storage in the United States: An update on market trends [https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf]
- U.S. Energy Information Administration, Annual Energy Outlook 2020 (Table 13. Natural Gas Supply, Disposition, and Prices) [https://www.eia.gov/outlooks/aeo/excel/aeotab_13.xlsx]