STORAGE TECHNOLOGY SUMMARY for EPC-19-060

(Deliverable for Subtask 3.2)

July 2021

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Executive Summary

This Storage Technology Summary reviews the long-duration storage technologies that may be useful to California in meeting the SB100 goals. A number of technologies are poised to contribute. An overview of these is presented in Table Exec 1.

This version is presented as a draft to be updated to the final version incorporating:

1. NREL plans to publish the 2021 ATB on July 6. We plan to review the changes there to identify useful updates before finalizing the inputs.

2. RESOLVE is being rewritten and the structure of the input files is being modified. We plan to update those tables based on input from E3 later in the month.

3. We would like to circulate this draft to the companies for their review and comment.

After completing the above three modifications, we would like to explore publication of the report by CEC.

Table Exec 1 Summary of energy storage technologies

Technology	Strengths	Opportunities	Policy needs
Lithium batteries	High efficiency; ease of use	Continued growth – is currently the technology to beat	Modify market structure to enable more effective use; Include in ITC even without solar
Pumped hydropower	High-efficiency; least cost over 100-year lifetime; well established, though additional development may require closed loop implementation	Can provide long-term benefit to the community if the initial investment can be completed	Support to implement large projects through permitting and financing of large projects
Flow batteries	Potential to be lower cost than Li batteries for higher energy-to-power ratios	Has the potential to be lower cost that Li batteries for longer durations, but may be locked out of market by initial high cost	Support R&D and deployment to prevent being locked out by Li batteries
Compressed air storage	Decades of experience with two large installations; Advanced technology has higher efficiency and more flexibility in siting	Has potential for large scale, low-cost deployment, but needs to demonstrate performance before scaling	Support deployment
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
Thermal – CSP	Recent cost reductions combined with synergy of CSP + storage	May be able to combine generation with storage if costs can come down	Support deployment
Thermal – without solar	May be combined with decarbonization of industrial heating	May 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	Incentivize decarbonization projects that also provide storage; support retrofits
Geomechanical	Leverages oil & gas; could scale rapidly to GWs; should reach higher efficiencies than other large-scale storage	Leverages oil & gas expertise and workforce. Needs to be de-risked and then could scale very rapidly	Support deployment
Flywheels	Highest efficiency	New technology may allow longer duration applications	Modify market structure to enable more effective use; Include in ITC even without solar
Hydrogen	Can be used as a fuel to replace hydrocarbons	Could provide backbone of decarbonized energy system	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 revisiting during a transition to much higher-penetration intermittent 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 1.464 MW and 3276 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]

1.2 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[6]
- Wood Mackenzie U.S. Energy Storage Monitor
- Lazard Cost of Energy and Storage[7]
- IHS Markit report[8]

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[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

[6] https://atb.nrel.gov/electricity/2020/index.php?t=in

[7] https://www.lazard.com/media/451418/lazards-levelized-cost-of-storage-version-60.pdf

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

- DOE OE Global Energy Storage Database[9]
- ISO interconnection queues, especially CAISO[10]
- EIA[11]

1.3 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 more important than cost: 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.

For storage technologies, will the conclusion 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.

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.

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[9] https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/
[10] http://www.caiso.com/PublishedDocuments/PublicQueueReport.xlsx
[11] www.eia.gov

(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.

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. Ultimately, if storage became cheap enough, it could be possible to remove the grid, but today's technologies are inadequate for reaching that goal.

1.4 Report structure

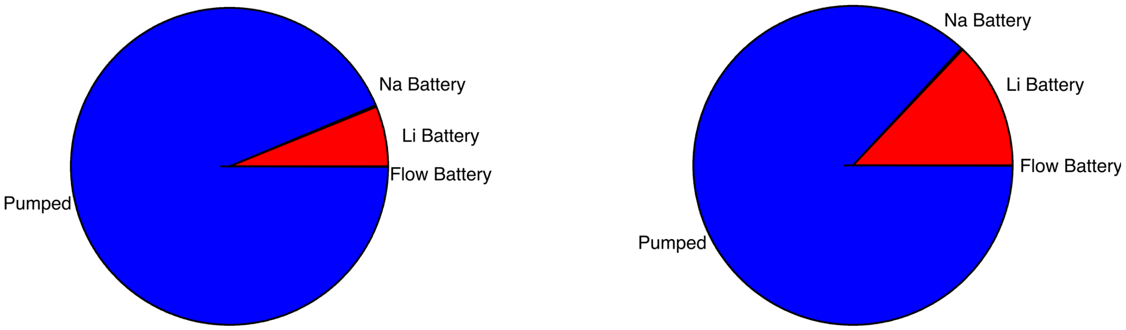
Section 2 of this report discusses the status of each storage technology. Section 3 provides a summary of all of the inputs that we will use in RESOLVE for the baseline modeling and for various scenarios.

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.



2019
Pumped hydropower: 3.7 GW
Li, Na (7 MW), and Flow (2 MW) batteries: 255 MW

2020
Pumped hydropower: 3.7 GW
Li, Na (7 MW), and Flow (2 MW) batteries: 538 MW

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
- 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 may be dominated by 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 and with reduced flammability issues. As an example of this trend, Tesla recently announced use of the lithium iron phosphate chemistry for its Megapack utility-scale battery.[12] 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, as is happening for many supply chains coming out of the pandemic.

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.

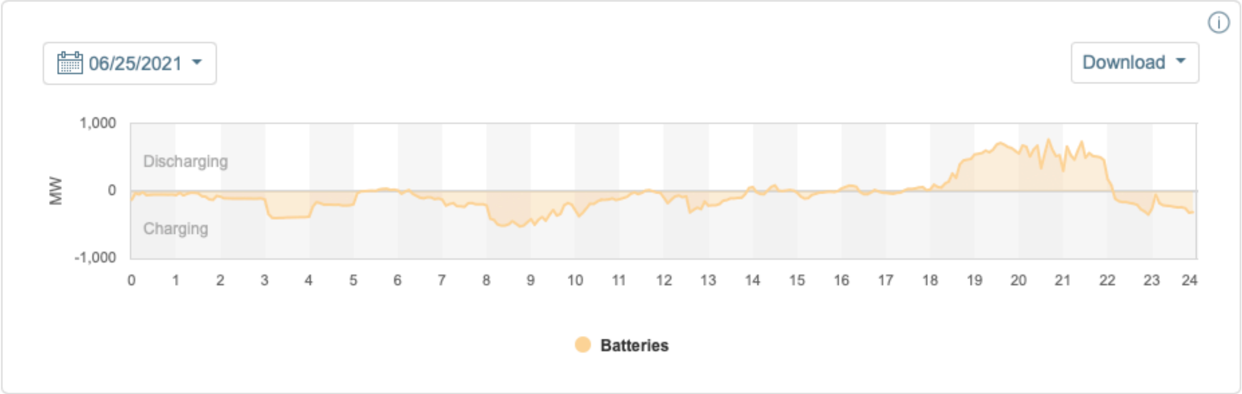


Fig. 2. 2 CAISO's use of batteries on June 5, 2021.[13]

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 whether more lithium batteries are built, and the durations selected. 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

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

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

non-battery costs, while the 4-h battery system 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.

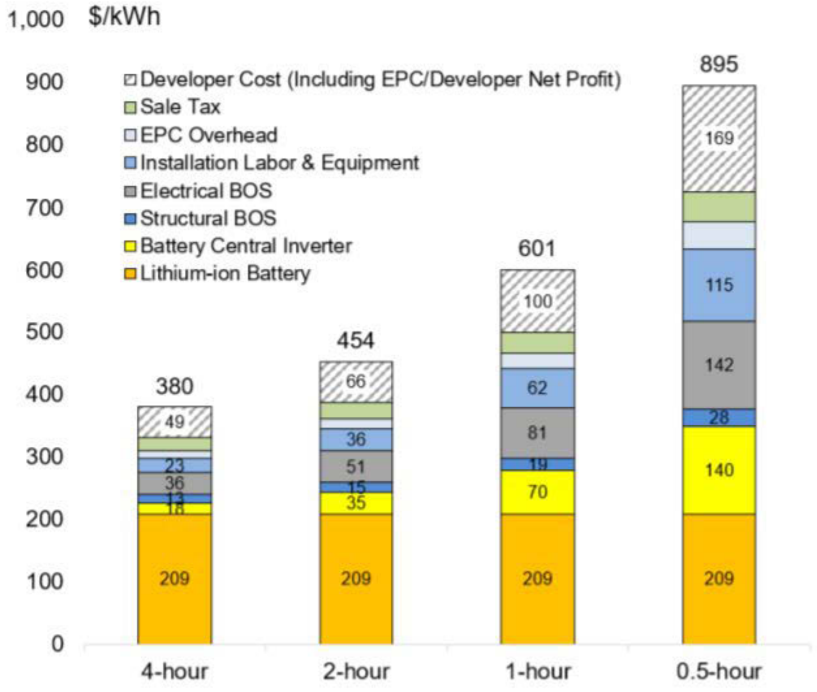

Fig. 2. 3 Cost breakdown of 2018 U.S. utility-scale lithium-ion battery standalone storage costs (60 MW$_{DC}$)[14]

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.

As we noted in our previous report, 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 makes 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. It could also be possible to change the capacity rating with time, but that is not currently included in the RESOLVE code.

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[14] 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

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	2020	TBD	TBD	
NREL 2021 ATB	2030	TBD	TBD	

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 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 net efficiency of the battery.

We summarize the input data for modeling in Section 3.

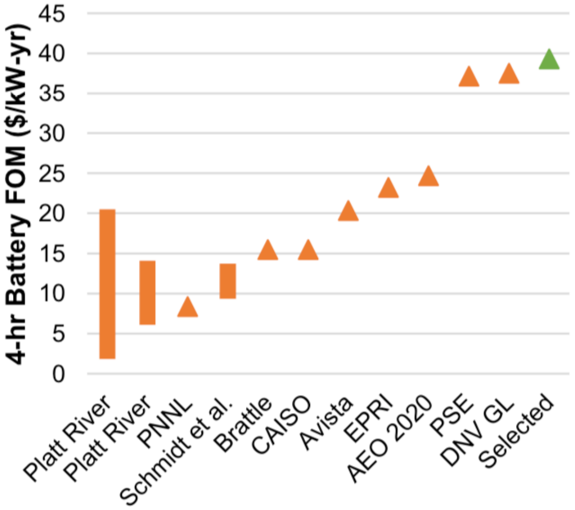

Fig. 2. 4 Battery fixed O&M cost as reported by different sources (Source: NREL)[15]

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

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. It is demonstrated to be low in cost when the appropriate geographical considerations are met but can be difficult to execute because of the geographical requirements and difficulty with initial 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 more than 4 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. It’s useful to consider that, while these projects have been discussed for years, the need for storage that can be deployed for more than about four hours at a time has not yet provided strong motivation to invest in pumped hydro. The motivation will increase significantly as we approach a zero-carbon grid. Pumped hydro also provides the substantial long-term benefit that its operating costs are very low, 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 would provide support for these large projects that would be in the public interest in the long term. It is difficult to make a case for private investment in a project that would provide the biggest benefits after those individuals and companies have moved on to other things. Nevertheless, there are some organizations working toward these projects. Government support 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 near California

Project name	Company	Location	Capacity (MW)	Planned start	Notes
Cat Creek Energy and Water Storage	Cat Creek Energy	Idaho	720		110 MW wind; 150 MW solar
Eagle Mountain	Eagle Crest Energy	Desert Center (Southern California)	1300		Closed loop
Mokelumne Water Battery	GreenGenStorage	Calaveras County (Central California)	250-800	2027	
Swan Lake	Rye Development	Oregon	393	2026	Closed loop
Goldendale	Rye Development	Washington	1200	2028	Closed loop

Pumped hydro technology is well established, but 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 lake while enabling dual use of the space (for both PV and the reservoir). 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 government support, large pumped-hydro projects are unlikely to reach completion. A particularly difficult question arises when a pumped hydro project is associated with environmental concerns. The tradeoffs between the environmental damage done by the project with the societal benefit that would come from the project can be difficult to assess, especially because there is likely to be a greater harm done to local residents, while the benefit may be felt by many more people, but not as acutely.

As part of the SB100 analysis,[16] 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. (which is longer than is likely to be practical; 35 years is recommended by Cat Creek)
- Fixed O&M of $25/kW-yr with an annual escalation of 2% - an increase from the 2018 RSP. (It is not clear that this is appropriate: 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).

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[17] that pumped hydro could meet all of our storage needs by executing projects that are

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

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

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 that may provide a pathway to this vision. Changes in policy could rapidly make a big difference in realizing the vision of pumped hydro being a large contributor to the needed storage.

2.3 Flow 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 for flow batteries.

- 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-air (commercialized by Zinc8) and zinc-bromine (commercialized by Primus Power and RedFlow) flow batteries are typically lower efficiency compared to vanadium-redox flow batteries, but they may be lower in cost.

- Aqueous-air/aqueous-sulfur batteries are anticipated to be lower in cost. Form Energy has announced deployment of a 1 MW, 150 MWh aqueous-air battery in Minnesota.

- Iron flow batteries (commercialized by ESS) offer portability and transportability as key advantages for projects that require mobility such as temporary micro-grids or other portable long-duration applications.

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%.

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 flow 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.[18]

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. 2.5. Under no condition (year of 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

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

commercialization phases. We will model these with variable costs to understand what cost target they must hit to be adopted more broadly.

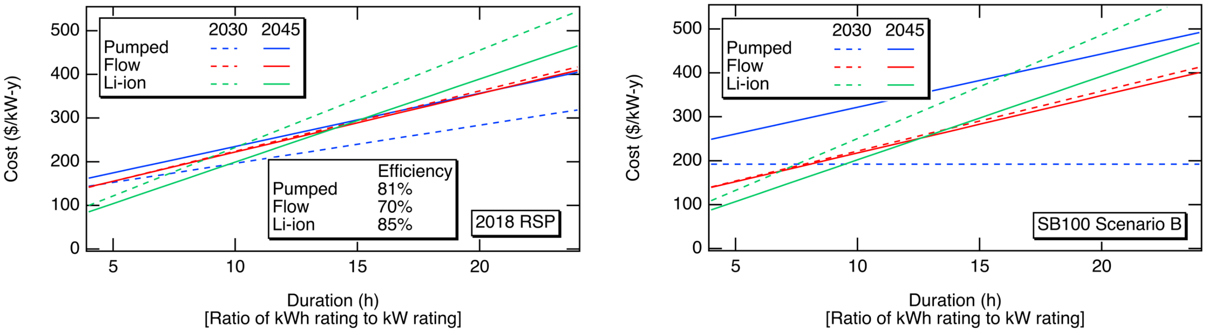

Fig. 2. 5 Annualized costs used by RESOLVE for modeling storage resources

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. 2.6. The advantages of the technology they are developing 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)

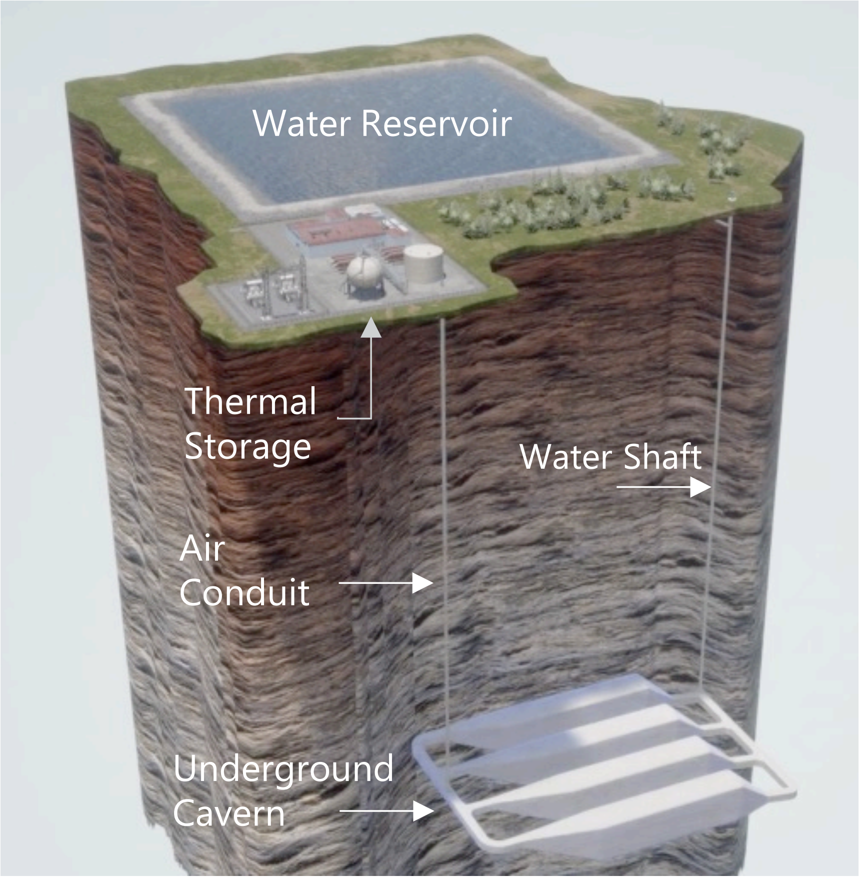

Fig. 2. 6 Schematic of Hydrostor's advanced compressed air storage approach

These advanced, adiabatic systems only reached commercial production recently. After completion of their Toronto Island Demonstration Facility in 2015, Hydrostor opened their Goderich A-CAES site (1.75 MW and 10 MWh) to commercial service in 2019 in Ontario. Augwind announced a 5 MW, 20 MWh pilot in Israel. 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.

Hydrostor is an interesting company to watch because they are advancing a well-established technology with a number of useful innovations. Their approach can leverage well established processes and supply chains, positioning them to scale up quickly. Their efficiency and cost are similar to many of the other technologies. Our interactions with Hydrostor have reflected very thoughtful and thorough analysis from Hydrostor.

2.5 Liquid air energy storage

Liquid air energy storage has been developed by Highview Power. 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.

Thus, this technology is at a critical time in its development. 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.

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.[19] 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. 2.7.

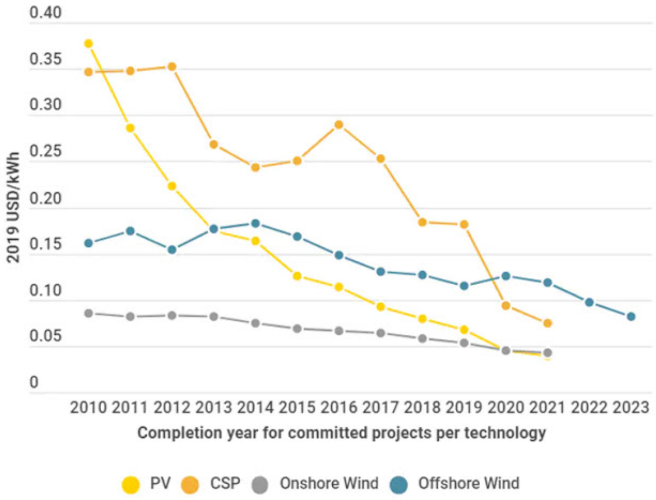

Fig. 2. 7 Cost evolution showing how CSP has recently been catching up with other renewable technologies[20]

Deployment of CSP systems may continue to lag those of PV (electricity generation from CSP is less than 10% 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. 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.[21] 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.

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

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

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

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,[22] and using an 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 10 MW pre-production prototype of a molten salt based PHES system for 100 MW and 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.

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. 2.8. Having completed a 130 MWh demonstrator in Hamburg in 2019, they are currently working on the first series of commercial pilots.

Another sensible heat, but non-PHES system is being developed by Antora Energy. 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.

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[22] 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.

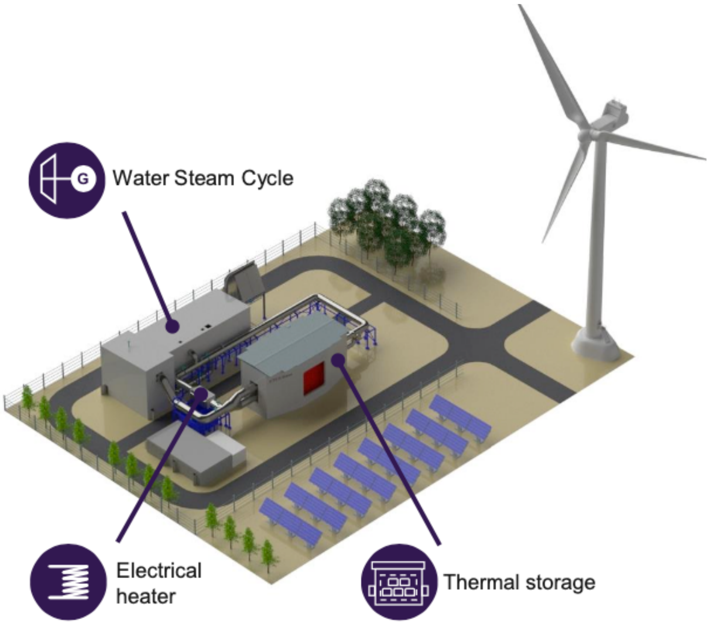

Fig. 2. 8 Schematic of Electrical Thermal Energy Storage (ETES) system

A PCM AC-to-AC 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[23] use a daily value of 1% in their projected estimate of a PHES system, as does Siemens for their ETES. Malta predicts <1% daily for a 10 MW system, and <0.5% daily at 100 MW. 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 substantial 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 an obvious option for electrification of an industrial thermal process. Once the investment is made in that thermal storage system, the addition of 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 the sun sets, daytime electricity may be used to charge the thermal reservoir more than would be needed for 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.

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[23] 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.

2.8 Geomechanical storage

Geomechanical storage is a little-known storage technology 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. The technique requires identifying suitable subterranean rock (e.g. shale) and drilling a well that can inject pressurized water. The rock is initially cracked with pressurized water to form a horizontal fracture. The fracture is then sealed from further horizontal propagation using a proprietary technique. Subsequently, water is injected under pressure to expand the fracture vertically and compress the adjacent rock by forming a water pocket that takes the shape of a lens. The pressures that are applied must be kept low enough to prevent further fracture of the rock. Initial trials have verified that the fracture can be made and used in this way. Quidnet Energy is pioneering this geomechanical technique. 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 potential of many TWh, with enough in California to meet most of California's storage needs.

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.

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, pumped hydropower is well established. Although 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 mastered the art of creating the subterranean cavity that will be stable in its operation. 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 Flywheels

Flywheels are typically viewed as short-duration storage, but recent developments have enabled them to increase the hours they can retain charge. Amber Kinetics is an example of a company – they have received CEC funding and have increased their deployment experience. They offer smaller size systems (32 kWh) and claim 86% round trip efficiency including idle losses for a 4-

hour storage system.[24] These systems have some of the highest efficiencies, but may not reach low costs because of the large amount of steel.

2.10 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

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[24] https://amberkinetics.com/wp-content/uploads/2020/05/Amber-Kinetics-DataSheet.pdf

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.

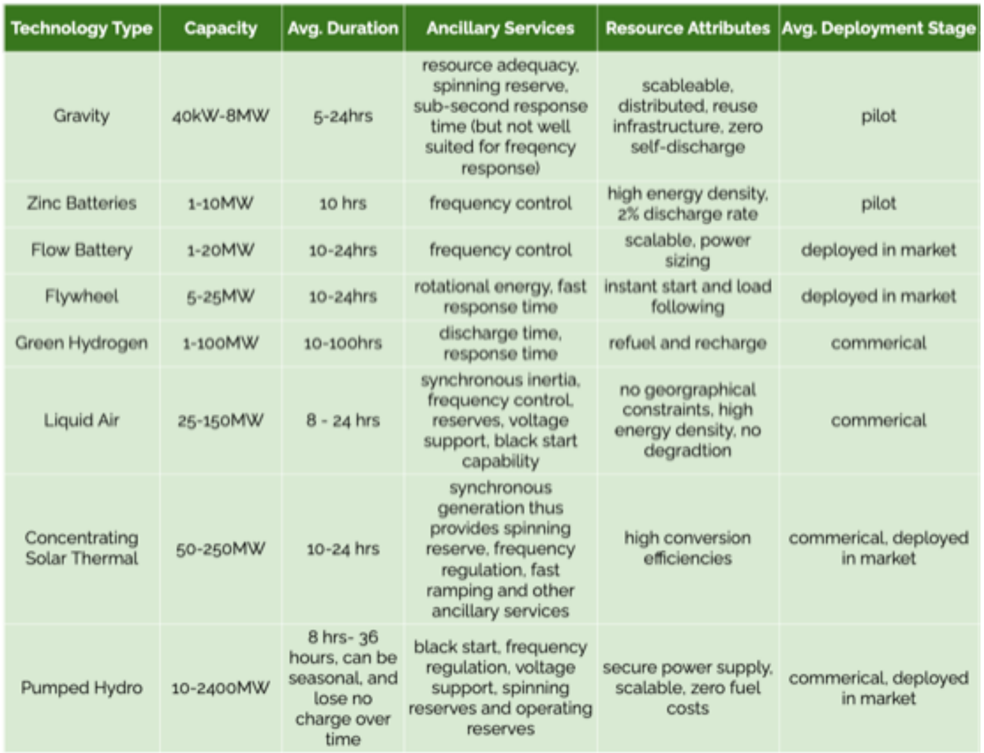
2.11 Summary of attributes of storage technologies

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 2.4. 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-time-frame needs.

Additional statistics compiled as part of this study are summarized in Table 2.5. 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 2.4 and 2.5 reflect both the uncertainty in the numbers and the methodologies used for defining them. Table 2.6 summarizes similar information that was collected directly from the companies. Again, ranges are used to indicate the breadth of projects that each company anticipates.

Table 2. 4 Summary of storage technologies[25]



Technology Type	Capacity	Avg. Duration	Ancillary Services	Resource Attributes	Avg. Deployment Stage
Gravity	40kW-8MW	5-24hrs	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	frequency control	high energy density, 2% discharge rate	pilot
Flow Battery	1-20MW	10-24hrs	frequency control	scalable, power sizing	deployed in market
Flywheel	5-25MW	10-24hrs	rotational energy, fast response time	instant start and load following	deployed in market
Green Hydrogen	1-100MW	10-100hrs	discharge time, response time	refuel and recharge	commerical
Liquid Air	25-150MW	8 - 24 hrs	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	synchronous generation thus provides spinning reserve, frequency regulation, fast ramping and other ancillary services	high conversion efficiencies	commerical, deployed in market
Pumped Hydro	10-2400MW	8 hrs- 36 hours, can be seasonal, and lose no charge over time	black start, frequency regulation, voltage support, spinning reserves and operating reserves	secure power supply, scalable, zero fuel costs	commerical, deployed in market

Table 2. 5 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 (%)
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	100-500	1000-5000	~10	0.5	55-75
Concentrated solar power with thermal storage	10-300	40-2000	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

In Tables 2.5 and 2.6, 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

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

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. 6 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	25-100	25-100		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
Quidnet	Geomechanical	15-300	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	10-200	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 2.7 and 2.8, 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. 7 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. 8 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	3800	475	45	20-50	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		
Hydrostor	Advanced compressed air	1500-2500	125-360	80	17-19	100-400	10-50
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 2.8.

The strengths of each storage technology and what policy steps might best help advance that technology are summarized in Table 2.9.

Table 2. 9 Summary of strengths and policy needs for each storage technology

Technology	Strengths	Opportunities	Policy needs
Lithium batteries	High efficiency; ease of use	Continued growth – is currently the technology to beat	Modify market structure to enable more effective use; Include in ITC even without solar
Pumped hydropower	High-efficiency; least cost over 100-year lifetime; well established, though additional development may require closed loop implementation	Can provide long-term benefit to the community if the initial investment can be completed	Support to implement large projects through permitting and financing of large projects
Flow batteries	Potential to be lower cost than Li batteries for higher energy-to-power ratios	Has the potential to be lower cost that Li batteries for longer durations, but may be locked out of market by initial high cost	Support R&D and deployment to prevent being locked out by Li batteries
Compressed air storage	Decades of experience with two large installations; Advanced technology has higher efficiency and more flexibility in siting	Has potential for large scale, low-cost deployment, but needs to demonstrate performance before scaling	Support deployment
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
Thermal – CSP	Recent cost reductions combined with synergy of CSP + storage	May be able to combine generation with storage if costs can come down	Support deployment
Thermal – without solar	May be combined with decarbonization of industrial heating	May 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	Incentivize decarbonization projects that also provide storage; support retrofits
Geomechanical	Leverages oil & gas; could scale rapidly to GWs; should reach higher efficiencies than other large-scale storage	Leverages oil & gas expertise and workforce. Needs to be de-risked and then could scale very rapidly	Support deployment
Flywheels	Highest efficiency	New technology may allow longer duration applications	Modify market structure to enable more effective use; Include in ITC even without solar
Hydrogen	Can be used as a fuel to replace hydrocarbons	Could provide backbone of decarbonized energy system	Infrastructure development as well as R&D

3. Modeling of storage technologies

The rewrite of RESOLVE has defined a new file format. To ease the translation of these modeling plans into RESOLVE, we will use that new file format here. Two types of files are used as shown in Tables 3.1 and 3.2 for definition of the CAISO battery resource. Any value that may change with time is entered in the dynamic file. The timestamp field in this file defines times associated with both the vintage of when a system is installed, and the day/hour of the year being modeled. The two files are grouped together in a single folder to define that the static values in the static input file are relevant to all resources in the dynamic file. That single folder is then grouped with similar folders for other resources in a folder called "resource_inputs". The example files that were supplied to us by E3 do not share the final format. We will update these tables to agree with E3's final format when we receive it.

Table 3. 1 Example dynamic file format for new RESOLVE software

timestamp	resource	attribute	value
1/1/20	CAISO_Battery	planned_installed_capacity	100
1/1/30	CAISO_Battery	planned_installed_capacity	1300
1/1/20	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	5.86
1/1/30	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	5.86
1/1/20	CAISO_Battery	planned_storage_capacity	400
1/1/30	CAISO_Battery	planned_storage_capacity	5200
1/1/20	CAISO_Battery	planned_storage_capacity_fixed_om	0
1/1/30	CAISO_Battery	planned_storage_capacity_fixed_om	0
1/1/20	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	45
1/1/30	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	24
1/1/20	CAISO_Battery	planned_provide_power_capacity_fixed_om	6
1/1/30	CAISO_Battery	planned_provide_power_capacity_fixed_om	6
1/1/20	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	64
1/1/30	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	34

Table 3. 2 Example static file format for new RESOLVE software

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.85
discharging_efficiency	1

SWITCH enters information about the storage resources in multiple files such as the large Table 3.3 and smaller tables 3.4 & 3.5.

Table 3. 3 SWITCH generation_projects_info 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	82822.425
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	0.75
gen_store_to_release_ratio	1
gen_can_provide_cap_reserves	1

Table 3. 4 SWITCH gen_build_costs file format

GENERATION_PROJECT	1191209739	1191209739	1191209739	1191209739
build_year	2020	2030	2040	2050
gen_overnight_cost	414708.3	150026.3	126912	113216.2
gen_fixed_om	32043.494	20981.9	17749.3	15834
gen_storage_energy_overnight_cost	295794.675	172312.8	145764.7	130034.6

Table 3. 5 SWITCH gen_build_predetermined file format

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

In Section 3, we provide the relevant inputs for each of the storage resources that we intend to model either as part of the baseline scenario or evaluation of that baseline scenario.

3.1 Lithium batteries

Modeling inputs for Li batteries are summarized in Tables 3.6 and 3.7 for RESOLVE and in Tables 3.8 - 3.10 for SWITCH.

Table 3. 6 RESOLVE dynamic inputs for Li batteries

Timestamp	**Resource**	**Attribute**	**Value**
1/1/25	CAISO_Battery	planned_installed_capacity	15000
1/1/30	CAISO_Battery	planned_installed_capacity	15000
1/1/35	CAISO_Battery	planned_installed_capacity	15000
1/1/40	CAISO_Battery	planned_installed_capacity	15000
1/1/45	CAISO_Battery	planned_installed_capacity	15000
1/1/25	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	0.52
1/1/30	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	0.42
1/1/35	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	0.40
1/1/40	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	0.38
1/1/45	CAISO_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	0.36
1/1/25	CAISO_Battery	planned_storage_capacity	60000
1/1/30	CAISO_Battery	planned_storage_capacity	60000
1/1/35	CAISO_Battery	planned_storage_capacity	60000
1/1/40	CAISO_Battery	planned_storage_capacity	60000
1/1/45	CAISO_Battery	planned_storage_capacity	60000
1/1/25	CAISO_Battery	planned_storage_capacity_fixed_om	4.
1/1/30	CAISO_Battery	planned_storage_capacity_fixed_om	3.
1/1/35	CAISO_Battery	planned_storage_capacity_fixed_om	2.5
1/1/40	CAISO_Battery	planned_storage_capacity_fixed_om	2.25
1/1/45	CAISO_Battery	planned_storage_capacity_fixed_om	2.
1/1/25	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	38.23
1/1/30	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	30.40
1/1/35	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	28.41
1/1/40	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	27.21
1/1/45	CAISO_Battery	new_provide_power_capacity_annualized_fixed_cost	26.00
1/1/25	CAISO_Battery	new_provide_power_capacity_fixed_om	0.52

1/1/30	CAISO_Battery	new_provide_power_capacity_fixed_om	0.42
1/1/35	CAISO_Battery	new_provide_power_capacity_fixed_om	0.40
1/1/40	CAISO_Battery	new_provide_power_capacity_fixed_om	0.38
1/1/45	CAISO_Battery	new_provide_power_capacity_fixed_om	0.36
1/1/25	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	27.42
1/1/30	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	22.31
1/1/35	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	20.92
1/1/40	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	19.53
1/1/45	CAISO_Battery	new_storage_capacity_annualized_fixed_cost	18.13
1/1/25	CAISO_Battery	new_storage_capacity_fixed_om	4.
1/1/30	CAISO_Battery	new_storage_capacity_fixed_om	3.
1/1/35	CAISO_Battery	new_storage_capacity_fixed_om	2.5
1/1/40	CAISO_Battery	new_storage_capacity_fixed_om	2.25
1/1/45	CAISO_Battery	new_storage_capacity_fixed_om	2.

Table 3. 7 RESOLVE static inputs for Li batteries

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.93
discharging_efficiency	0.93

SWITCH enters information about the storage resources in multiple files such as the large Table 3.3 and smaller tables 3.4 & 3.5. These files give example data. The SWITCH modeling of WECC will include many zones and copying all of the data here would take substantial space.

Table 3. 8 SWITCH generation_projects_info 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	82822.425
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

* This highlighted number represents a change and is highlighted to ensure that it is updated later.

Table 3. 9 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. 10 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.[26] 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 have used inputs suggested by CatCreek. Specifically, we use $9.4/kW/yr for O&M of new installations. We retained the higher O&M cost for older hardware. For the annualized cost, we used $2220/kW with a 35-year finance period at 5% interest.

Loan guarantees or low-interest loans could reduce the annualized cost input.

The model inputs for pumped hydropower storage are summarized in Tables 3.11-3.15.

Table 3. 11 RESOLVE dynamic inputs for pumped hydro storage

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_PHS	planned_installed_capacity	3059.2
1/1/30	CAISO_PHS	planned_installed_capacity	3059.2
1/1/35	CAISO_PHS	planned_installed_capacity	3059.2
1/1/40	CAISO_PHS	planned_installed_capacity	3059.2
1/1/45	CAISO_PHS	planned_installed_capacity	3059.2
1/1/25	CAISO_PHS	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	24
1/1/30	CAISO_PHS	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	24
1/1/35	CAISO_PHS	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	24
1/1/40	CAISO_PHS	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	24
1/1/45	CAISO_PHS	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	24
1/1/25	CAISO_PHS	planned_storage_capacity	252821.124
1/1/30	CAISO_PHS	planned_storage_capacity	252821.124
1/1/35	CAISO_PHS	planned_storage_capacity	252821.124
1/1/40	CAISO_PHS	planned_storage_capacity	252821.124
1/1/45	CAISO_PHS	planned_storage_capacity	252821.124
1/1/25	CAISO_PHS	planned_storage_capacity_fixed_om	0
1/1/30	CAISO_PHS	planned_storage_capacity_fixed_om	0
1/1/35	CAISO_PHS	planned_storage_capacity_fixed_om	0
1/1/40	CAISO_PHS	planned_storage_capacity_fixed_om	0
1/1/45	CAISO_PHS	planned_storage_capacity_fixed_om	0
1/1/25	CAISO_PHS	new_provide_power_capacity_annualized_fixed_cost	135.
1/1/30	CAISO_PHS	new_provide_power_capacity_annualized_fixed_cost	135.
1/1/35	CAISO_PHS	new_provide_power_capacity_annualized_fixed_cost	135.
1/1/40	CAISO_PHS	new_provide_power_capacity_annualized_fixed_cost	135.
1/1/45	CAISO_PHS	new_provide_power_capacity_annualized_fixed_cost	135.
1/1/25	CAISO_PHS	new_provide_power_capacity_fixed_om	9.4
1/1/30	CAISO_PHS	new_provide_power_capacity_fixed_om	9.4
1/1/35	CAISO_PHS	new_provide_power_capacity_fixed_om	9.4
1/1/40	CAISO_PHS	new_provide_power_capacity_fixed_om	9.4

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

1/1/45	CAISO_PHS	new_provide_power_capacity_fixed_om	9.4
1/1/25	CAISO_PHS	new_storage_capacity_annualized_fixed_cost	0
1/1/30	CAISO_PHS	new_storage_capacity_annualized_fixed_cost	0
1/1/35	CAISO_PHS	new_storage_capacity_annualized_fixed_cost	0
1/1/40	CAISO_PHS	new_storage_capacity_annualized_fixed_cost	0
1/1/45	CAISO_PHS	new_storage_capacity_annualized_fixed_cost	0

Table 3. 12 RESOLVE static inputs for pumped hydro storage

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.9
discharging_efficiency	0.9
Minimum duration	12

Table 3. 13 SWITCH generation_projects_info file format

GENERATION_PROJECT	gen_tech	gen_energy_source	gen_load_zone	gen_max_age	gen_is_variable	gen_is_baseload	gen_variable_om	gen_connect_cost_per_mw
154342	Hydro_Pumped	Water	CA_PGE_CEN	200	FALSE	FALSE	0	0
154359	Hydro_Pumped	Water	AZ_PHX	200	FALSE	FALSE	0	0
154363	Hydro_Pumped	Water	AZ_PHX	200	FALSE	FALSE	0	0
154501	Hydro_Pumped	Water	CA_SCE_CEN	200	FALSE	FALSE	0	0
154546	Hydro_Pumped	Water	CA_PGE_N	200	FALSE	FALSE	0	0
154554	Hydro_Pumped	Water	CA_PGE_CEN	200	FALSE	FALSE	0	0
154556	Hydro_Pumped	Water	CA_PGE_CEN	200	FALSE	FALSE	0	0
154566	Hydro_Pumped	Water	CO_NW	200	FALSE	FALSE	0	0
154607	Hydro_Pumped	Water	CO_DEN	200	FALSE	FALSE	0	0
154812	Hydro_Pumped	Water	CA_PGE_CEN	200	FALSE	FALSE	0	0
154821	Hydro_Pumped	Water	WA_N_CEN	200	FALSE	FALSE	0	0
154833	Hydro_Pumped	Water	CO_NW	200	FALSE	FALSE	0	0
154910	Hydro_Pumped	Water	AZ_APS_N	200	FALSE	FALSE	0	0
155959	Hydro_Pumped	Water	CA_SDGE	200	FALSE	FALSE	0	0

gen_scheduled_outage_rate	gen_forced_outage_rate	gen_capacity_limit_mw	gen_min_build_capacity	gen_is_cogen	gen_storage_efficiency	gen_store_to_release_ratio	gen_can_provide_cap_reserves
0.05	0.05	199.8	.	FALSE	.	.	1
0.05	0.05	99.8	.	FALSE	.	.	1
0.05	0.05	54.3	.	FALSE	.	.	1
0.05	0.05	1626	.	FALSE	.	.	1
0.05	0.05	293.1	.	FALSE	.	.	1
0.05	0.05	25.2	.	FALSE	.	.	1
0.05	0.05	424	.	FALSE	.	.	1
0.05	0.05	300	.	FALSE	.	.	1
0.05	0.05	8.5	.	FALSE	.	.	1
0.05	0.05	702	.	FALSE	.	.	1
0.05	0.05	314	.	FALSE	.	.	1
0.05	0.05	200	.	FALSE	.	.	1

0.05	0.05	40	.	FALSE	.	.	1
0.05	0.05	42	.	FALSE	.	.	1

Table 3. 14 SWITCH gen_build_costs file format

GENERATION_PROJECT	build_year	gen_overnight_cost	gen_fixed_om	gen_storage_energy_overnight_cost
154342	1987	0	0	.
154359	1972	0	0	.
154363	1971	0	0	.
154501	1973	0	0	.
154501	1974	0	0	.
154501	1976	0	0	.
154501	1977	0	0	.
154501	1978	0	0	.
154546	1968	0	0	.
154546	1969	0	0	.
154554	1967	0	0	.
154554	1968	0	0	.
154556	1967	0	0	.
154556	1968	0	0	.
154566	1967	0	0	.
154607	1954	0	0	.
154812	1984	0	0	.
154821	1973	0	0	.
154821	1983	0	0	.
154821	1984	0	0	.
154833	1981	0	0	.
154833	1984	0	0	.
154910	1993	0	0	.
154959	1983	0	0	.

Table 3. 15 SWITCH gen_build_predetermined file format

GENERATION_PROJECT	build_year	gen_predetermined_cap
154342	1987	199.8
154359	1972	99.8
154363	1971	54.3
154501	1973	271
154501	1974	271
154501	1976	271
154501	1977	542
154501	1978	271
154546	1968	195.4
154546	1969	97.7
154554	1967	12.6
154554	1968	12.6
154556	1967	318
154556	1968	106
154566	1967	300
154607	1954	8.5
154812	1984	702
154821	1973	100

154821	1983	160.5
154821	1984	53.5
154833	1981	100
154833	1984	100
154910	1993	40
154959	1983	11.5

3.3 Flow batteries

The inputs for flow batteries in RESOLVE are summarized in Tables 3.16 and 3.17. SWITCH does not currently include an explicit input for flow batteries. We intend to model flow batteries in SWITCH as a generic storage resource with variable inputs values.

Table 3. 16 RESOLVE dynamic inputs for flow batteries

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_Flow_Battery	planned_installed_capacity	0
1/1/30	CAISO_Flow_Battery	planned_installed_capacity	0
1/1/35	CAISO_Flow_Battery	planned_installed_capacity	0
1/1/40	CAISO_Flow_Battery	planned_installed_capacity	0
1/1/45	CAISO_Flow_Battery	planned_installed_capacity	0
1/1/25	CAISO_Flow_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	N/A
1/1/30	CAISO_Flow_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	N/A
1/1/35	CAISO_Flow_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	N/A
1/1/40	CAISO_Flow_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	N/A
1/1/45	CAISO_Flow_Battery	planned_capacity_fixed_o_and_m_dollars_per_kw_yr	N/A
1/1/25	CAISO_Flow_Battery	planned_storage_capacity	0
1/1/30	CAISO_Flow_Battery	planned_storage_capacity	0
1/1/35	CAISO_Flow_Battery	planned_storage_capacity	0
1/1/40	CAISO_Flow_Battery	planned_storage_capacity	0
1/1/45	CAISO_Flow_Battery	planned_storage_capacity	0
1/1/25	CAISO_Flow_Battery	planned_storage_capacity_fixed_om	N/A
1/1/30	CAISO_Flow_Battery	planned_storage_capacity_fixed_om	N/A
1/1/35	CAISO_Flow_Battery	planned_storage_capacity_fixed_om	N/A
1/1/40	CAISO_Flow_Battery	planned_storage_capacity_fixed_om	N/A
1/1/45	CAISO_Flow_Battery	planned_storage_capacity_fixed_om	N/A
1/1/25	CAISO_Flow_Battery	new_provide_power_capacity_annualized_fixed_cost	84.2
1/1/30	CAISO_Flow_Battery	new_provide_power_capacity_annualized_fixed_cost	78.6
1/1/35	CAISO_Flow_Battery	new_provide_power_capacity_annualized_fixed_cost	78.6
1/1/40	CAISO_Flow_Battery	new_provide_power_capacity_annualized_fixed_cost	78.6
1/1/45	CAISO_Flow_Battery	new_provide_power_capacity_annualized_fixed_cost	78.6
1/1/25	CAISO_Flow_Battery	new_provide_power_capacity_fixed_om	7.6
1/1/30	CAISO_Flow_Battery	new_provide_power_capacity_fixed_om	7.1
1/1/35	CAISO_Flow_Battery	new_provide_power_capacity_fixed_om	6.98
1/1/40	CAISO_Flow_Battery	new_provide_power_capacity_fixed_om	6.98
1/1/45	CAISO_Flow_Battery	new_provide_power_capacity_fixed_om	6.98
1/1/25	CAISO_Flow_Battery	new_storage_capacity_annualized_fixed_cost	13.65
1/1/30	CAISO_Flow_Battery	new_storage_capacity_annualized_fixed_cost	12.41
1/1/35	CAISO_Flow_Battery	new_storage_capacity_annualized_fixed_cost	11.67
1/1/40	CAISO_Flow_Battery	new_storage_capacity_annualized_fixed_cost	11.78
1/1/45	CAISO_Flow_Battery	new_storage_capacity_annualized_fixed_cost	11.88
1/1/25	CAISO_Flow_Battery	new_storage_capacity_fixed_om	1.32
1/1/30	CAISO_Flow_Battery	new_storage_capacity_fixed_om	1.23

1/1/35	CAISO_Flow_Battery	new_storage_capacity_fixed_om	1.21
1/1/40	CAISO_Flow_Battery	new_storage_capacity_fixed_om	1.21
1/1/45	CAISO_Flow_Battery	new_storage_capacity_fixed_om	1.21

Table 3. 17 RESOLVE static inputs for flow batteries

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.88
discharging_efficiency	0.88

3.4 Advanced compressed air energy storage

RESOLVE has not historically included compressed air storage as an explicitly described storage resource. The inputs for adiabatic compressed air storage in RESOLVE are summarized in Tables 3.18 and 3.19. SWITCH does not currently include an explicit input for compressed air storage. We intend to model compressed air storage in SWITCH as a generic storage resource with variable input values.

Table 3. 18 RESOLVE dynamic inputs for advanced compressed air energy storage

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_CAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/30	CAISO_CAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/35	CAISO_CAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/40	CAISO_CAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/45	CAISO_CAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/25	CAISO_CAES	new_provide_power_capacity_fixed_om	17
1/1/30	CAISO_CAES	new_provide_power_capacity_fixed_om	17
1/1/35	CAISO_CAES	new_provide_power_capacity_fixed_om	17
1/1/40	CAISO_CAES	new_provide_power_capacity_fixed_om	17
1/1/45	CAISO_CAES	new_provide_power_capacity_fixed_om	17
1/1/25	CAISO_CAES	new_storage_capacity_annualized_fixed_cost	4.7
1/1/30	CAISO_CAES	new_storage_capacity_annualized_fixed_cost	4.7
1/1/35	CAISO_CAES	new_storage_capacity_annualized_fixed_cost	4.7
1/1/40	CAISO_CAES	new_storage_capacity_annualized_fixed_cost	4.7
1/1/45	CAISO_CAES	new_storage_capacity_annualized_fixed_cost	4.7
1/1/25	CAISO_CAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/30	CAISO_CAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/35	CAISO_CAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/40	CAISO_CAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/45	CAISO_CAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004

Table 3. 19 RESOLVE static inputs for advanced compressed air energy storage

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.78
discharging_efficiency	0.78

3.5 Liquid air energy storage

RESOLVE has not historically included liquid air storage as an explicitly described storage resource. The inputs for liquid air energy storage in RESOLVE are summarized in Tables 3.20 and 3.21. SWITCH does not currently include an explicit input for liquid air energy storage. We intend to model liquid air energy storage in SWITCH as a generic storage resource with variable inputs.

Table 3. 20 RESOLVE dynamic inputs for liquid air energy storage

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_LAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/30	CAISO_LAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/35	CAISO_LAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/40	CAISO_LAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/45	CAISO_LAES	new_provide_power_capacity_annualized_fixed_cost	60
1/1/25	CAISO_LAES	new_provide_power_capacity_fixed_om	17
1/1/30	CAISO_LAES	new_provide_power_capacity_fixed_om	17
1/1/35	CAISO_LAES	new_provide_power_capacity_fixed_om	17
1/1/40	CAISO_LAES	new_provide_power_capacity_fixed_om	17
1/1/45	CAISO_LAES	new_provide_power_capacity_fixed_om	17
1/1/25	CAISO_LAES	new_storage_capacity_annualized_fixed_cost	6
1/1/30	CAISO_LAES	new_storage_capacity_annualized_fixed_cost	6
1/1/35	CAISO_LAES	new_storage_capacity_annualized_fixed_cost	6
1/1/40	CAISO_LAES	new_storage_capacity_annualized_fixed_cost	6
1/1/45	CAISO_LAES	new_storage_capacity_annualized_fixed_cost	6
1/1/25	CAISO_LAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/30	CAISO_LAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/35	CAISO_LAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/40	CAISO_LAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004
1/1/45	CAISO_LAES	New_provide_power_capacity_variable_om_$_per_kWh	0.004

Table 3. 21 RESOLVE static inputs for liquid air energy storage

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.75
discharging_efficiency	0.75

3.6 Thermal storage – combined with concentrated solar power

RESOLVE has not historically included thermal energy storage as an explicitly described storage resource. SWITCH includes a resource for thermal storage combined with concentrated solar power, but it is not selected because of the high price that is assumed, so we omit the documentation here.

Before modifying the RESOLVE code to model CSP plus storage, we reviewed the costs. According to the 2020 NREL ATB, a CSP system with 10 hours of storage costs $6747/kWe. That same system is estimated to generate 5589 kWh/kW/y in a location with very good solar resource. This would result in a 64% capacity factor.

For comparison, according to the NREL ATB, a typical PV system costs $1566/kW and would generate 3079 kWh/kW/y in the best location (Daggett). For a PV system to generate 5589 kWh/y, we need 5589/3079 = 1.815 kW, which would cost 1.815 X $1566 = $2843.

To provide the 64% capacity factor the PV system would need batteries. In 2021, a 4-h Li battery is estimated by the ATB to cost $1365/kW using the "moderate" number.

If two 4-hour batteries are used, the total cost would be $2843 + $1365 + $1365 = $5573, which is less than the cost of the solar thermal system.

We will check the NREL ATB that is scheduled to be released next week to see if the numbers have changed this year. If the CSP costs have not yet decreased adequately, then we will omit CSP plus thermal storage from our analysis.

3.7 Thermal storage – without solar

RESOLVE has not historically included thermal storage as an explicitly described storage resource. The inputs for thermal storage in RESOLVE are summarized in Tables 3.22 and 3.23. These tables give one set of values, but the companies we have talked with show a wide range of capital costs and round-trip efficiencies. Most of the companies are moving toward a business model in which the thermal storage is used to run an industrial process. In this case, the electricity-to-thermal conversion and thermal storage hardware may be built primarily for operating the industrial process. On a day when the grid would be in need of extra electricity, the existing storage reservoir could be used to put electricity back on the grid. In such a scenario, the associated cost would reflect the thermal-to-electric conversion hardware plus the marginal cost of making the storage and electricity-to-thermal energy conversion hardware, substantially reducing the capital cost relative to a dedicated system. SWITCH does not currently include an explicit input for thermal storage.

Table 3. 22 RESOLVE dynamic inputs for thermal storage

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_Thermal	new_provide_power_capacity_annualized_fixed_cost	60
1/1/30	CAISO_Thermal	new_provide_power_capacity_annualized_fixed_cost	60
1/1/35	CAISO_Thermal	new_provide_power_capacity_annualized_fixed_cost	60
1/1/40	CAISO_Thermal	new_provide_power_capacity_annualized_fixed_cost	60
1/1/45	CAISO_Thermal	new_provide_power_capacity_annualized_fixed_cost	60
1/1/25	CAISO_Thermal	planned_provide_power_capacity_fixed_om	17
1/1/30	CAISO_Thermal	planned_provide_power_capacity_fixed_om	17
1/1/35	CAISO_Thermal	planned_provide_power_capacity_fixed_om	17
1/1/40	CAISO_Thermal	planned_provide_power_capacity_fixed_om	17
1/1/45	CAISO_Thermal	planned_provide_power_capacity_fixed_om	17
1/1/25	CAISO_Thermal	new_storage_capacity_annualized_fixed_cost	1
1/1/30	CAISO_Thermal	new_storage_capacity_annualized_fixed_cost	1
1/1/35	CAISO_Thermal	new_storage_capacity_annualized_fixed_cost	1
1/1/40	CAISO_Thermal	new_storage_capacity_annualized_fixed_cost	1
1/1/45	CAISO_Thermal	new_storage_capacity_annualized_fixed_cost	1

Table 3. 23 RESOLVE static inputs for thermal storage

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.7
discharging_efficiency	0.7

3.8 Geomechanical storage

RESOLVE has not historically included geomechanical storage as an explicitly described storage resource. The inputs for geomechanical storage in RESOLVE are summarized in Tables 3.24 and 3.25. SWITCH does not currently include an explicit input for geomechanical.

Table 3. 24 RESOLVE dynamic inputs for geomechanical storage

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_Geomech	new_provide_power_capacity_annualized_fixed_cost	38
1/1/30	CAISO_Geomech	new_provide_power_capacity_annualized_fixed_cost	38
1/1/35	CAISO_Geomech	new_provide_power_capacity_annualized_fixed_cost	38
1/1/40	CAISO_Geomech	new_provide_power_capacity_annualized_fixed_cost	38
1/1/45	CAISO_Geomech	new_provide_power_capacity_annualized_fixed_cost	38
1/1/25	CAISO_Geomech	planned_provide_power_capacity_fixed_om	15
1/1/30	CAISO_Geomech	planned_provide_power_capacity_fixed_om	15
1/1/35	CAISO_Geomech	planned_provide_power_capacity_fixed_om	15
1/1/40	CAISO_Geomech	planned_provide_power_capacity_fixed_om	15
1/1/45	CAISO_Geomech	planned_provide_power_capacity_fixed_om	15
1/1/25	CAISO_Geomech	new_storage_capacity_annualized_fixed_cost	0.6
1/1/30	CAISO_Geomech	new_storage_capacity_annualized_fixed_cost	0.6
1/1/35	CAISO_Geomech	new_storage_capacity_annualized_fixed_cost	0.6
1/1/40	CAISO_Geomech	new_storage_capacity_annualized_fixed_cost	0.6
1/1/45	CAISO_Geomech	new_storage_capacity_annualized_fixed_cost	0.6

Table 3. 25 RESOLVE static inputs for geomechanical storage

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.84
discharging_efficiency	0.84

3.9 Flywheels

RESOLVE has not historically included flywheels as an explicitly described storage resource. The inputs for flywheels in RESOLVE are summarized in Tables 3.26 and 3.27. SWITCH does not currently include an explicit input for flywheels.

Table 3. 26 RESOLVE dynamic inputs for flywheels

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_Flywheel	new_provide_power_capacity_annualized_fixed_cost	65
1/1/30	CAISO_Flywheel	new_provide_power_capacity_annualized_fixed_cost	65
1/1/35	CAISO_Flywheel	new_provide_power_capacity_annualized_fixed_cost	65
1/1/40	CAISO_Flywheel	new_provide_power_capacity_annualized_fixed_cost	65
1/1/45	CAISO_Flywheel	new_provide_power_capacity_annualized_fixed_cost	65
1/1/25	CAISO_Flywheel	planned_provide_power_capacity_fixed_om	1
1/1/30	CAISO_Flywheel	planned_provide_power_capacity_fixed_om	1
1/1/35	CAISO_Flywheel	planned_provide_power_capacity_fixed_om	1
1/1/40	CAISO_Flywheel	planned_provide_power_capacity_fixed_om	1
1/1/45	CAISO_Flywheel	planned_provide_power_capacity_fixed_om	1
1/1/25	CAISO_Flywheel	new_storage_capacity_annualized_fixed_cost	20
1/1/30	CAISO_Flywheel	new_storage_capacity_annualized_fixed_cost	20
1/1/35	CAISO_Flywheel	new_storage_capacity_annualized_fixed_cost	20
1/1/40	CAISO_Flywheel	new_storage_capacity_annualized_fixed_cost	20
1/1/45	CAISO_Flywheel	new_storage_capacity_annualized_fixed_cost	20

Table 3. 27 RESOLVE static inputs for flywheels

Attribute	Value
can_build_new	1
can_retire	0
charging_efficiency	0.93
discharging_efficiency	0.93

3.10 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. This is a new and unique (as far as we know) approach to modeling cross-sector hydrogen. So, we may vary these inputs. 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 more. The inputs for hydrogen in RESOLVE are summarized in Tables 3.28 and 3.29.

Table 3. 28 RESOLVE dynamic inputs for hydrogen

Timestamp	Resource	Attribute	Value
1/1/25	CAISO_Electrolyzer	new_provide_power_capacity_annualized_fixed_cost	29
1/1/30	CAISO_Electrolyzer	new_provide_power_capacity_annualized_fixed_cost	25
1/1/35	CAISO_Electrolyzer	new_provide_power_capacity_annualized_fixed_cost	20
1/1/40	CAISO_Electrolyzer	new_provide_power_capacity_annualized_fixed_cost	15
1/1/45	CAISO_Electrolyzer	new_provide_power_capacity_annualized_fixed_cost	12.5
1/1/25	CAISO_Electrolyzer	planned_provide_power_capacity_fixed_om	1
1/1/30	CAISO_Electrolyzer	planned_provide_power_capacity_fixed_om	1
1/1/35	CAISO_Electrolyzer	planned_provide_power_capacity_fixed_om	1
1/1/40	CAISO_Electrolyzer	planned_provide_power_capacity_fixed_om	1
1/1/45	CAISO_Electrolyzer	planned_provide_power_capacity_fixed_om	1
1/1/25	CAISO_Electrolyzer	Price_hydrogen_$_per_kg	2
1/1/30	CAISO_Electrolyzer	Price_hydrogen_$_per_kg	1.8
1/1/35	CAISO_Electrolyzer	Price_hydrogen_$_per_kg	1.6
1/1/40	CAISO_Electrolyzer	Price_hydrogen_$_per_kg	1.3
1/1/45	CAISO_Electrolyzer	Price_hydrogen_$_per_kg	1

Table 3. 29 RESOLVE static inputs for hydrogen

Attribute	Value
can_build_new	1
can_retire	0
Electricity_to_hydrogen_kWh_kg	65
Price_hydrogen_$_per_kg	0.93

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