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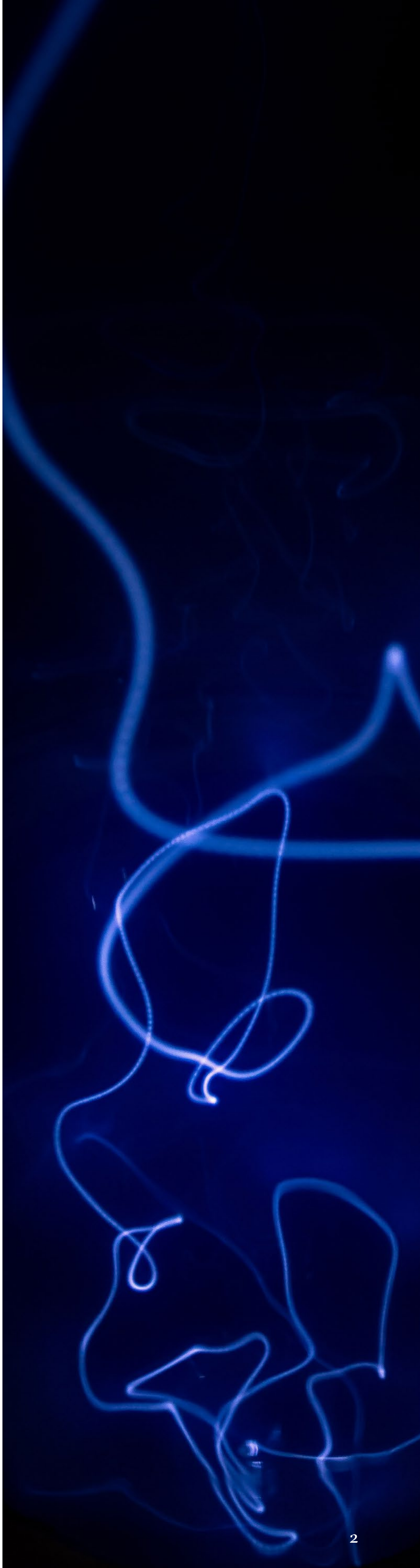
Renewable & Appropriate Energy Laboratory
RAEL

The Role of Storage in the Path to Net Zero

A study in collaboration with the
University of California - Berkeley

Contents



Executive Summary

The transition to a low-carbon sustainable future in the western United States and worldwide is underway, with an increasing number of U.S. states—and utilities—setting ambitious clean energy and electricity targets. The shape the transition will take is still being determined, with key questions including: how to think about meeting minimum power needs, the volume and type of renewables that will be needed to meet the clean electricity goals and how to manage the variability of energy production that comes from renewables.

This study seeks to understand how the transition in the western United States is unfolding and, more specifically, the role energy storage will play in providing flexibility to the grid. The study leverages the University of California – Berkeley, Renewable and Appropriate Energy Laboratory's (RAEL) utility-sector operation and capacity expansion modeling capability (SWITCH), alongside Accenture's research and experience working with clients on the deployment of energy storage, to explore the lowest-cost path to net zero in the Western Electricity Coordinating Council (WECC) region.[1]

Utilizing SWITCH, we assessed four scenarios to net zero in the WECC and found that not only are the scenarios that rely on significant renewables penetration the most cost effective, but also that there is a critical role for energy storage to play across these scenarios. Indeed, while the modeling showed power system costs in the WECC to rise across all scenarios, the Sunshot + Low-cost Batteries scenario resulted in 40% lower power system costs than in the reference scenario. This scenario further requires large amounts of storage to be feasible with the demands on storage reaching 100 times the levels of the 2010 Skinner Bill (AB 2514) or approximately 131 GW by 2050.[2] While this finding is likely an overestimate given the potential for distributed storage, vehicle-to-grid (V2G) and hydrogen to play a role in providing storage and grid reliability and in reducing the need for central-station storage, it emphasizes how underexplored an opportunity storage remains.

Study scenarios:

1. **Reference scenario:** Business as usual (BAU costs) to achieve zero emissions by 2050.

2. **Sunshot scenario:** Low-cost solar to achieve zero emissions by 2050.

3. **Accelerated Sunshot scenario:** Low-cost solar and an accelerated pathway achieving zero emissions by 2040.

4. **Sunshot + Low-cost Batteries scenario:** Low-cost solar and low-cost battery storage to achieve zero emissions by 2050.

Through an assessment of the current starting point, we find that while positive steps have been taken to encourage the adoption of storage through regulatory policy and market incentives—particularly within the California ISO (CAISO)—barriers remain. First, much of the focus to date has been on short-duration batteries (up to four hours) with more research and development (R&D) required to support the commercialization of longer-duration storage options. Second, the ability of batteries to capture revenue from their deployment has been limited to participation in the energy and ancillary services market. This makes the business case for batteries challenging to achieve and limits deployment.

We see three imperatives to bridge this gap:

1. **Re-examine market structures and incentivize R&D.** Shift mindsets away from viewing storage as a "last resort" and continue to invest in R&D and the establishment of fair market rules to incentivize greater deployment of a variety of storage options.

2. **Invest in digital capabilities to optimize storage,** both at an asset level to enhance the revenue potential of each individual asset (and across a portfolio of assets) and at a system level to optimize for the needs of the system. Cloud should be explored as a critical backbone to these digital investments.

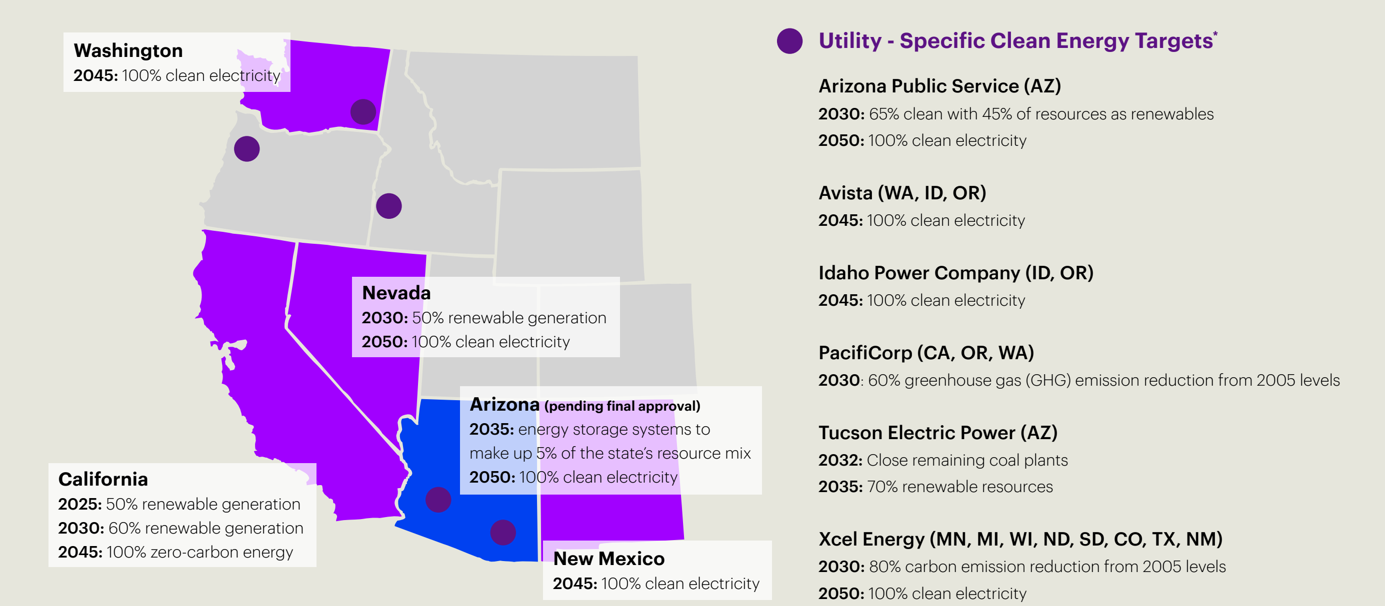
3. **Integrate storage into a broader system framework to accelerate the path to net zero.** Storage alone will not be enough to achieving net-zero goals. A holistic approach that applies all levers at our disposal, including power market reform and demand-side optimization, is needed to move beyond just clean electricity to a net-zero economy. Achieving this will require continued innovation and a greater array of cross-industry partnerships.

There has never been such urgency—or momentum—behind the path to net zero. Regulators, system operators, and utilities and asset owners must come together to continuously tackle the challenges, share lessons learned and open new opportunities for continued innovation in the path to net zero.

Introduction and Study Overview

The transition to a low-carbon sustainable future in the western United States and worldwide is underway, with an increasing number of U.S. states—and utilities—setting ambitious clean energy targets. Figure 1 depicts these announcements as of November 2020.

Figure 1. Clean energy targets and mandates across the western United States.



Washington
2045: 100% clean electricity

Nevada
2030: 50% renewable generation
2050: 100% clean electricity

Arizona **(pending final approval)**
2035: energy storage systems to make up 5% of the state's resource mix
2050: 100% clean electricity

California
2025: 50% renewable generation
2030: 60% renewable generation
2045: 100% zero-carbon energy

New Mexico
2045: 100% clean electricity

● **Utility - Specific Clean Energy Targets***

Arizona Public Service (AZ)
2030: 65% clean with 45% of resources as renewables
2050: 100% clean electricity

Avista (WA, ID, OR)
2045: 100% clean electricity

Idaho Power Company (ID, OR)
2045: 100% clean electricity

PacifiCorp (CA, OR, WA)
2030: 60% greenhouse gas (GHG) emission reduction from 2005 levels

Tucson Electric Power (AZ)
2032: Close remaining coal plants
2035: 70% renewable resources

Xcel Energy (MN, MI, WI, ND, SD, CO, TX, NM)
2030: 80% carbon emission reduction from 2005 levels
2050: 100% clean electricity

Source: Accenture analysis. * Clean energy includes both renewable energy resources as well as nuclear energy.

While these commitments leave no doubt to the forward movement of the energy transition, the shape it takes is still being determined. Key questions include: how to think about meeting minimum power needs, the volume and type of renewables needed to meet the clean electricity goals and how to manage the variability of energy production from renewables. As these questions continue to be explored, it will be critical to continue managing grid flexibility while maintaining reliability and, increasingly, resiliency. Wildfires across the western U.S. and the August 2020 rolling blackouts in California have brought added urgency to the need to both examine energy options in a regionally integrated and smart systems-enabled framework, and to examine how accelerating the technology, market and policy landscape can bring diverse benefits to society from the integration of clean electricity.

Energy storage has been identified as a critical enabler to the transition, given its ability to level the variability of electricity production, which in turn should increase grid reliability and stability. This potential, alongside technology developments and declining costs, has resulted in dramatic market growth. Wood Mackenzie estimates that the U.S. market will increase from 1.2 GW in 2020 to nearly 7 GW by 2025, representing a six-fold increase.[3] Furthermore, the Energy Storage Association recently announced a goal to achieve 100 GW of energy storage by 2030, updating a previous goal of 35 GW by 2025 and demonstrating how quickly this market is moving.[4] This potential has been increasingly recognized by regulators as evidenced by the Federal Energy Regulatory Commission's (FERC) recent upholding of Order 841, which opened batteries up to wholesale markets across the country,[5] and the California Public Utilities' Commission's (CPUC) historic announcement in Resolution E-5077 changing the marginal energy source standard for calculating distributed energy resources (DERs) from natural gas to energy storage.[6]

FERC Order 841 was passed in February 2020 and was eventually upheld in July 2020. The new order states that barriers to distributed and behind-the-meter energy storage participating in wholesale electricity markets should be removed, enabling these assets to provide grid services on a level playing field with fossil fuel resources. The order has been heralded as the "most important step" toward a clean energy future in the United States.[7]

Resolution E-5077, adopted by the California Public Utilities Commission (CPUC) in June 2020, incorporates updates to its Avoided Cost Calculator, which is used in the cost-effectiveness analysis of DERs. One of the principal updates made as part of this resolution was to change the way the Avoided Cost Calculator estimated the avoided cost of generation capacity. Previously this was done using a natural gas combustion turbine as a proxy but, going forward, a new four-hour battery storage resource will be used as the proxy.[8] This change will positively impact the cost-effectiveness of behind-the-meter investments, further enabling the growth of more distributed, clean energy.

This study seeks to better understand how the energy transition in the western United States is unfolding, and, more specifically, the role energy storage will play in enabling the transition by bringing together decarbonization modeling with market insights.

Three main steps were followed to develop this study:

1. **Scenario modeling of the WECC region** utilizing a platform developed in the RAEL at the University of California, Berkeley—SWITCH—to explore the lowest-cost decarbonization pathway considering current policy targets including the expected energy mix, required transmission and distribution capacity and storage volumes.
2. **Accenture research** on the potential value pools for storage and assessment of the economic challenges and opportunities associated with deploying storage onto the grid in the current market environment.
3. **Validation of research findings** to overcome challenges, capture opportunities and further accelerate the transition through a virtual innovation session with key players operating within WECC.

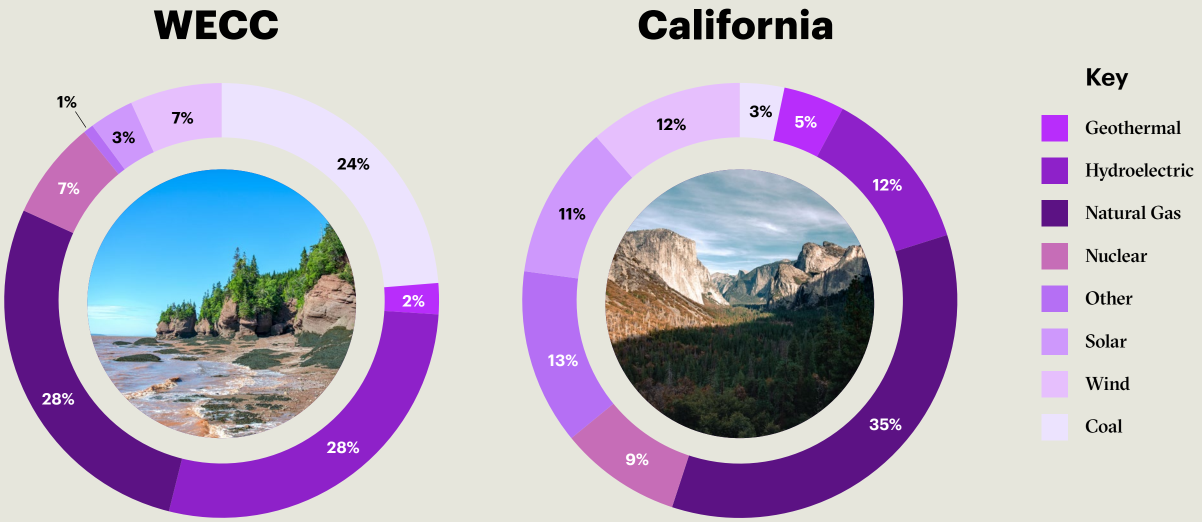
The Western Electricity Coordinating Council (WECC) and California's role

The Western Electricity Coordinating Council (WECC) is the North American Electric Reliability Corporation (NERC) designated organization responsible for reliability and compliance monitoring in the Western Interconnection. Geographically WECC is the largest of the eight NERC regions, with a diverse mix of generation resources spread across its territory. The WECC region encompasses a variety of market constructs including traditional utility control areas, CAISO and the Western Energy Imbalance Market (EIM). In 2018, the region hosted a nameplate capacity of 258,200 MW.[9]

California has been leading the charge in the transformation of WECC, with its aggressive clean energy targets and CAISO's creation of the EIM. California is currently the largest net importer of electricity, with approximately 32% of demand addressed through imports from the wind and hydroelectric Northwest and the nuclear- and coal-dominant Southwest.[10] For California to meet its zero-carbon electricity targets by 2050, it must actively enable tools and policies that will lead to decarbonization of the WECC region. Figure 2 depicts the generation mix of the two entities and demonstrates the hurdle California must overcome.

Most notable is the role of coal: while it makes up 3% of California's energy mix, coal accounts for ~24% of the entire region's generation due to its prominence in the Southwest region of the country. [11]

Figure 2. Comparison of WECC and California generation mix (2018).



Source: 2019 Total System Electric Generation, California Energy Commission, https://www.energy.ca.gov; State of the Interconnection Digest, WECC, https://www.wecc.org.

Active steps are being taken to enable the change required across the WECC. The further development of the EIM will be instrumental in integrating renewables, as it will allow CAISO and other balancing authorities to make low-cost excessive renewable energy available to one another, as opposed to curtailing assets. One of the more integral steps still needed across the region is the further development of energy storage. California, which has deployed 8.35 GW of storage to date, currently accounts for ~46% of the entire region's storage capacity of 18.39 GW.[12] This capacity is largely driven by California's recent uptake in battery storage projects, with much of the remaining capacity attributable to the Pacific Northwest's hydroelectric storage assets. Storage development throughout the other regions in WECC would allow those regions to better capture excess electricity from California and enable the growth of renewables that are needed to meet state and utility clean energy targets.

Energy Storage Primer

Energy storage has the potential to transform the electric grid to a flexible adaptive system that can accommodate variable renewable energy, and bank and redistribute energy from stationary power plants and from electric vehicles (EVs).[13] Utilities, regulators and the private sector are actively exploring utility-scale and behind-the-meter residential and commercial energy storage technologies that provide the means to turn the power system into a dynamic market of distributed producers and consumers, also referred to as "prosumers" of energy.

The rise of storage diversity

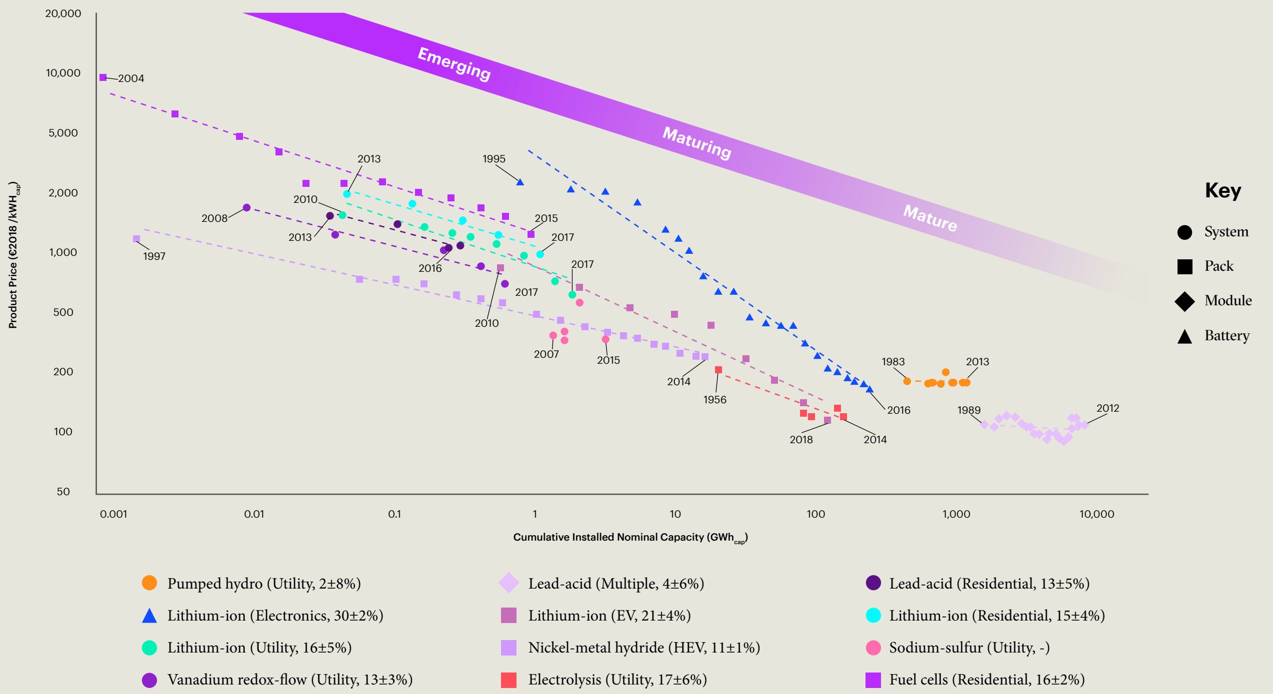
Electricity can be stored through conversion of different types of energy such as mechanical energy in the form of pumped hydropower or flywheels, electrochemical energy for batteries, electrical energy storage in capacitors, chemical energy in the form of hydrogen, and thermal energy such as pumped heat or cooling devices. Pumped hydro storage has provided electricity storage for decades; however, the market for a diverse variety of grid-scale storage solutions is rapidly growing with more technology options. For electrochemical applications, lithium-ion batteries have dominated the battery conversation for the past five years due to their multiple applications at the grid-scale, and rapid cost declines for consumer products and EVs. However, there is increased attention to non-lithium battery storage applications including flow batteries, fuel cells, compressed air energy storage, supercapacitors and flywheels.

The diversity of this landscape makes the push to a low- and zero-carbon energy system so important to evaluate now, to model going forward, and to capture in-market opportunities and policy advances. Technological learning, leading to cost reduction and performance improvements for these storage technologies, could enable reliable electricity supply with variable renewable sources directly competitive with fossil fuel-based electricity. Assessment of the rate and modes of technological learning is critical to informing the evolving landscape and reducing the uncertainty level of future capital costs and technology applications. The results for energy storage experience curves are differentiated along two main dimensions—application category and technology scope. Application category covers portable (electronics), transport (hybrid EV, or HEV, and EV) and stationary (residential, utility). Technology scope covers cell, battery, module, pack, ex-works system and system.

Figure 3 shows the diversity of storage technologies and decreasing product prices per energy capacity with increasing cumulative installed nominal energy capacities for most storage technologies. Pumped hydro (system), lead acid (module), alkaline electrolysis (pack) and lithium-ion for consumer electronics (battery) and EVs (pack) exhibit current prices below \$200/kWh above 100 GWh installed. The relatively low experience rates below 5% of the first two are contrasted by 17% for electrolysis (pack) and 30% and 22% for lithium-ion batteries and packs respectively. Technologies with between 1 and 100 GWh cumulative installed capacity, such as nickel-metal hydride (pack), utility-scale lithium-ion (system) or sodium-sulfur (system) show current prices between \$100/kWh and \$200/kWh and experience rates of 11% and 16%. Those below 1 GWh like residential lithium-ion (system), lead acid (system), redox flow (system) and fuel cells (pack) cost more than \$900/kWh with experience rates between 13% and 16%.

The price and cumulative capacity data used for electricity storage technologies come from peer-reviewed literature, research and industry reports, news items, energy storage databases and interviews with manufacturers. In the literature, learning (based on manufacturing cost) and experience rates (based on product price) are sometimes used interchangeably. The sources in the referenced literature were double-checked to verify the use of actual product price data.

Figure 3. Experience curves for electricity storage technologies.



Source: Noah Kittner, Oliver Schmidt, Iain Staffell, Daniel M. Kammen (2019) "Grid scale energy storage," Technological Learning in the Transition to a Low-Carbon Energy System, 119 – 143.

Note: Results shown for product prices per nominal energy capacity. Dotted lines represent the resulting experience curves based on linear regression of the data. Top legend indicates technology scope and bottom legend denotes technology (including application and experience rate with uncertainty). Experience rate uncertainty is quantified as its 95% standard error confidence interval. Gray bars indicate overarching trend in cost reduction relative to technology maturity. Fuel cell and electrolysis must be considered in combination to form an electricity storage technology. kWh$_{cap}$ is the nominal energy storage capacity.

The policy choices and market opportunities that this diverse range of commercially viable and emerging energy storage technologies enable is remarkable. Short-duration (less than one day) storage will likely remain dominated by lithium-ion battery systems for some time, but weekly and long-term storage are critical in all energy systems, and are vital in places like California and the western U.S., where the August 2020 heat waves, lightning strikes, wildfires and the regular seasonal variability in wind need to be addressed in decarbonized, reliable power systems.[14]

The Path to Net Zero

Capacity-planning models like SWITCH offer a helpful approach to examining the role of storage in low GHG-emission grids. Their purpose is to explore how total system cost—capital, fixed and variable costs—can be reduced, and to co-optimize storage deployment and investment in other system infrastructure. As variable renewable generation achieves higher penetration levels, integration alternatives such as transmission expansion, fast-ramping generation, storage and demand response must be considered and compared in a single framework. RAEL has incorporated operational detail into the SWITCH long-term capacity-planning model to allow for more accurate economic evaluation of variable renewables, storage technologies and other integration alternatives. Wind and solar generation technologies have low variable costs but require investment in capital-intensive infrastructure capacity, so employing models like SWITCH can aid the understanding of and planning for the most cost-effective resource combinations as the power system evolves.

For the purposes of this study, we analyzed four zero-emission scenarios for the WECC region:

1. **Reference scenario:** Business as usual (BAU costs) to achieve zero emissions by 2050.
2. **Sunshot scenario:** Low-cost solar to achieve zero emissions by 2050.
3. **Accelerated Sunshot scenario:** Low-cost solar and an accelerated pathway achieving zero emissions by 2040.
4. **Sunshot + Low-cost Batteries scenario:** Low-cost solar and low-cost battery storage to achieve zero emissions by 2050.

The SWITCH modeling did not consider long term (monthly to seasonal) storage, and this remains a challenge that would potentially further increase system costs. However, there are a number of local solutions such as demand response, vehicle to grid and microgrids that can bring the costs down significantly. In addition, increased interconnection and the potential utilization of hydrogen for energy storage in the longer term could provide cost-effective solutions for season-scale storage as well as providing additional short-term storage capacity.

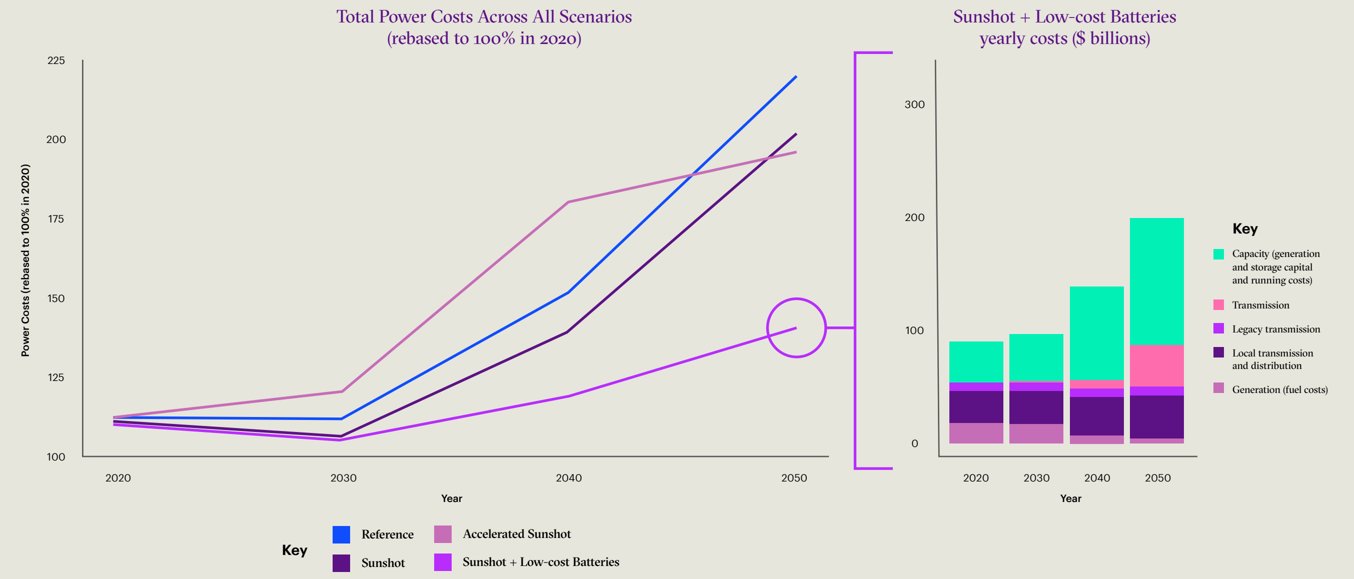
Scenarios assume base-case demand driven by population growth, high electrification of buildings and transportation but not smart charging or smart building controls. Long-term storage, demand response and new interconnections outside of WECC are not included. Cost assumptions are further detailed in Table 1.

Table 1. Study cost assumptions by scenario.

	2020			2030			2040			2050		
Scenario	1	2, 3	4	1	2, 3	4	1	2, 3	4	1	2, 3	4
Solar costs ($'000/MW)	1,126			1,126	520		1,100	470		1,000	430	
Battery costs ($'000/MW)	1,068			1,012		534	956		267	900		133

Source: Hidalgo-Gonzalez, P., Szinai, J., Kammen, D. M., "Zero Carbon Emissions in the Electricity System in Western North America" (in prep.).

Figure 4. Power system costs, 2020-2050 by scenario.



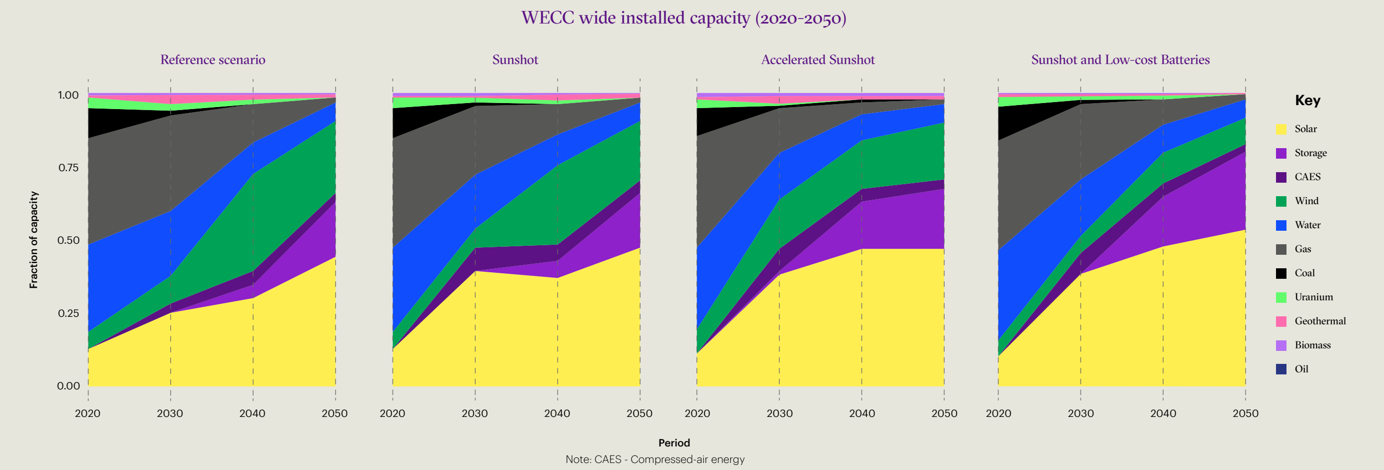
Source: Hidalgo-Gonzalez, P., Szinai, J., Kammen, D. M., "Zero Carbon Emissions in the Electricity System in Western North America" (in prep.).

Without accelerating the rate of innovation and deployment of storage, the 2050 least-cost power system in the Reference scenario has much higher costs than present day, with an average cost per MWh produced nearly doubling between 2020 and 2050 to ~$225/MWh, even if aggressive levels of energy efficiency are implemented. The Sunshot + Low-cost Batteries scenario shows the lowest cost in 2050, roughly 40% cheaper than the Reference scenario. This highlights the key role successful R&D can have in the path toward zero emissions. If the cost declines assumed for the Sunshot + Low-cost Batteries scenario do not materialize, the next scenario that shows the lowest cost of power by 2050 is the Accelerated Sunshot. Here we find that having a zero-emissions carbon cap by 2040 will lead to cost reductions in 2050, while maintaining zero emissions.

An interesting aspect to note is that although transmission costs represent approximately 15% of total costs by 2050 across scenarios, transmission capacity in the WECC needs to double between 2020 and 2050 to reach zero emissions. The political challenge this is likely to entail sheds light on the need to explore pathways that do not rely as heavily on new transmission deployment (e.g., distributed resources deployment, storage coupled with rooftop solar, etc.).

Utilizing SWITCH, we find the scenarios that rely on variable renewables all require large amounts of storage (see Figure 5).

Figure 5. Installed generation capacity by scenario.



Source: Hidalgo-Gonzalez, P., Szinai, J., Kammen, D. M., "Zero Carbon Emissions in the Electricity System in Western North America" (in prep.).

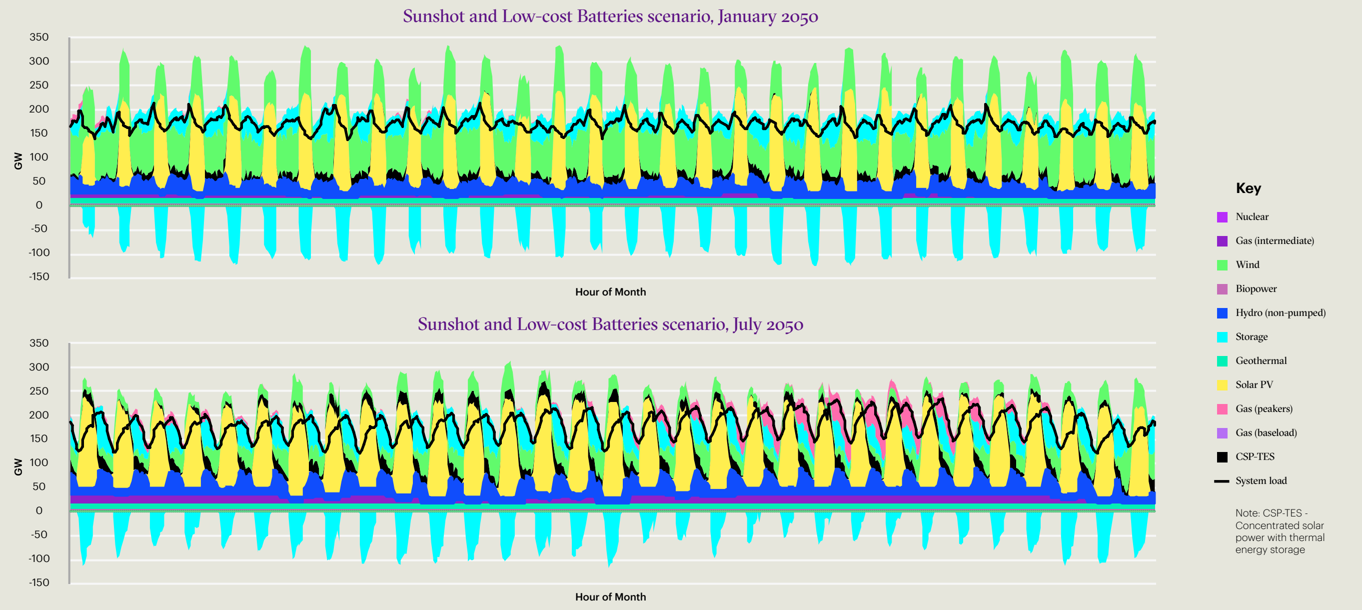
If we focus on solar- and wind-intensives (depicted in the Sunshot and Low-cost Batteries scenarios), the demands on storage reach 100 times the levels of the 2010 Skinner Bill (AB 2514), or 131 GW of storage. This would represent a massive scale-up of central-station storage and, while likely an overestimate, is important to highlighting how underexplored an opportunity storage remains. There are several markets which would expand the ability of diverse actors to play a role in providing storage and thus enhancing grid reliability. These include:

- Distributed stationary storage (both residential and commercial) and V2G present opportunities to leverage and amortize costs and spread the benefits of revenue from storage to traditionally excluded and marginalized communities.

- The role of hydrogen is frequently absent from current modeling efforts but has significant potential to provide both long-term storage as well as for direct industrial uses. The potential for a rapid scale-up of offshore wind would be a welcome complement to the daily generation profile of onshore wind and solar and could further reduce the need for central station storage.

An example of why programs to develop and deploy both short-duration (daily) storage and long-duration storage are so important are further illustrated in Figure 6.

Figure 6. WECC system hourly dispatch in January and July 2050 in the Sunshot and Low-cost Batteries scenarios.

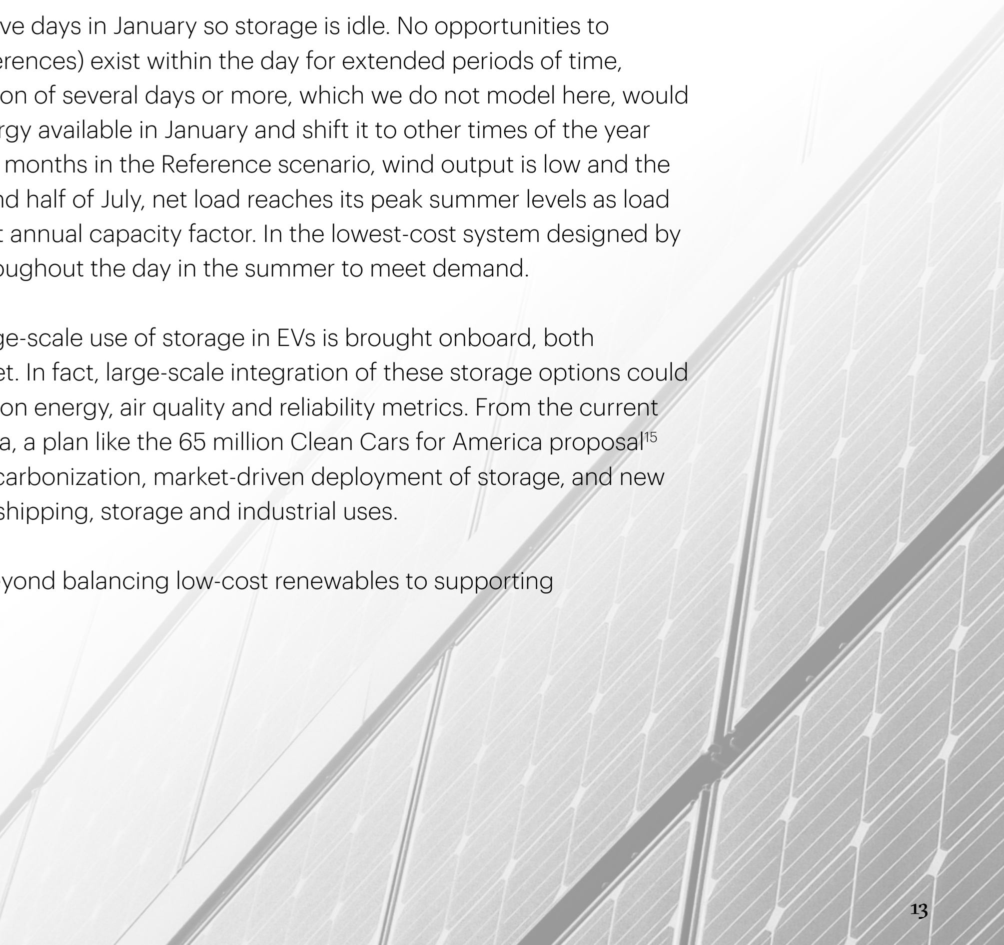


Source: Hidalgo-Gonzalez, P., Szinai, J., Kammen, D. M., "Zero Carbon Emissions in the Electricity System in Western North America" (in prep.).

In the WECC, winter net load can be low. In SWITCH we then find that curtailment conditions occur throughout the day for multiple consecutive days in January so storage is idle. No opportunities to provide arbitrage (i.e., sufficient price differences) exist within the day for extended periods of time, as gas is rarely used. Storage with a duration of several days or more, which we do not model here, would be better suited to absorb the excess energy available in January and shift it to other times of the year when prices increase. During the summer months in the Reference scenario, wind output is low and the Reference system is stressed. In the second half of July, net load reaches its peak summer levels as load is high and wind generation is at its lowest annual capacity factor. In the lowest-cost system designed by SWITCH, peaker gas generation is run throughout the day in the summer to meet demand.

If instead, hydrogen production or the large-scale use of storage in EVs is brought onboard, both reliability and cost goals can be readily met. In fact, large-scale integration of these storage options could accelerate the market benefits of storage on energy, air quality and reliability metrics. From the current total approaching 1 million EVs in California, a plan like the 65 million Clean Cars for America proposal[15] could lead to unprecedented levels of decarbonization, market-driven deployment of storage, and new opportunities for hydrogen integration in shipping, storage and industrial uses.

The role storage can play then extends beyond balancing low-cost renewables to supporting system-wide decarbonization.



Where We Are Today

Storage will play a key role in supporting the path to net zero. To realize what the power sector can do to support this role, it is important to understand where we are today. This next section describes the starting point from both a regulatory and market perspective.

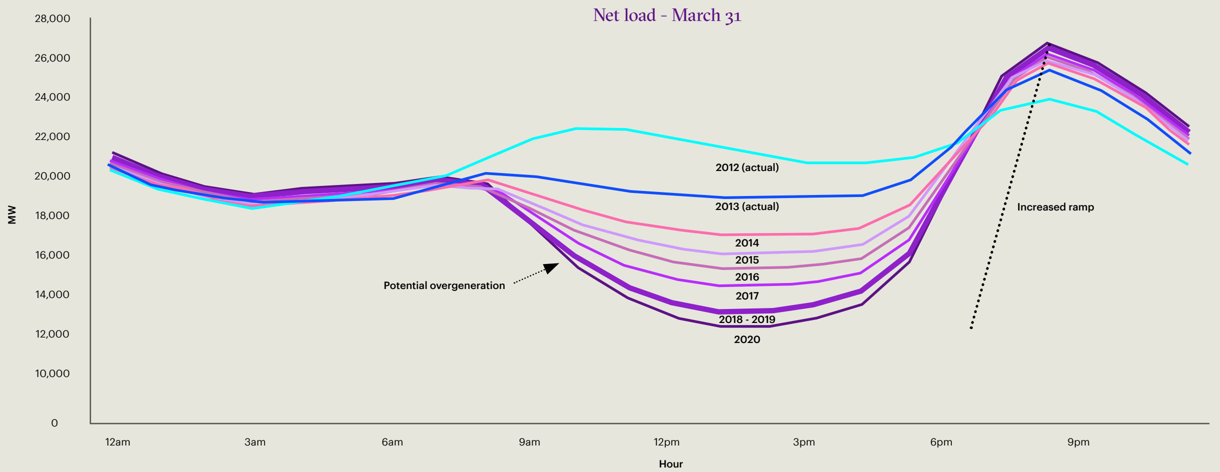
Spotlight on California and the California ISO

CAISO is the only independent western U.S. grid operator, handling roughly 35% of the load in the West, including 80% of California and parts of Nevada. As an independent system operator (ISO), CAISO is charged with providing equal market access to nearly 26,000 miles of transmission, coordinates diverse energy resources into the grid and operates a competitive wholesale power market for its member participants.

CAISO has been a leader in incorporating renewables into the grid in support of California's renewable portfolio standards. Current renewables installed capacity stands at 24 GW, with solar accounting for more than half of this capacity at approximately 13.4 GW. Installed wind capacity follows at almost 7 GW, with less than 1.6 GW of geothermal, small hydro and biofuels.[16]

Due to the exponential growth of renewables in CAISO's operating footprint, several operational issues have arisen and need to be addressed. The most infamous of these issues is the energy load "duck curve" resulting from mid-day generation oversupply, largely due to high solar penetration, leading to market supply demand imbalances, depressing market prices and impacting grid reliability (See Figure 7). Renewables oversupply and the variability of this generation source has made it difficult for CAISO operators to effectively balance energy supply and demand, specifically the afternoon ramp-up of demand leading to the evening peak period. This effect requires additional generation resources specifically required to meet peak demand requirements and the associated ramp (e.g., natural gas peaker plants) which poses a risk to grid stability. As more solar is added to the grid, the grid changes from one that managed central synchronous generation to one with more distributed power electronics- (inverter-) based solar. This increases the need for regulation services.

Figure 7. CAISO net load - March 31, 2012-2020.



Source: Fast Facts, California ISO (CAISO), https://www.caiso.com.

While there has been heavy investment in procuring renewable resources, CAISO imports more than a quarter of its electricity needs from surrounding states. In 2016, CAISO represented 29% of the total generation in WECC while accounting for 39% of the demand. This reliance on import capacity poses a risk during summer months, when extreme heat weather conditions can limit the ISO's ability to draw upon power from other regions within the interconnection—as recently experienced with the August 2020 heatwave.

In the face of these challenges, CAISO is deploying a variety of levers to further integrate renewables into the grid and increase system resiliency.

Renewable integration levers

CAISO's approach to overcoming these challenges and integrating renewables has included changes to system operation to better manage resource volatility, expansion of the EIM to benefit from greater connectivity across markets, more flexible management of load and baseload generation and use of storage to counteract variability. Table 2 employs a framework developed by the National Renewable Energy Laboratory (NREL), defining the levers available to integrate renewables and mapping the actions CAISO has taken against them.

Table 2. CAISO's approach to renewables integration.

Integration Levers	Description	CAISO Approach
System Operation	Changes to rules for unit commitment and dispatch, including forecasting, reliability requirements for participants and links to other systems.	• Solar forecast is used to procure operating reserves in the day-ahead market. • Residual unit commitment includes an automatic adjustment to account for differences between the day-ahead schedules of bid-in variable energy resources and the forecast output of these renewable resources. • The real-time market system dispatches resources every 15 and five minutes, although under certain grid conditions the ISO can dispatch for a single one-minute interval.
Markets	Changes to the rules in how the markets operate to better match variable renewable generation and increased connectivity across markets.	• Manages the western EIM designed to provide benefits from increased regional integration, e.g., enhanced dispatch instruction efficiency, reduced renewable curtailment and reduced total requirements for flexible reserves. $1 billion in gross benefits realized since its inception in 2014. • Flexible resource adequacy requirement and procurement in place for the past four years. The flexible ramping product procures both upward and downward flexible capacity. In 2019, CAISO procured flexible ramping from hydro, coal, wind, geothermal, gas, demand response and battery.
Load	Management of demand.	• Allows demand response to participate in day-ahead, real-time energy and ancillary services market. Demand-response resources are comparable to supply resources and can set real-time prices. Large resources with direct telemetry to the ISO can also be sent direct response signals to curtail.
Flexible Baseload Generation	Use of baseload generation.	• Hydro levels have high impact on both energy and ancillary services availability to CAISO. • Natural gas generation is the marginal technology in the generation mix.
Networks	Expansion of the transmission network and connectivity across markets.	• Expansion of the western EIM from 11 to 21 participants and 82% of the total WECC load by 2022. • "Storage as a Transmission Asset" initiative looking to provide reliability-based transmission grid support under a regulated cost-of-service model. Currently on hold pending market design and policy developments.
Storage	Mechanism to absorb energy when its value is low and release energy when needed.	• 136 MW deployed by end of 2019 with the figure expected to grow to 923 MW by end of 2020. California's storage procurement target of securing 1,325 MW by 2020, set by AB 2514, has been met by the three investor-owned utilities (IOUs). • Ongoing "Energy Storage and Distributed Energy Resources" initiative to enhance the ability of ISO and distribution–connected resources to participate in the market. Outcomes to date have included enhanced participation capabilities for grid-connected storage and demand-response bidding options. Currently the initiative is in "Phase 4," refining DER and storage participation models and lowering integration barriers for demand-response resources.

Source: Accenture analysis.

Storage: Increasing market integration

While CAISO has taken several actions to tackle these challenges and reliably integrate renewables, the hallmark of its actions has centered on energy storage. This focus has been supported by the CPUC's 2013 Decision (D.)13-10-040, which set an AB 2514 energy storage procurement target of 1,325 MW by 2020[17] (about 2% of peak load) and was formulated to support three primary goals:

1. **Grid optimization,** including peak reduction, contribution to reliability needs, or deferral of transmission and distribution upgrade investments
2. **Integration of renewable energy**
3. **GHG reductions in support of the state's targets**

This target has been critical in mobilizing energy storage providers and the IOUs to explore and deploy storage. The bill's preference for green storage solutions, seen by the exclusion of pumped storage and compressed air from the 1.325 GW target, encourages new storage technologies to enter the market. Key opportunities exist to learn from this landmark ruling and to expand it in scope and in market sophistication.

In response, CAISO first implemented policy enhancements and updates to its market participation construct, enabling energy storage devices to participate in ancillary service regulation markets. Regulation Energy Management (REM) is the CAISO initiative specifically designed to accommodate non-generator resources (NGRs), as battery resources are classified, to participate in CAISO's regulation markets.

Further in this effort, CAISO has leveraged the NGR model definition to serve as the foundation for battery assets to participate fully across both energy and ancillary markets. CAISO created the Energy Storage and Distributed Energy Resources (ESDER) initiative to expand and develop battery asset rules governing resource control, operating parameters and financial settlement to address NGRs' unique capabilities. Key areas of policy focus include asset bidding and capacity commitment rules, award obligations and constraints and compensation calculations, which are unique to storage assets.

Specifically, cost curve development, market offers, make-whole payments and operating capacity (state of charge) become complex when the "fuel" provided to the battery is based on energy captured from the grid and stored for later discharge.

The final area of consideration CAISO is looking to address is the incorporation of storage resources in the wholesale market to provide reliability-based services. The specific CAISO policy being explored is called Storage as a Transmission Asset (SATA). The primary purpose of the battery asset is to provide reliability-based transmission grid support under a regulated cost-of-service model, while also retaining the right to participate in the wholesale energy market. SATA policy development is currently suspended pending further market development and design issues being addressed within the ESDER initiative to accommodate this dual-service capability.

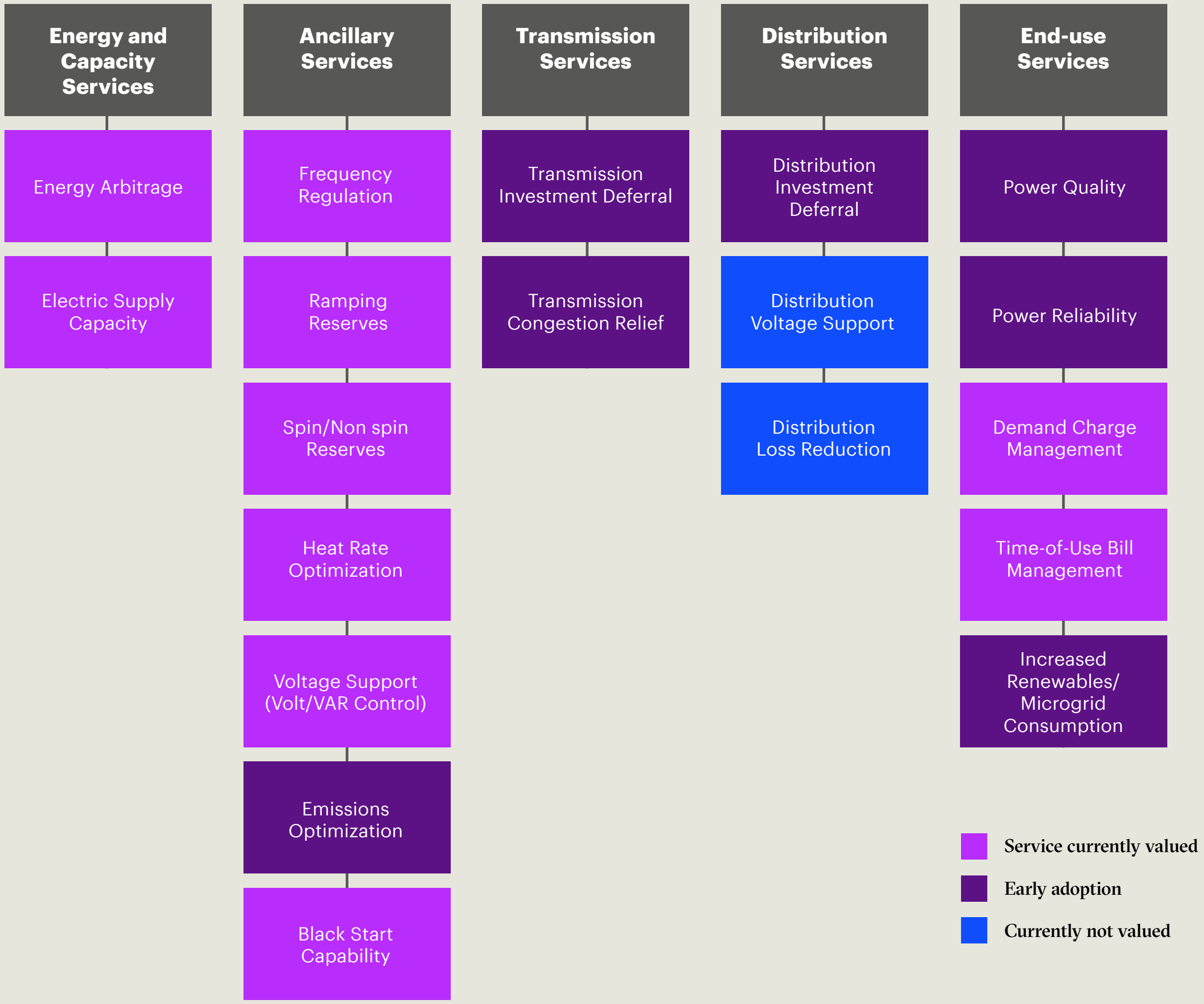
CAISO's progressive effort in developing policies and market design changes to incorporate the unique capabilities of energy storage resources while providing fair compensation is an important factor for why CAISO is such an attractive environment for storage deployment.

Driving Commercial and Asset Optimization of Storage

With the significant potential of energy storage to support the path to a decarbonized future, it is no wonder it has gotten so much attention over the past few years. More specifically, batteries have dominated the market. They offer unmatched flexibility in addressing the additional variability inherent in renewables, helping maintain grid stability. Their unique capability of acting as both a generation resource and point of energy demand and the speed to which they can respond to operational signals allows them to provide a wide variety of services including peak load shaving, load shifting, demand response, capacity reserve/resource adequacy and ancillary services.

Figure 8 depicts the key services that can be provided by battery storage and stacked together to provide multi-value streams for battery storage systems: energy and capacity, ancillary services, transmission infrastructure services, distribution services, and end-use/customer management services.

Figure 8. Battery storage value pools.



Source: Adapted from IRENA (2015) & OSTI (2017).

Indeed, the versatility of battery assets offers a range of opportunities. The ability to deploy battery storage either at solar or wind farms enhances revenue opportunities of each asset, while deploying storage at brownfield asset sites significantly lowers interconnection-related costs. Battery storage is also being deployed as transmission system assets to address grid inefficiencies or localized pockets of congestion that would otherwise require costly infrastructure investments.

To date, however, the ability of asset owners to capture this opportunity has been limited to participation in wholesale markets, and more specifically to energy and ancillary service participation. The main areas of opportunity include:

- **Energy time-shift arbitrage.**
- **Ancillary services (primarily regulation services and secondarily reserve services).**
- **Energy vs. ancillary services arbitrage.**
- **Market settlement arbitrage (day-ahead vs real-time).**

Energy time-shift arbitrage

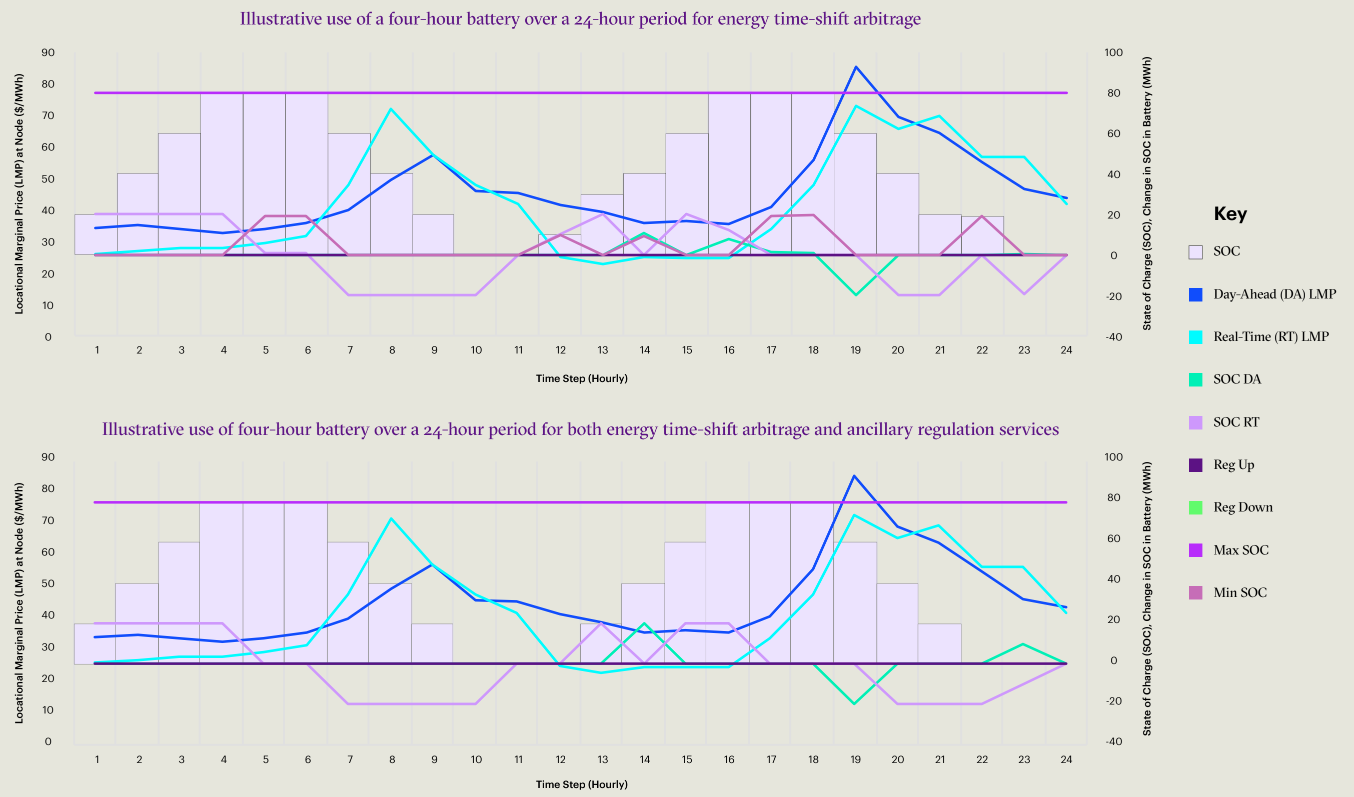
Energy time-shift arbitrage opportunities exist in the market due to supply demand imbalances created by both over-penetration of renewable generation and natural patterns of energy demand. At its most basic level, time-shift arbitrage involves charging a battery asset across the lowest-price hours of the day, typically mid-afternoon and late evening, and discharging energy back to the grid during peak morning and late-afternoon hours. The strategy employed is to capture the greatest price spread available between these charging and discharging events, referred to as cycles. As battery penetration increases, this time-shift arbitrage opportunity potentially decreases, particularly once market-installed battery capacity becomes large enough to replace natural gas or fuel oil peaker power plants.

The CAISO market has received special attention due to the duck curve when the net demand production curve falls drastically during mid-day—when solar production peaks and energy usage falls—resulting in an extreme oversupply situation and negative wholesale power prices.

Battery storage resources target these time-shift opportunities to take power off the grid at extremely low prices to store and discharge later across higher-priced peak demand periods. System operators are keen to employ battery resources to help smooth the peaks and troughs of the daily supply demand curve to stabilize the grid leveraging this cycle capability. Figure 9 is an example, using recent historic CAISO locational marginal prices (LMP), that demonstrates battery charging and discharging cycle solely for energy time-shift arbitrage. Here we can visualize and gain some insight on how a battery operator can optimize asset charging and discharging to best take advantage of the pricing at any given time.

In Figure 9, state of charge (SOC), which represents the energy available within the batteries, is shown as the bar charts. The day-ahead market LMP and real-time market LMP curves represent energy prices in dollars per MWh for those specific hours across a 24-hour operating period. The delta in SOC day-ahead market and delta in SOC real-time market lines represent instances where the market awards charge and discharge (cycle) energy from and to the grid, respectively, and would take place based on pricing arbitrage opportunities between the day-ahead and real-time markets. Instances where the associated line is above zero indicate charging activity, and instances where the line is below zero represent discharging activity. The interplay of pricing dictates when and where the battery is discharging its energy to the grid as well as recharging energy from the grid at the most optimal time periods.

Figure 9. Examples of the use of a four-hour battery to support energy and ancillary services.



Source: Accenture analysis.

As the number of batteries increase, they will absorb excess energy generated by renewables. Their operators will often seek to store energy when renewable generation is more than enough to meet regular energy demand. When these batteries attempt to simultaneously store energy, they increase total demand. The increase in total demand may require the market operator to dispatch non-renewable generation having non-zero marginal costs. Dispatch of this type of generation raises market clearing prices in both day-ahead and real-time markets.

Conversely, when energy in batteries is released to realize their net revenue potential during hours when demand is high and renewable generation is low, such as during late-afternoon to early-evening hours, the energy released may be so high that it would be sufficient to meet demand without having the market operator dispatch non-renewable generation having (more) expensive marginal costs. When these (more) expensive non-renewable generation are not dispatched, market clearing prices in both day-ahead and real-time markets will likely drop. These two phenomena yield reduced spread between discharging and charging prices and thus lower the money-making potential for batteries as the market is getting increasingly more saturated with batteries or any other energy storage devices.

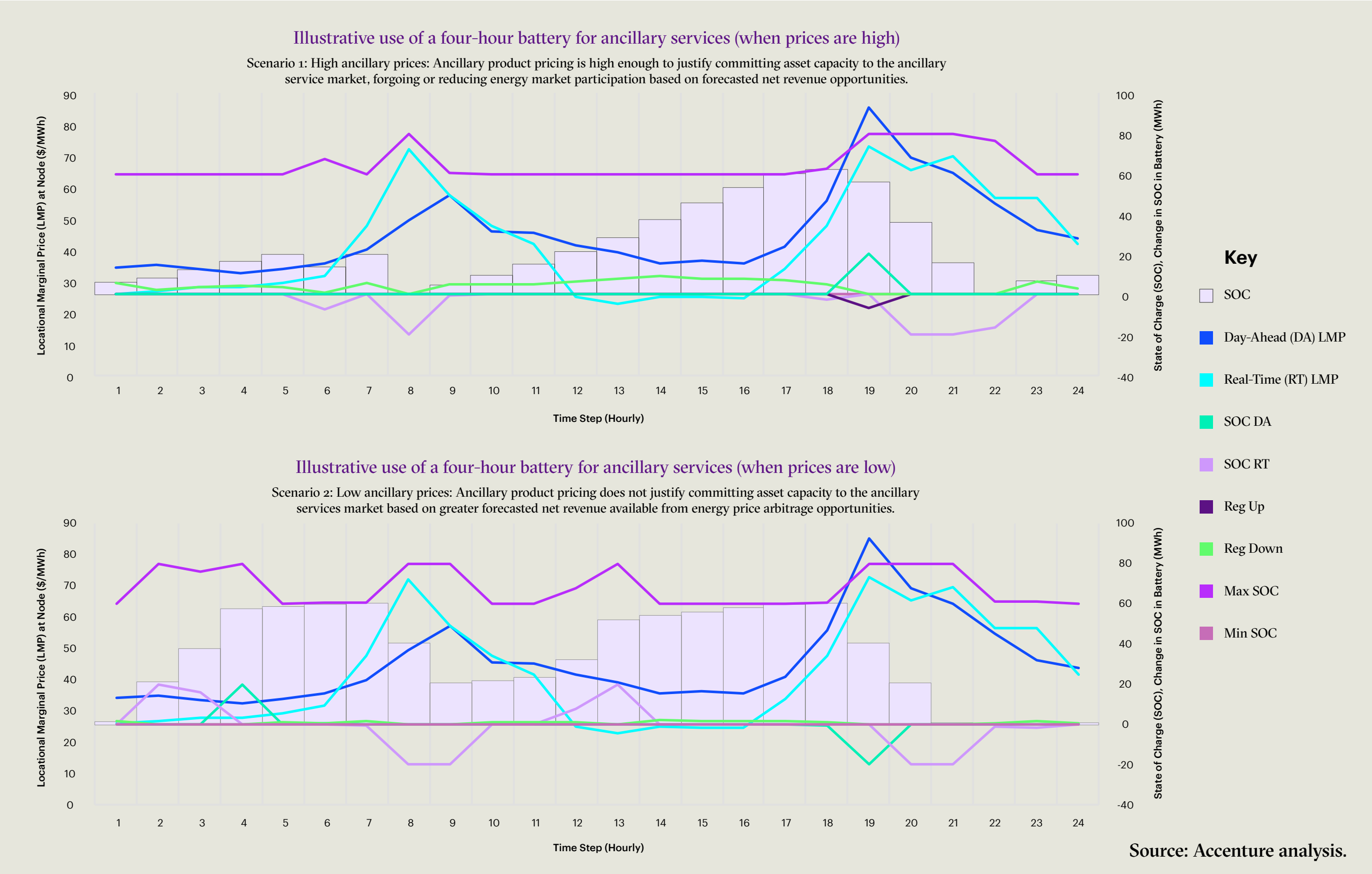
Ancillary services

Another key focus area of battery resource applications for system operators and resource owners is in ancillary services markets. Ancillary services are products necessary to support grid operations and stability during the distribution of power from generation sources to end users. Services including voltage support, frequency regulation, ramping capability and management, and black start are essential in supporting the incorporation of variable renewable generation.

Battery resource owners can capture revenue through wholesale market awards leveraging the assets' flexibility to provide fast grid synchronization and ramping as well as multi-directional dispatch defined within ancillary service product categories. Across most markets, we find that frequency regulation services—those that respond to instantaneous changes in energy demand—are the most profitable product and most frequently provided.

The ability of batteries to provide ancillary services, particularly reserve and regulation-up services, will of course depend on their SOC and how they participate in regulation-down services that allow them to restore and/or add to their SOC. Figure 10 demonstrates two dispatch scenarios focused on regulation services. Both demonstrate that regulation-down services are more often preferred as the asset gets paid to charge while providing the service and is then able to sell the charge gathered in the real-time market. Regulation-up is recommended in hour 19 of scenario 1, as the higher ancillary pricing provides a brief window of economic dispatch.

Figure 10. Storage dispatch scenarios for providing ancillary services.



Source: Accenture analysis.

Energy vs. ancillary services arbitrage

Battery resources can participate in both energy and ancillary markets simultaneously, which creates complexity, but also opportunity if managed effectively. For this reason, an important aspect of battery resource management is optimizing asset capacity across both product categories finding "the sweet spot" to maximize revenue. Constantly changing market dynamics require continual adjustments to market participation strategies for asset cycling to capture energy spreads, while at the same time reserving capacity for ancillary service awards to maximize revenue.

Market settlement arbitrage (day-ahead vs. real-time)

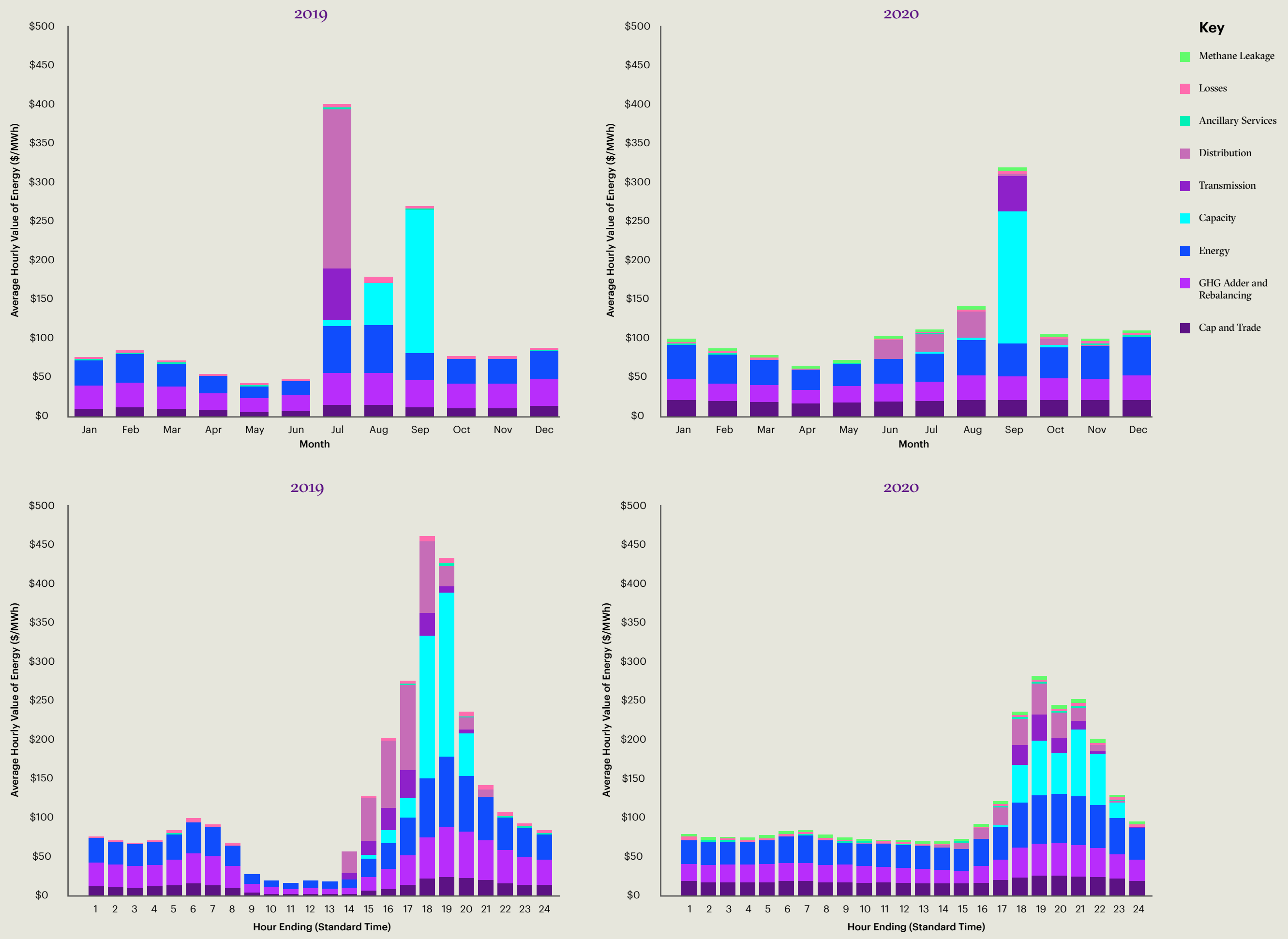
The final area of financial opportunity for battery resources involves participation in ISOs and regional transmission operators (RTO) that have two settlement market structures. The markets are generally referred to as day-ahead and real-time markets and provide arbitrage opportunities based on the interplay between the two. Each market is run and managed independently with different operating rules and procedures resulting in completely separate market prices. Asset operators can participate in both markets simultaneously, which presents the opportunity to profit from price differentials resulting from operational inefficiencies and constantly changing market dynamics. Customized strategies for charging and discharging the asset across markets comes with a level of risk but, when managed effectively, provide battery resource operators attractive revenue opportunities.

The current limited participation of batteries in markets means optimization is critical to the individual asset's business case. The parameters highlighted above, including the market dynamics and the operational constraints set by the batteries themselves, render this optimization incredibly challenging. A greater array of market participation opportunities would provide added flexibility to asset owners, empowering them to strengthen their revenue stack.

Batteries and the demand-side response market

In June 2020, the CPUC issued Resolution E-5077 to update how the avoided costs of electricity due to demand-side DERs are calculated.[18] A key part of the resolution updated the marginal resource of generation from a gas-fired combustion turbine to a four-hour battery storage unit for better alignment with its integrated resource plan (IRP). The impact of the decision can be seen in Figure 11, developed by the CPUC. The first set of comparisons demonstrate the implications of the change from the 2019 to 2020 Avoided Cost Calculator on the projected monthly value of electricity in 2025, while the second set of charts demonstrate the implications for the hourly value of electricity. The initial analysis stacks price arbitrage, capacity and ancillary service revenues. This results in higher mid-day and lower evening hourly avoided costs as well as higher energy and GHG monthly avoided costs, with the exception of July and August. By valuing avoided electricity using a battery rather than natural gas, the value of behind-the-meter storage will significantly increase.

Figure 11. Comparison of the CPUC forecast for the monthly and hourly value of energy for the Los Angeles region in 2025, based on 2019 and 2020 Avoided Cost Calculator parameters.



Source: Cutter, E. (2020). Energy, Ancillary Services and Capacity Avoided Costs [PowerPoint presentation]. 2020 ACC Workshop, ftp://ftp.cpuc.ca.gov.

Enabling the Path to Net Zero

The starting point describes the limited role storage currently plays across the WECC, highlighting a significant gap against the potential of storage to support the path to net zero. What steps then can the power sector take to bridge this gap? In the following section, we outline three imperatives:

1. **Re-examine regulatory and market structures to better support and incentivize deployment.**
2. **Invest in digital capabilities to optimize storage.**
3. **Integrate storage into a broader system framework to accelerate the path to net zero.**

Imperative 1: Re-examine market structures and incentivize R&D

Now and in the future, energy storage can make economically feasible both variable renewables and electricity generated at times and in locations where marginal prices are low. This means not only is the future of energy storage critical to the clean energy economy, but also that storage will be in a position to complement zero-carbon generation, as well as directly compete with renewables diverse markets.

Vital to the continued evolution of energy storage is sustained thoughtful investments in R&D and fair market rules. The combination of technical and economic advances so far seen in energy storage is based on several key aspects of what might call the "storage fundamentals" namely:

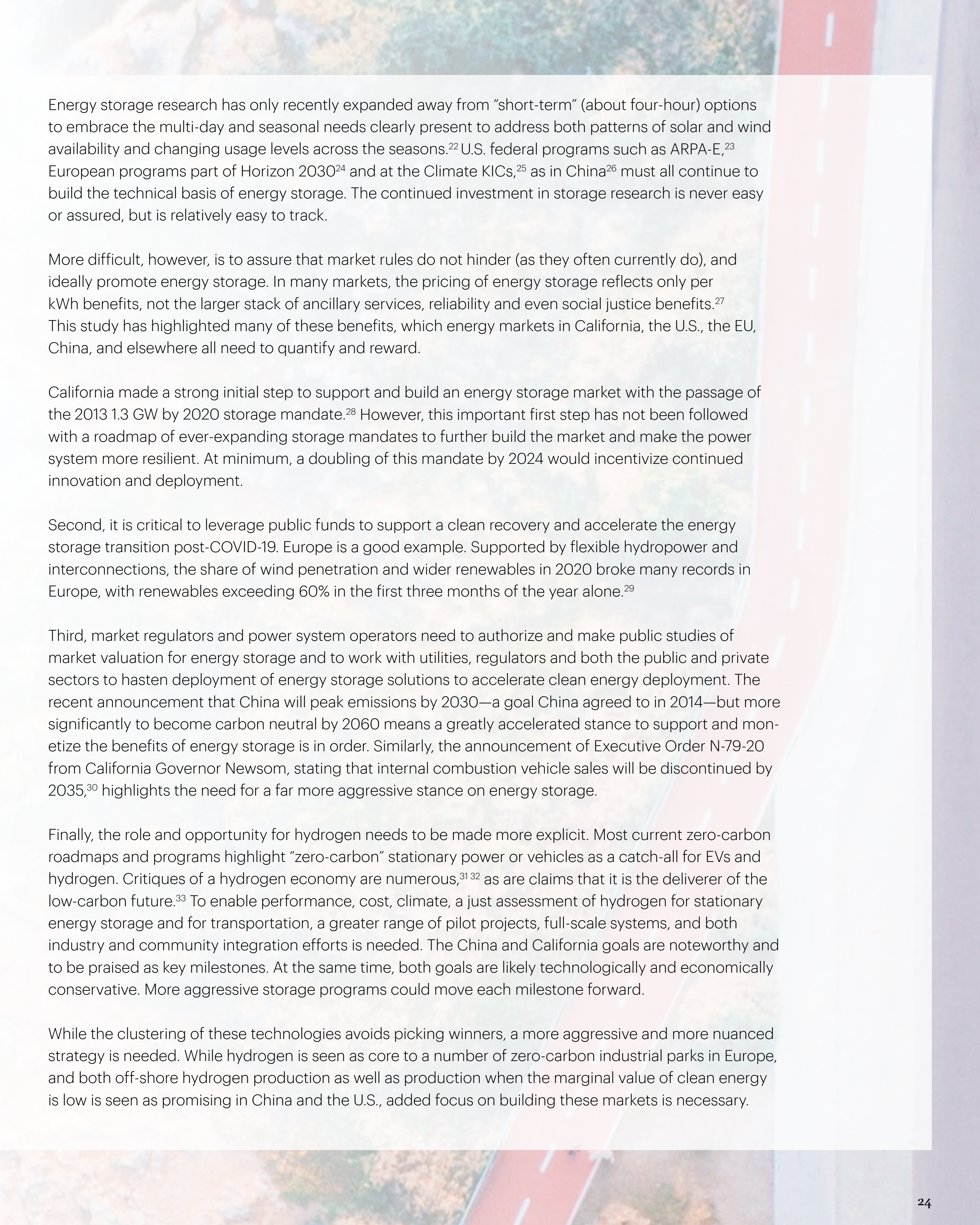
- **The storage industry is diverse,** with multiple materials science and technology options for short-, medium- and long-term storage,[19] each of which can be cost-effective options at scale for the clean energy transition.[20]

- **Energy storage enables "crossover applications"** that link stationary power generation and needs with energy for heat and transport, including vehicles, rail, shipping and, ultimately, zero-carbon air travel. Technology and cost improvements in clean energy generation or in energy storage enable the other, linking three sectors previously seen as largely separate.

- **Energy storage enables both central-station and distributed energy systems.** With continued debate over the costs and benefits of largely traditional utility-scale energy systems—versus the rise of distributed-, industry- and community-scaled energy systems—storage enables both paths. In fact, energy storage is likely in the "technology sweet spot" that permits greater reliability, price declines, and greater reliance on clean energy in synergistic large and distributed-scale clean energy systems.[21]

All of this contributes to a large, dynamic future for energy storage.

At the same time, several barriers and underexploited scientific, engineering, market and policy levers need to be addressed.



Energy storage research has only recently expanded away from "short-term" (about four-hour) options to embrace the multi-day and seasonal needs clearly present to address both patterns of solar and wind availability and changing usage levels across the seasons.[22] U.S. federal programs such as ARPA-E,[23] European programs part of Horizon 2030[24] and at the Climate KICs,[25] as in China[26] must all continue to build the technical basis of energy storage. The continued investment in storage research is never easy or assured, but is relatively easy to track.

More difficult, however, is to assure that market rules do not hinder (as they often currently do), and ideally promote energy storage. In many markets, the pricing of energy storage reflects only per kWh benefits, not the larger stack of ancillary services, reliability and even social justice benefits.[27] This study has highlighted many of these benefits, which energy markets in California, the U.S., the EU, China, and elsewhere all need to quantify and reward.

California made a strong initial step to support and build an energy storage market with the passage of the 2013 1.3 GW by 2020 storage mandate.[28] However, this important first step has not been followed with a roadmap of ever-expanding storage mandates to further build the market and make the power system more resilient. At minimum, a doubling of this mandate by 2024 would incentivize continued innovation and deployment.

Second, it is critical to leverage public funds to support a clean recovery and accelerate the energy storage transition post-COVID-19. Europe is a good example. Supported by flexible hydropower and interconnections, the share of wind penetration and wider renewables in 2020 broke many records in Europe, with renewables exceeding 60% in the first three months of the year alone.[29]

Third, market regulators and power system operators need to authorize and make public studies of market valuation for energy storage and to work with utilities, regulators and both the public and private sectors to hasten deployment of energy storage solutions to accelerate clean energy deployment. The recent announcement that China will peak emissions by 2030—a goal China agreed to in 2014—but more significantly to become carbon neutral by 2060 means a greatly accelerated stance to support and monetize the benefits of energy storage is in order. Similarly, the announcement of Executive Order N-79-20 from California Governor Newsom, stating that internal combustion vehicle sales will be discontinued by 2035,[30] highlights the need for a far more aggressive stance on energy storage.

Finally, the role and opportunity for hydrogen needs to be made more explicit. Most current zero-carbon roadmaps and programs highlight "zero-carbon" stationary power or vehicles as a catch-all for EVs and hydrogen. Critiques of a hydrogen economy are numerous,[31] [32] as are claims that it is the deliverer of the low-carbon future.[33] To enable performance, cost, climate, a just assessment of hydrogen for stationary energy storage and for transportation, a greater range of pilot projects, full-scale systems, and both industry and community integration efforts is needed. The China and California goals are noteworthy and to be praised as key milestones. At the same time, both goals are likely technologically and economically conservative. More aggressive storage programs could move each milestone forward.

While the clustering of these technologies avoids picking winners, a more aggressive and more nuanced strategy is needed. While hydrogen is seen as core to a number of zero-carbon industrial parks in Europe, and both off-shore hydrogen production as well as production when the marginal value of clean energy is low is seen as promising in China and the U.S., added focus on building these markets is necessary.

Imperative 2: Invest in digital to improve storage usage

To improve the use of battery storage to support system level needs while enhancing revenue stacking opportunities, digital capabilities are required. Through our experiences working with clients on these complex optimization strategies, the need to apply digital solutions in data management, application and analysis is non-negotiable. The sheer amount of data, the democratization and speed at which the data is available and increasing complexity of market dynamics continue to marginalize solely human decision making. Asset owners and operators will need to pivot toward incorporating digital solutions leveraging machine learning/artificial intelligence (AI) methodologies to create decision-support tools while developing market strategies based on exhaustive and sound data analysis instead of human "gut feel" and more limited information interpretation.

The ability of machine learning to analyze fundamental data sets on a scale and granularity a human decision maker cannot evaluate and interpret at the speed needed is many times the difference between profit and loss or missed opportunity. An example of this was seen when solving for energy time-shift arbitrage and working with standard load, weather data, fuel prices and historical market prices from a data set extending over five years. The machine learning model was able to identify specific feature correlations and prioritize data sets, in this case load deviations from a second-tier location, that directly impacted strategy recommendations never considered by human decision makers. The recommended shift in hours of participation from the model and missed by human decision makers resulted in avoiding a complete lost opportunity scenario in a market with razor-thin margins.

From the system's perspectives, leveraging advanced digital technologies including the internet of things (IoT) and machine learning would enable real-time communication to and enhancement of the batteries deployed on the grid based on the needs of the network at that moment in time. This could include aggregation of these assets into a virtual power plant (VPP) to support grid reliability. Enel's JuiceNet, a V2G platform which aggregates EVs to create a virtual battery and manages charging station demand to provide reliability to the grid, is one innovative market example of this.[34]

From the perspective of the battery owner and operator, forecasting and asset optimization models will be critical to improving revenue stacking while managing asset operations. Forecasting represents the most important aspect of the optimization effort, as data elements being fed into prescriptive models for recommended actions must be of high value to run scenarios. Forecasting approaches require applications of machine learning and statistical applications to produce the data sets required as inputs for prescriptive optimization models.

The actual prescriptive optimization model requires the classification of the problem to apply fit-for-purpose algorithms. The problem is evaluated based on the type of data, constraints (including to manage overall battery health), objectives and data accuracy. Optimization solvers are programs that embed power algorithms and allow users to focus on modeling and applying these pre-developed mathematical engines to perform complex calculations.

Cloud represents an important backbone across these use cases. Cloud not only offers unrestricted access to leading-edge technologies and capabilities—including advanced analytics, AI and machine learning—but the ability to rapidly experiment and, given the instant access to additional computing power, to quickly scale once proven.

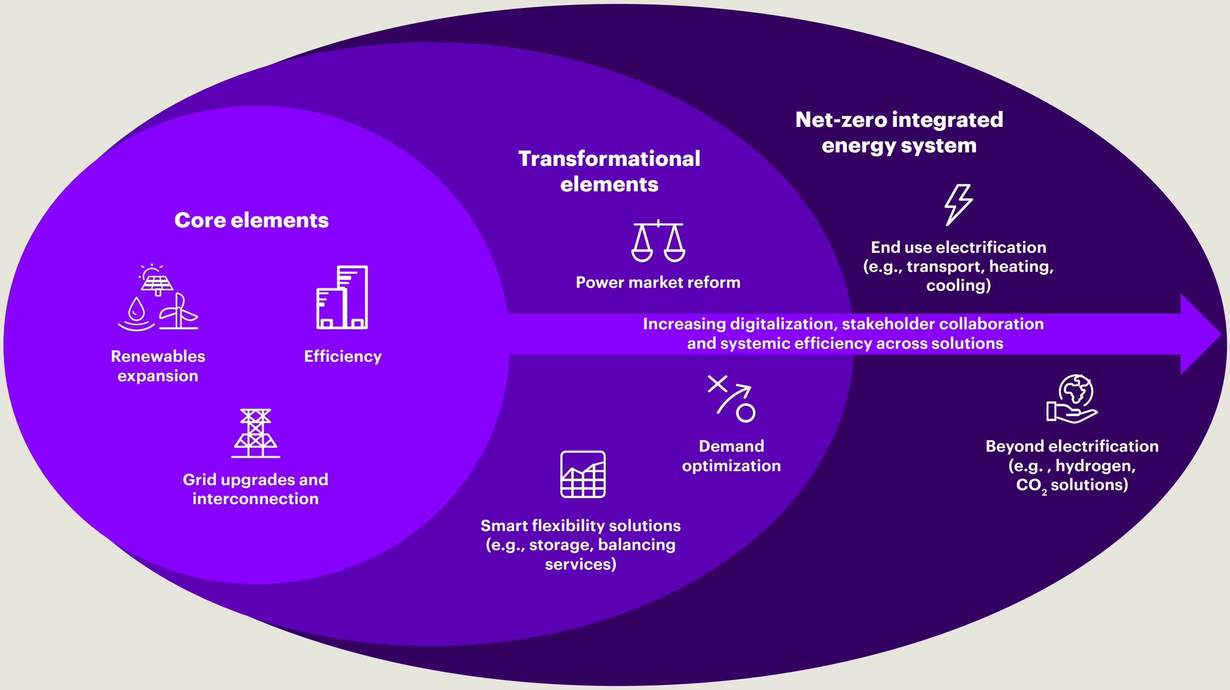
While the underlying technologies required to manage and optimize energy storage largely exist and are deployed and proven at scale, the combination of talent and digital operating model that turns generic technology into industry-specific solutions demands a greater degree of focus. The industry, policymakers and regulators will need to collaborate to make an industry digital revolution viable. And this will need to happen quickly so that technology constraints do not act as a limiting factor to the pace of renewable integration, with storage a key enabler.

Imperative 3: Integrate storage into a broader system framework to accelerate the path to net zero

As this study has shown, storage can play a significant role in the path to net zero. However, its potential is not adequately reflected in policy or market participation rules. More needs to be done to shift mindsets away from storage as a last resort and incent greater storage deployment to support our path to net zero at least cost, including increased investment into R&D and fairer market participation rules. Partnerships between industry and academia—with governments, businesses and social justice groups—are all needed to move storage more rapidly into the mainstream of the energy transition.

But even if these steps are taken, storage alone will not be enough. The path to decarbonization is challenging, and reaching net zero will require a holistic approach using all levers at our disposal, including power market reform and demand-side optimization. Accenture and the World Economic Forum's recently published a perspective on the need to take a system value approach to a clean energy recovery articulates three key phases to transition, each requiring a different set of and an increasing number of levers to ultimately achieve net zero.[35] Which levers to invest in and when will depend on the individual market.

Figure 12. The path to maximizing system value.



Source: The World Economic Forum in collaboration with Accenture, System Value Framework, October 2020, https://www.weforum.org.

Implications for Market Participants

We see a variety of implications for regulators, system operators and asset owners.

Recommendations for regulators

Effective policy is critical to achieving net zero within the timeframes needed to avoid irreversible climate impacts. While regulators should avoid picking "winners," they should seek to understand where they are on the path to net zero, the levers with the greatest impact and, as a result, where to invest. This understanding should be followed by continued investment in R&D—both in evolving technologies, but also in business case modeling to define new value pools for these technologies, as well as continued dialogue with system operators, utilities and asset owners to understand the ongoing challenges and enact supporting policy accordingly.

For storage, regulators should explore opportunities to create additional flexibility for assets of different types—including storage—to participate in the market and look to simplify and standardize permitting and deployment regulations. These efforts would go a long way to creating the appropriate supporting conditions to accelerate adoption and deployment of storage technologies.

Recommendations for system operators

System operators need to redesign for a variable energy system—with greater resilience than ever before. In doing so, they should be transparent about their vision for the future grid and the architectural implications of this vision. This will help to create clarity and confidence on the path forward.

Storage has an important role to play on this path. System operators should move away from a mindset of viewing storage as a last resort and instead work with regulators to create flexibility for a variety of assets to participate in the market. Looking beyond just storage, and given the variety of levers that system operators will need to utilize to achieve net zero, they should also devise comprehensive digital strategies to support system optimization at least cost.

Recommendations for utilities and asset owners

Utilities and asset owners are on the frontlines of storage deployment. They should continue to explore new opportunities and business cases for storage to fulfill its technological potential and should share these learnings as they emerge. These successes, lessons learned and ongoing challenges would create a repository of industry case studies from which regulators, system operators and other utilities or asset owners could learn from to accelerate the pace of change.

To enhance revenue of their deployments, utilities and asset owners should invest in digital technologies. Digital can empower them to optimize individual market participation strategies as well as integrated asset strategies.

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Glossary of terms

SOC – Battery Asset State of Charge (Energy Capacity)

DA LMP – Day-Ahead Energy Price

RT LMP – Real-Time Energy Price

SOC DA – Day-Ahead Award Cycling Activity

SOC RT – Real-Time Award Cycling Activity

Reg Up – Regulation Up Ancillary Svcs. Activity

Reg Down – Regulation Down Ancillary Svcs Activity

Max SOC – Maximum Battery Asset SOC

Min SOC – Minimum Battery Asset SOC

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