Stacked Benefits:

Comprehensively Valuing Battery Storage in California

THE **Brattle** GROUP

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Executive Summary

Introduction

Several ongoing initiatives in California are facilitating the deployment of battery storage technology. One such initiative is the California Energy Commission's (CEC's) sponsorship of energy storage pilots and demonstration projects. Included in those projects are various battery storage deployments developed by Eos Energy Storage ("Eos"). Among the research objectives of the Eos projects is an assessment of the potential economic benefits of energy storage in California. This report provides the assessment of energy storage economics. The study was developed by The Brattle Group under a contract with Eos.

Methodology

Much of the existing research on energy storage value focuses only on isolated use cases for the technology, such as energy price arbitrage or peak capacity deferral. In fact, an advantage of battery storage is its ability to capture multiple sources of value.[1] Accurately capturing these "stacked benefits" of battery storage requires detailed analysis of both the operational characteristics of the battery and the nature of the value streams it captures. In this study, we have used a modeling approach designed to accurately quantify the benefits of multiple value streams. Other noteworthy aspects of the scope include:

- We assess battery storage value under a broad range of California-specific market conditions and system costs observed between 2013 and 2016. We account for the value of avoided energy, generation capacity (i.e., resource adequacy), transmission and distribution capacity, and ancillary services.

- We model two battery discharge cases to account for differences in the battery operator's ability to predict future market prices. In the Perfect Foresight case, the battery is assumed to operate with perfect foresight into all future market prices and marginal costs. In the Limited Foresight case, the battery is operated with realistic constraints around the ability to predict prices.

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[1] The importance of accounting for "stacked benefits" was also previously addressed in The Brattle Group's 2014 assessment of distributed storage in Texas. See Judy Chang, et al., "The Value of Distributed Electricity Storage in Texas," prepared for Oncor by The Brattle Group, November 2014. The stacked benefits issue has also been examined in studies by Lawrence Livermore National Laboratory (LLNL) and the National Renewable Energy Laboratory (NREL).

- We analyze the incremental value of a single battery storage project on the California power system. We have not analyzed the impact that the addition of large quantities of storage could have on market prices.

- The scope of our analysis is focused exclusively on quantifying avoided system costs (i.e., we quantify the system-wide benefits of deploying batteries). We do not specifically quantify the value that could be captured at the retail level by individual customers with distributed storage.

Key Findings

Our analysis suggests that, in many cases, the "stacked" benefits of battery storage compare favorably to recent estimates of new battery costs. This finding is sensitive to the marginal cost of generation capacity but is otherwise robust across the sensitivity cases we analyzed. The quantified benefits appear to be in line with those of other studies. Important observations from our assessment of the value of battery storage in California include:

- Under our Base Case assumptions, with limited market foresight, the total value of "stacked benefits" in California for one kilowatt / four kilowatt-hours of battery storage could be around $280/kW-year. By comparison, recent estimates of battery costs have been in the range of $200 to $500/kW-year (though they vary significantly by technology type and configuration).

- Accounting for the "stacked" benefits of battery storage by optimizing its dispatch across all analyzed value streams significantly increases the total value of the battery relative to any individual value stream (by a factor of at least 2x to 3x over individual uses cases).

- Avoided generation capacity, frequency regulation, and energy price arbitrage are the largest sources of quantified value. However, the "depth" of each market should be taken into consideration when valuing large quantities of energy storage. Frequency regulation in particular is a highly valuable service with a very limited system need. At the same time, the need for frequency regulation is likely to increase with greater renewable resource deployment. This consideration is particularly relevant in the California market, as the state progresses toward its 50% renewable energy target.

- Sensitivity cases suggest that uncertainty about the capacity value of storage could significantly impact estimates of total value. In the short run, excess supply means that the capacity value of energy storage in California will be modest unless there are local needs for resource adequacy. In the longer term, as planning reserve margins tighten, system-wide capacity value could approach the levels quantified in this study. Aside from sensitivity to generation capacity cost assumptions, the Base Case results are fairly

robust across a range of assumptions about T&D capacity costs, location, and historical study year.

A summary of the Base Case estimate of battery value is provided in Figure ES-1.

Figure ES-1: Battery Value for Individual Use Cases and with "Stacked" Benefits
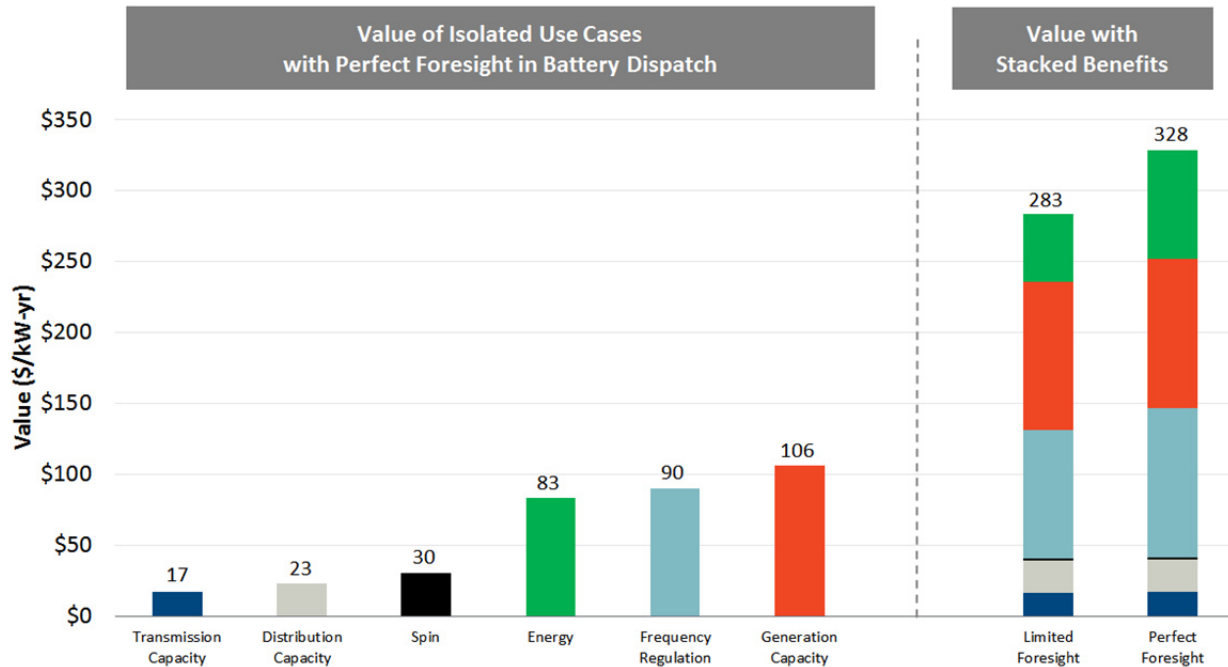
Figure notes: Results shown for San Diego. Value in other California locations is assessed through sensitivity analysis. Energy and ancillary services value is an average across market conditions between 2013 and 2016.

Addressing Barriers

California is considered to be a leader in its efforts to facilitate the adoption of energy storage. Noteworthy energy storage initiatives in California include:

- An aggressive storage procurement mandate for the investor-owned utilities (IOUs);
- The Self Generation Incentive Program (SGIP), which provides incentive payments to behind-the-meter storage;
- Enhancements to CAISO's energy and A/S markets to support storage participation;
- CAISO's implementation of new wholesale market products that are amenable to storage, such as the flexible ramping product;
- CAISO's Energy Storage and Distributed Energy Storage (ESDER) stakeholder group, which works to enhance the market participation of grid-connected storage;
- CPUC proceedings to quantify the locational value of distributed energy resources; and
- The CPUC requirement that load serving entities contract for sufficient flexible capacity, which storage is eligible to provide.

Generally, there has been a heavy focus in California on addressing energy storage participation barriers at the wholesale market level. While we have not quantitatively analyzed the customer-side economics of battery ownership and utilization, there are also clear options for addressing barriers to distributed storage adoption at the retail level. As such, our scope for this study specifically called for an exploration of opportunities to increase the system value of storage through retail rate redesign. It would be a valuable future research activity to comprehensively evaluate all opportunities to address barriers at both the retail and wholesale levels.

Better alignment of the retail rate design with the underlying structure of system costs can incentivize customers to adopt battery storage and use it in a way that produces system benefits.[2] In this study, we discuss two specific innovative rate designs which could provide significant opportunities for monetizing the value of behind-the-meter energy storage. The first is a "three-part rate" which consists of three charges, each designed to recover different types of costs. The "demand charge" in a three-part rate is based on a customer's peak electricity demand and can provide a particularly strong incentive for battery owners to discharge the battery during peak times in order to reduce capacity costs.

The other retail rate design that could facilitate the capture of battery storage value is a "smart home/business rate." A smart home/business rate is a form of real-time pricing in which all energy and capacity costs vary on an hourly or even sub-hourly basis. The hourly variation creates opportunities for the battery operator not only to capture fluctuations in energy value, but also to provide resource adequacy in a price-based manner that is tied directly to the underlying drivers of capacity needs.

Conclusion

Operating batteries to capture "stacked" benefits could unlock significantly more value than using batteries to pursue individual value streams in isolation. This finding is fairly robust across a range of sensitivity cases. However, challenges to simultaneously capturing multiple value streams remain. Some of the barriers are technical in nature, and may be overcome as new battery management algorithms and software are developed. Other barriers may be overcome through new policy initiatives. Offering new or revised rate designs which more fully reflect the time-varying nature of the cost of generating and delivering electricity is one of many possibilities. Costs of energy storage are expected to continue to decline, and market adoption is likely to increase as a result. In this scenario, considerations at both the retail and wholesale level will play an increasingly important role in the formation of energy storage policy initiatives.

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[2] Of course, with the introduction of any new rate design, it is necessary to consider the rate's broader implications, including distributional effects on customer bills and implications for the utility's ability to fully recover its costs.

I. Introduction

Emerging changes to the U.S. power system are creating unique opportunities for battery storage. In particular, the growing adoption of wind and solar generation has introduced a greater demand for flexible resources. At the same time, large capital investments will be needed to replace aging power system infrastructure. Utilities, regulators, and other industry stakeholders are exploring opportunities to defer or avoid these investments through deployment of energy storage.

Battery storage has received considerable attention in California. Several open regulatory proceedings at the California Public Utilities Commission (CPUC) are addressing issues related to energy storage. These include a docket on the integration of distributed energy resources (R.14-10-003), a docket on the state's storage mandate (R.15-03-011), and a proceeding on rules and policies related to distributed generation (R.12-11-005). Additionally, the California Independent System Operator (CAISO) has introduced new market products designed to provide energy storage with an opportunity to participate in the state's wholesale electricity markets.

The California Energy Commission (CEC) is also actively facilitating the deployment of battery storage technology.[3] The CEC's activities have primarily focused on energy storage research, development, and deployment. An important aspect of this activity has been the sponsorship of energy storage pilots and demonstration projects.

The CEC's ongoing demonstration projects include three battery storage deployments by Eos Energy Storage ("Eos"). One deployment is a 125 kW / 500 kWh battery in Northern California, and the other deployments will be smaller installations at the University of California, San Diego (UCSD) campus, ranging in size from 2 to 40 kW. The deployments will be operated to collect data on a wide range of potential storage use cases. Among the research objectives of the Eos projects is an assessment of the potential economic benefits of energy storage in California. The purpose of this report is to provide that assessment of energy storage economics. The study was developed by The Brattle Group under a subcontract with Eos.

DISTINGUISHING FEATURES OF THE STUDY

Given the high degree of industry interest in energy storage, it is not surprising that many studies have been conducted to assess the value of the technology. Several of these studies have been

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[3] For instance, in collaboration with the CPUC and CAISO, the CEC introduced a roadmap for advancing energy storage in California. "Advancing and Maximizing the Value of Energy Storage Technology: A California Roadmap," California ISO, December, 2014. http://www.energy.ca.gov/research/energystorage/tour/roadmap/.

specific to the California market. Notable studies on the value of energy storage in California over the past several years were authored by Lawrence Livermore National Laboratory (LLNL), the Electric Power Research Institute (EPRI), Rocky Mountain Institute (RMI), and the National Renewable Energy Laboratory (NREL).[4]

The existing research on energy storage uses a broad range of modeling techniques to explore different sources of battery storage value. However, the studies commonly focus only on isolated use cases for the technology, such as energy price arbitrage or peak capacity deferral.[5] In fact, an advantage of battery storage is its ability to capture multiple sources of value.

Accurately capturing these "stacked benefits" of battery storage requires detailed analysis of both the operational characteristics of the battery and the nature of the value streams it captures. In this study, we have used a modeling approach designed to accurately quantify the benefits of multiple value streams. Distinguishing features of our study include:

- Our approach accounts for the simultaneous capture of multiple value streams rather than analyzing individual use cases in isolation. An important feature of battery storage is that it can be used to provide many different sources of value by changing its utilization over short time horizons to pursue those services with the largest benefits.

- We utilize sophisticated modeling software to accurately represent the dispatch of the battery subject to pre-defined operational characteristics. The software allows for dispatch optimization to capture difficult-to-quantify benefits such as the value that can be created through price arbitrage between day-ahead and real-time energy markets.

- We assess battery storage value under a broad range of California-specific market conditions and system costs. The value of various services can differ significantly from one year to the next and within different geographical locations in the state. We have considered a broad range of possible market conditions.

- Our study includes a discussion of retail-level regulatory reforms that could increase the ability of storage to create and monetize wholesale market value.

SCOPE OF THE STUDY

We analyze the incremental value of a single battery storage project on the California power system. We have not analyzed the impact that the addition of large quantities of storage could

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[4] See the bibliography for a complete list of the energy storage studies we reviewed.

[5] Some studies, such as the Rocky Mountain Institute study, considered stacked benefits but across a limited number of specific use cases.

have on market prices. All else being equal, at higher levels of storage adoption we would expect the energy market price profile to flatten to some degree, and the remaining supply of capacity and ancillary services to begin to become saturated. As a result, the per-unit value of energy storage would decrease as additional storage capacity is added to the system. This dynamic could be explored in future research through power systems modeling.[6]

The scope of this study is focused exclusively on quantifying avoided system costs. We do not specifically quantify the value that could be captured at the retail level by individual customers with distributed storage. The value to end-use customers with battery storage could include, for instance, reduced bills through the avoidance of demand charges or time-varying rates, and enhanced reliability by using the battery as a form of backup power. These would also be valuable areas to explore through further research.

To establish the system costs that could be avoided through battery storage dispatch, we use recent historical market prices and costs, rather than projected prices. This approach ensures that we are capturing realistic market conditions.

Further, we do not conduct a detailed cost-effectiveness assessment of batteries. Rather, the study is intended to highlight the potential benefits of a given battery configuration – in other words, the magnitude of the opportunity. Similarly, this is not a "potential assessment" and is not intended to indicate the total quantity of energy storage that may be economic in the California market. There would be considerable value to state policymakers and utilities in conducting such a study.

We explore barriers to capturing the full system value of energy storage in California and explore options for overcoming the barriers. Consistent with our scope of work for this study, we exclusively consider how retail rate reform could help to address the barriers. While we do not specifically quantify the customer benefits of behind-the-meter storage, it is still possible to establish principles for promoting energy storage through retail rate design. It would be a valuable future research activity to comprehensively evaluate opportunities to address barriers at both the retail and wholesale levels.

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[6] This was the finding, for example, of Brattle's recent assessment of battery storage value in Texas. See Chang, Judy, et al., "The Value of Distributed Electricity Storage in Texas," Prepared for Oncor by The Brattle Group, November 2014. This dynamic has also been examined in the aforementioned studies by Lawrence Livermore National Laboratory (LLNL) and the National Renewable Energy Laboratory (NREL).

ORGANIZATION OF THE REPORT

The remainder of this report is organized as follows: Section II describes the methodological framework. Section III summarizes key findings. Section IV concludes the report with a brief discussion of important policy considerations.

II. Methodology

SOURCES OF VALUE

The focus of this study is on quantifying the value that distributed battery storage creates by reducing system costs.[7] This approach is sometimes referred to as quantifying "system value" or "societal value". As such, we are quantifying benefits from the perspective of the total power system, rather than from the specific perspective of the battery operator or an individual customer.

The following are sources of system value quantified in this study:

- **Energy price arbitrage:** The battery can be charged during low (or negative) priced hours and discharged during higher priced hours to avoid dispatching generators with high fuel and variable O&M costs.

- **Ancillary services:** The battery provides regulation (rapidly charging and discharging to in response to short-duration supply/demand imbalances) and spinning reserves (protecting against large contingencies). The need for these services may grow as market penetration of renewable generation grows.[8]

- **Generation capacity / resource adequacy:** The battery contributes to system resource adequacy by discharging during peak demand hours and scarcity events.

- **Transmission and distribution capacity:** Storage can be located in key constrained locations on the grid, reducing demand during times of capacity constraints and deferring the need for transmission and distribution capacity upgrades.[9]

- **Reduced CO_2 emissions:** The societal cost of CO_2 emissions is at least partially incorporated into the energy price due to California's "AB 32" climate policy. The extent

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[7] As is discussed throughout this report, the battery is modeled as a "price-taker," meaning we do not account for the impact that its dispatch could have on marginal costs. The impact is likely to be negligible at small levels of market penetration, but will likely become significant as market adoption of energy storage grows.

[8] Battery storage can also enlarge the pool of resources that provide (or qualify to provide) ancillary services. For instance, on-site batteries can be paired with generators to effectively reduce the generator's start time, allowing it to participate in quick-start ancillary services markets.

[9] Further, storage can increase transfer capability by eliminating voltage constraints. That possible benefit is not quantified in our analysis.

to which there is an increase or decrease in CO_2 emissions will depend on whether the battery is being charged during hours with higher- or lower-than-average marginal emissions. This value (or cost) is captured in our analysis of energy value.

Other potential sources of system value from battery storage are not quantified in the analysis. The following sources of value were not quantified because they are difficult to accurately quantify or are likely to be small relative to the quantified sources of value. The non-quantified potential benefits of battery storage include:

- Reduced transmission congestion
- Extension of transmission and distribution equipment life
- Additional ancillary services, such as ramping, voltage support, blackstart, and inertia
- Flexible resource adequacy value[10]
- Avoided startup costs of other generators on the system

Additionally, the following are possible retail-level benefits that would accrue to end-use owners of distributed batteries. As such, these benefits were beyond the scope of our valuation framework:[11]

- Bill reductions for end-use customers (e.g., avoided demand charge, TOU rate)
- Improved reliability for end-use customers (i.e., as backup generation)
- Enhanced power quality

ANALYTICAL FRAMEWORK

Using a battery to pursue one value stream may require forgoing opportunities to pursue other "competing" sources of value. For instance, on a peak load day it may be beneficial to store energy in the battery in anticipation of high-value reliability events and, as a result, bypass opportunities for energy price arbitrage. While the value streams quantified in this study can be estimated individually, those estimates are not purely additive. A battery operator must choose how much of the battery's capacity to allocate to pursuing each opportunity. Accurately estimating the comprehensive value of battery storage requires accounting for tradeoffs across the value streams.

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[10] CAISO has introduced market products for flexible resources and for ramping. There was not enough price data available for these products to accurately account for them in our analysis. Doing so would be a valuable future research activity.

[11] Note that these non-quantified sources of value would not necessarily be purely additive to the quantified sources of value; in some instances, they may reflect the same benefit as it accrues to as specific stakeholder (e.g., bill reductions through avoidance of demand charges would double-count avoided capacity costs).

Therefore, we "co-optimized" the battery's dispatch across multiple value streams, such that it maximizes overall system value. We used the Power System Optimizer (PSO) model to perform this co-optimization. PSO is a commercially-licensed production cost market simulator which allows for realistic representation of the battery's operations. Our simulations account for market rules, historical marginal prices, and operational parameters of the battery provided by Eos.

To the extent feasible, our approach to valuing battery storage is consistent with established methods for valuing distributed energy resources in California.[12] First, capacity costs are allocated to hours of the year proportional to the risk of capacity shortage in each hour. These hourly capacity costs are combined with hourly energy market prices and ancillary services prices to establish a "stacked" price series which reflects all avoidable costs. Then, operational characteristics of the battery are defined to account for technical constraints and limitations on the ability to capture multiple services simultaneously. The battery is dispatched against the price series subject to these constraints to produce an estimate of the net avoided marginal costs. This methodological framework is summarized in Figure 1.

Figure 1: Overview of the Methodological Framework
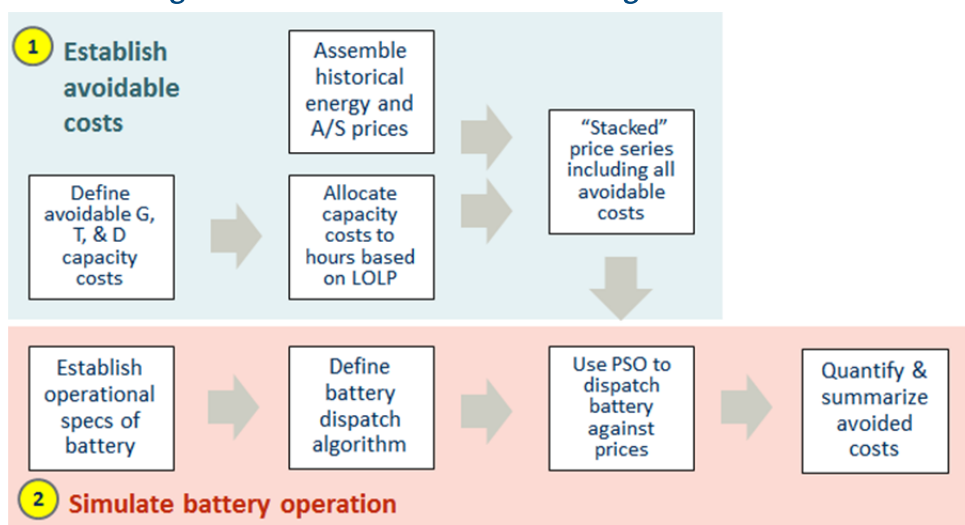
Charge/discharge algorithm

We model two battery discharge cases to account for differences in the battery operator's ability to predict future market prices. We refer to those two cases as the "Perfect Foresight" case and the "Limited Foresight" case.

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[12] For example, see E3, "Time Dependent Valuation of Energy for Developing Building Efficiency Standards," Prepared for the California Energy Commission, July 2016.

In the **Perfect Foresight** case, the battery is operated with perfect foresight into all future market prices and marginal costs. The battery is dispatched optimally against all value streams. It is scheduled first in the day-ahead (DA) market. The final dispatch is adjusted from the DA schedule in the real-time (RT) market to capture unexpected price arbitrage opportunities that can arise in real-time. In order to reflect the full potential value of battery storage, we assume that the battery operator is not constrained by any CAISO market participation rules.

The Perfect Foresight case effectively represents the theoretical upper-bound on system value that could be provided from a battery operating in both DA and RT markets.[13] The Perfect Foresight case is not intended to represent an estimate of the most likely value of battery storage in California.

In the **Limited Foresight** case, the battery is operated with realistic constraints around the ability to predict prices. Specifically, the battery dispatch schedule is optimized across all DA value streams with perfect foresight into prices over the next 24 hours. The battery is then dispatched in the RT market with only one hour of foresight. This case is similar to the way CAISO might dispatch the battery in the market.

Operational characteristics of the battery

The operational characteristics of the battery are based on technical specifications provided by Eos. Specifically, we modeled a 1 MW / 4 MWh system with roundtrip efficiency of 75%. The Eos battery relies on zinc hybrid cathode technology, which allows for full cycling of its 4 MWh capacity. The battery is rated at 5,000 cycles at full depth of discharge; we assess the sensitivity of the value estimates to cycling frequency later in this report.

Battery value is modeled on a $/kW-year basis. Value would scale linearly with the amount of battery capacity installed for modest amounts of storage that are added to the system. However, as was discussed in Section I of this report, we do not assume any price-setting ability for the battery. We focus only on the incremental value of an individual system. The operation of a significant amount of new storage capacity in the California market would likely tighten arbitrage opportunities and saturate ancillary service markets to some degree.

Location

Marginal costs vary by location across California. To test the sensitivity of battery value to location, we separately model storage in San Diego, Northern California (the NP-15 zone), and Southern California (the SP-15 zone). In the analysis, energy prices vary across these locations.

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[13] We also explored cases where the battery operates strictly in either the DA or in RT markets, with perfect foresight. See the appendix for further details.

The timing of the hours to which marginal network capacity costs are allocated varies as well, due to variation in load across the locations (discussed in more detail later in this section of the report). San Diego is modeled with actual hourly nodal LMPs for downtown (the Coronado 6 node). NP-15 and SP-15 reflect average prices across all trading hubs in Northern California and Southern California, respectively. Spinning reserves, regulation, and annual marginal capacity costs are held constant across locations. A map of the modeled locations is provided in Figure 2.

Figure 2: Map of California Transmission Congestion Zones
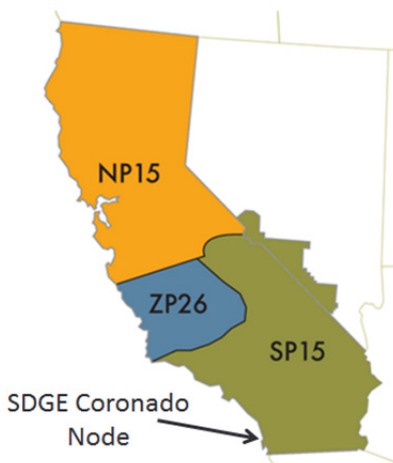
Source: CAISO OASIS, node used is Coronado_6_N001

ESTABLISHING MARGINAL COSTS

Energy price arbitrage value

We rely on historical hourly CAISO energy market prices to establish a range of realistic hourly marginal energy costs.[14] The market price data spans the period from 2013 through 2016. Higher peak prices tend to occur between 5 pm and 11 pm. The average daily price profile for San Diego in 2016 is illustrated in Figure 3.

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[14]   LMPs are used as a reasonable proxy for avoidable marginal energy costs. This is a standard approach to assessing the energy value of distributed energy resources. In practice, unit start-up costs, locational constraints, and other factors would also influence the precise energy value of distributed battery storage. More detailed dynamic modeling of energy storage dispatch using a production cost simulation model would be one way to account for these nuances in future research.

Figure 3: 2016 Average Daily Price Profile, San Diego
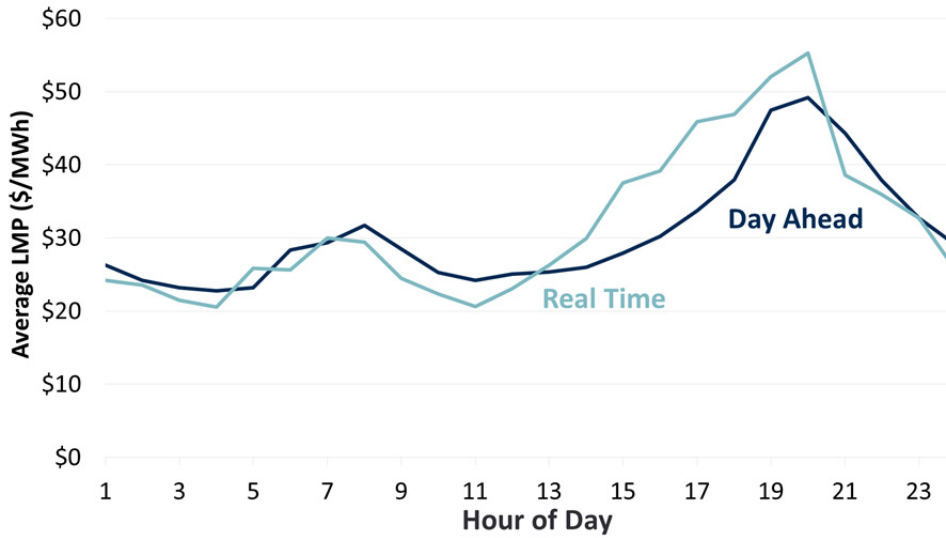
Source: Velocity Suite, ABB Inc. Prices from node Coronado_6_N001

Prices in the CAISO RT market are significantly more volatile than in the DA market. As a result, the RT market is generally a source of higher value for flexible resources like storage than the DA market. However, the participation of storage in the RT market could dampen this price volatility, limiting the incremental value in the RT market relative to the DA market. Figure 4 illustrates the relative price volatility in RT and DA markets in San Diego.

Figure 4: July 2016 Energy Prices, San Diego
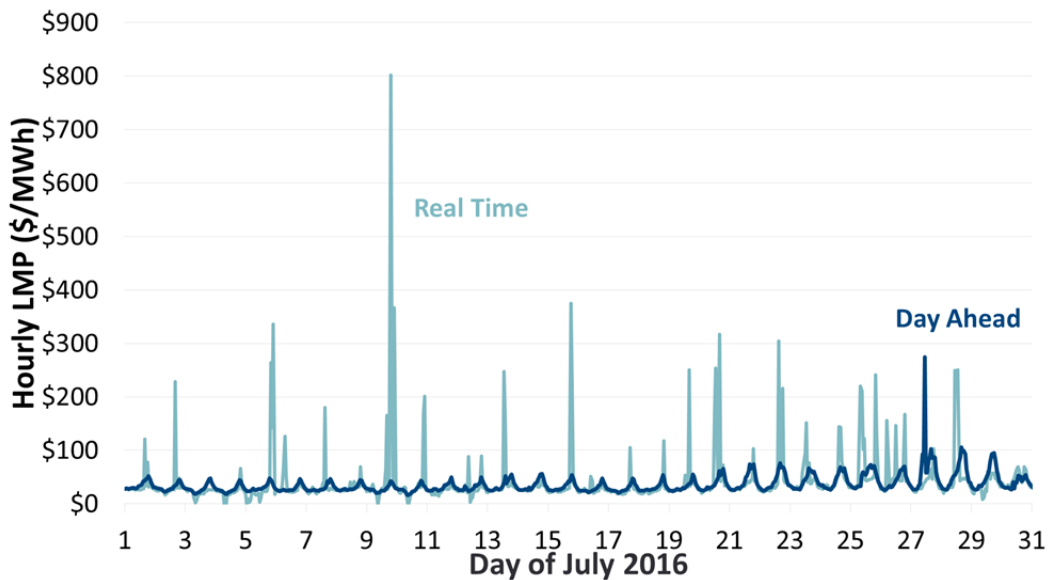
Source: Velocity Suite, ABB Inc. Prices from node Coronado_6_N001

We note that we have assessed the real-time portion of energy price arbitrage value on an hourly basis. In California, the real-time energy market is settled on a sub-hourly basis. Given the fast

response capabilities of battery storage, capturing price volatility at this level of granularity would likely increase the energy value relative to our estimates in this study. Modeling real-time energy value in sub-hourly increments would be a useful future research activity.

Ancillary services value

CAISO procures multiple ancillary services. "Frequency regulation" (which includes "Reg Up" and "Reg Down") is a fast-moving signal followed by flexible resources to manage system frequency. It requires the ability to respond to power fluctuations virtually instantaneously. "Spinning reserves" are resources held in reserve to respond quickly to a major contingency. Non-spinning reserves are contingency reserves that generally provide a lower associated degree of certainty than spinning reserves.

In this study, we rely on historical hourly CAISO ancillary services prices for 2013 through 2016. To capture the full potential value of battery storage, we allow the battery to participate in the spin and frequency regulation markets regardless of any potential constraints in current market participation rules.[15] Since participation in non-spin is universally less profitable than spin, non-spin has been excluded from this analysis.

The frequency regulation market is commonly considered a highly lucrative market for energy storage across the U.S. The high degree of operational flexibility in battery storage makes it ideally suited to provide this service. However, it is important to note that the frequency regulation market is "shallow" and can quickly saturate. For instance, in 2016 the CAISO system peak demand was 46 GW. In comparison, the total frequency regulation requirement has ranged from 400 to 800 MW (i.e., less than 2% of peak demand).[16]

To account for the potentially small size of the frequency regulation market opportunity, our sensitivity analysis includes a case in which frequency regulation is excluded from the dispatch optimization.

Generation capacity value

There are competing views on the value of peak demand reductions in California. On one hand, some share a view that the system is generally overbuilt with capacity until around 2025. In this view, peak demand reductions have very limited near-term capacity value. This was a finding,

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[15] Note that under CAISO market rules, a 1 MW, 15-min duration battery can provide as much regulation as a 1 MW, 4-hr duration battery.

[16] Peak demand and frequency regulation requirement from CAISO website. See: https://www.caiso.com/Documents/CaliforniaISOPeakLoadHistory.pdf. See also: http://www.caiso.com/Documents/Q2_2016_Report_on_Market_Issues_and_Performance_Final.pdf.

for instance, of Lawrence Berkeley National Lab's (LBNL's) recent study of demand response potential in California.[17] 50% of the recent resource adequacy contracts for existing generators in California include a resource adequacy payment of around $33/kW-year or less, supporting this view of modest capacity value.[18]

In the long run, however, as the system approaches an equilibrium balance of supply and demand, we would expect the marginal cost of capacity to be equal to the net cost of new entry (net CONE). Net CONE is the full capital cost of a peaking unit less the unit's energy and ancillary services earnings.

For the Base Case, we have assumed a marginal capacity cost of **$113/kW-year** based on a net CONE value that is consistent with recent studies in California.[19] It is common practice in California regulatory proceedings to use net CONE to assess the capacity value of distributed resources. Sensitivity analysis is conducted using the lower resource adequacy value of $33/kW-year discussed above.

In practice, the near-term capacity value of storage is likely somewhere in between the low resource adequacy payments to existing resources and the much higher net CONE value. There will be instances of local grid constraints in California. While limited in their pervasiveness, these locations will experience a near-term need for new capacity. SCE's response in Aliso Canyon and the resource void left by the retirement of the San Onofre Nuclear Generating Station (SONGS) are two such examples. In Aliso Canyon, where natural gas shortages rendered power plants inoperable, 60 MW of battery storage was procured and deployed in only 9 months.[20] Further, there are some features of energy storage that may increase its value relative to a new gas-fired simple-cycle combustion turbine (CT) – such as faster deployment capability, a

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[17] The study identified significant value in load flexibility, but found that there is limited value in conventional peak demand reductions. See Alstone, Peter, et al., "Final Report on Phase 2 Results 2025 California Demand Response Potential Study Charting California's Demand Response Future," Lawrence Berkeley National Laboratory, March 1, 2017.

[18] Contracts signed for the period from 2015 to 2019, for existing generators reported to the CPUC under RA contracts. See "Testimony of Jim Caldwell Exhibit CPUC 2015 Resource Adequacy Report," Docket 15-AFC-01 before the Public Utility Commission of the State of California, January 18, 2017.

[19] See Edmunds, Thomas, et al., "The Value of Energy Storage and Demand Response for Renewable Integration in California," Lawrence Livermore National Laboratory, February 2017. Higher estimates of net CONE ($154/kW-year) were reported in "Comments…on the CAISO's Capacity Procurement Mechanism," CAISO (2014). This value is similar to the marginal generation capacity cost in the CPUC's marginal cost calculator, which is used to assess the value of distributed energy resources.

[20] Trabish, Herman, "Is battery energy storage at a 'turning point' for US utilities," Utility Dive, April 11, 2017.

smaller physical footprint, and no local emissions – but these benefits are difficult to directly translate into financial value.

It is worth mentioning that "preferred resources" in California receive sizeable resource adequacy payments. These payments can be as high as $300/kW-year for new contracts (the majority of storage projects in CA have received these new contracts).[21] While this payment may appear to be significantly higher than the net CONE value described above, the two values are in fact largely consistent. The payments to preferred resources effectively levelize net CONE over a consolidated ten-year period rather than the full life of the asset. Thus, the preferred resource payment is higher in the years when it is accrued, but the payment ends after only ten years. As such, the preferred resource payment does not directly reflect a value of capacity that is higher than net CONE.

Transmission and distribution capacity value

Avoided transmission and distribution capacity costs tend to be the most challenging benefits of distributed energy resources to accurately quantify. This is partly because these benefits are very location-specific and partly because the analysis requires a large amount of granular network data which is typically not made publicly available. As a result, the most uncertainty is associated with these benefits, though some general rules of thumb can provide an average approximation of the value.

The CPUC recognizes the value of reducing peak-driven transmission capacity investment needs through reductions in peak demand. The CPUC's marginal cost calculator, which is commonly used in regulatory filings by the state's investor-owned utilities, includes a range of marginal transmission costs. We reviewed transmission cost estimates across several years of these studies and assumed a value of **$24/kW-year**, which was roughly in the middle of the observed range.[22]

There is increasing interest in the use of batteries or other distributed resources to defer the need for new distribution capacity. In California in particular, utilities are required to assemble Distribution Resource Plans to identify areas on the distribution system where new resources are valuable.[23] Avoidable distribution costs, though, are particularly difficult to quantify. Based on a review of the CPUC's marginal cost calculator, demand response filings in other jurisdictions,

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[21] See Pfeifenberger, Johannes P. et al., "Resource Adequacy in California," The Brattle Group, October 2012.

[22] Transmission cost values for SDG&E and SCE "sub transmission" based on a review of several years of the E3 avoided cost study titled "Energy Efficiency Avoided Costs." Various annual updates are available on the CPUC and E3 websites.

[23] Please see more information on the CPUC's Demand Response Evaluation and Research at http://www.cpuc.ca.gov/General.aspx?id=10622.

and studies on the value of energy storage, we have assumed an avoidable distribution cost of **$33/kW-year** in the Base Case.[24]

The estimates used for both transmission and distribution costs are representative of average avoidable costs across the power system. Some locations on the grid will have avoidable costs that are significantly higher than this average due to a near-term need for significant upgrades or expansions of existing infrastructure. Estimates of value for those specific locations could be higher than we have quantified in this study. Conversely, in other locations there will be little to no near-term need for new network capacity

Allocation of capacity costs to hours of year

Capacity costs are allocated to hours of the year proportional to the likelihood that those hours will drive the need for new capacity. In other words, the greater the risk of a capacity shortage in a given hour, the larger the share the marginal capacity cost that is allocated to that hour.

In the Base Case, capacity costs are allocated across the top 100 load hours of the year.[25] The allocation is proportional to each hour's share of total load in the hours. This means more capacity cost is allocated to the top load hour than the 100th load hour. Note that load used for allocation of capacity costs is net of expected output from wind and solar resources. This accounts for the impact of inflexible, intermittent generation in system planning.

Generation capacity costs are allocated based on hourly CAISO system load. Transmission and distribution (T&D) capacity costs are allocated based on zonal load to reflect the more local nature of the drivers of grid costs.[26]

A conceptually similar approach to quantifying capacity value has been used in the CEC's time-dependent valuation (TDV) methodology for quantifying the value of energy efficiency, and also in the CPUC's demand response cost-effectiveness protocols. This approach effectively derates

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[24] This estimate is consistent with the lower end of the range of values observed in recent E3 avoided cost studies for the CPUC. The estimate is conservative relative to the values in the 2016 update to that E3 study, which can be more than twice as high as this assumption.

[25] Sensitivity cases testing allocation over 50 hours and 250 hours indicated that the estimates of total value in this study are not highly sensitive to the number of assumed hours for allocation.

[26] Ideally, distribution value would be assessed on a much more geographically granular level, with marginal capacity costs being allocated to hours of the year based on location-specific load values. Such data is not typically publically available. Therefore, we make the simplifying assumption that distribution and transmission peaks coincide (but are non-coincident with the California system peak). With more granular data, accounting for coincidence of generation, transmission, and distribution peaks could potentially decrease the value estimates.

the value of distributed resources relative to the avoided cost of new peaking capacity by accounting for constraints that may exist on the operator's ability to predict and respond to resource adequacy needs. These constraints could result in battery utilization patterns that reflect a willingness to bypass some energy value in order to store sufficient levels of energy to meet anticipated resource adequacy requirements. The approach is akin to capacity value derates that are applied to demand response programs to account for limitations on the timing and frequency of customer load interruptions. The approach is effectively a theoretical construct intended to quantify long-term capacity value, rather than reflecting the way resource adequacy payments would be monetized by a battery operator in the CAISO market.

A summary of the allocation of all costs is shown in Figure 5. The figure shows, as an average across all hours of the year in 2016, the costs that could be avoided through the discharge of a battery in each hour of the day (and, conversely the costs that would be incurred when charging).

Figure 5: Allocation of Marginal Costs (2016 Annual Average)
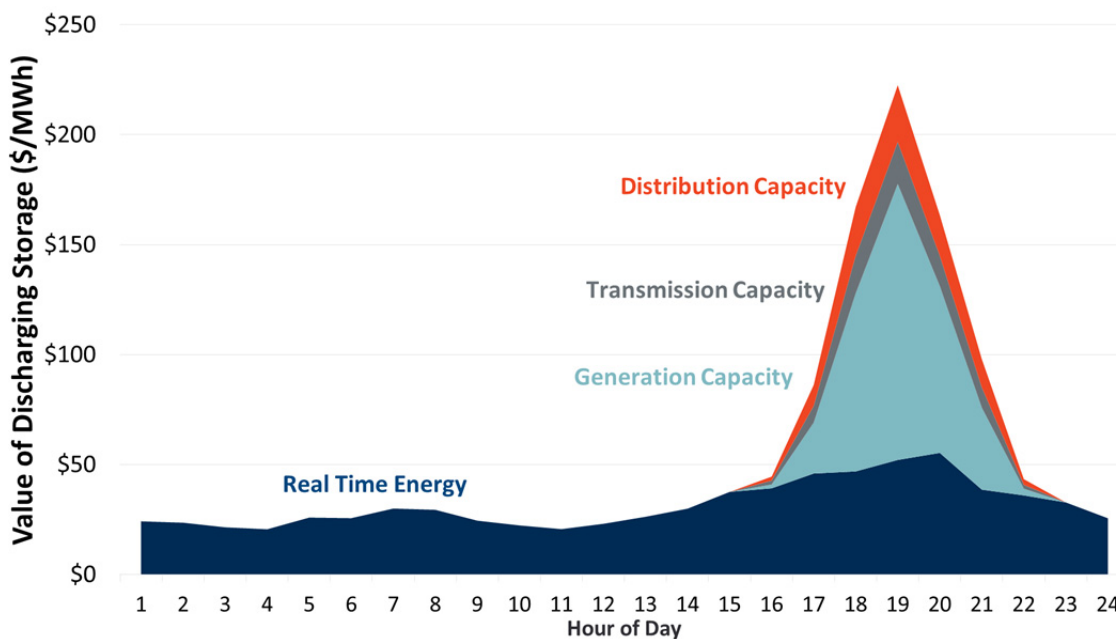
Notes: Marginal costs are shown for San Diego. Avoidable distribution costs will be significantly higher in areas of the network with localized constraints and on specific days with peak capacity needs. On days without peak capacity constraints, there is no allocation of capacity value.

While Figure 5 above illustrates average hourly value across all days of the year in 2016, the capacity costs are in fact assumed to be concentrated in just the top 100 load hours of the year (as described earlier). Figure 6 below shows this hourly allocation for a single week in August 2016. The lack of perfect coincidence between the generation peak and the T&D peak is highlighted by

the fact that some hours include only generation capacity costs while other have only T&D capacity costs.

Figure 6: Chronological Illustration of Marginal Cost Allocation (Week of August 15, 2016)
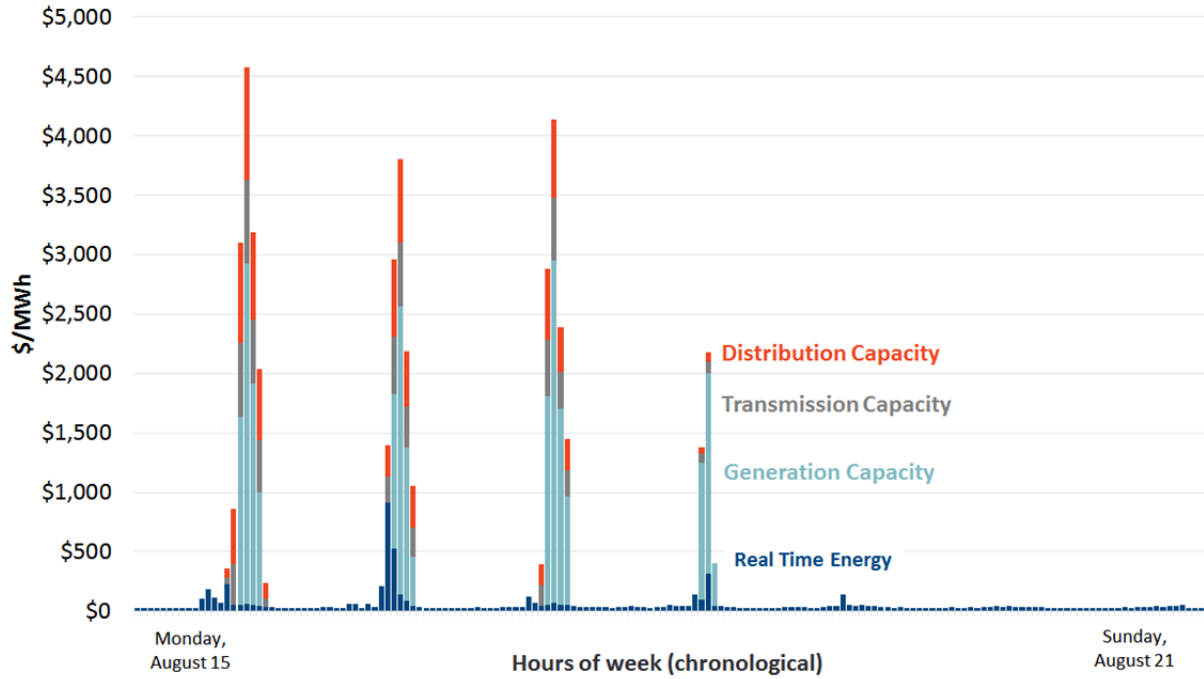
Notes: Marginal costs are shown for San Diego.

III. Key Findings

BASE CASE

Under the "Limited Foresight" case, which accounts for constraints around the battery operator's ability to predict prices, the total value of the battery to the power system is **$283/kW-year**. This estimate comprehensively includes all "stacked" value streams that could be simultaneously pursued through the battery's dispatch. To put this value in context, the costs of battery storage were recently reported to be in the range of $200 to $500/kW-year.[27] Battery costs have declined by more than 70% since 2010, and costs are expected to continue to decline in coming years.[28]

The "Perfect Foresight" case represents a theoretical upper-bound, with no limits on the battery operator's ability to optimize the dispatch of the battery against prices. Under this case, the value estimate increases to **$328/kW-year**. There is a difference in value of only 16% between the Limited Foresight and Perfect Foresight cases. This small difference highlights that much of the estimated value is coming from sources that are fairly predictable on a day-ahead basis (such as day-ahead energy prices and some system reliability events) and/or do not require that significant operational tradeoffs be made with other value streams (e.g., frequency regulation).

Most of the quantified value resides in avoided generation capacity costs and frequency regulation, with a fair amount of additional value in energy price arbitrage. Avoided T&D capacity costs are modest relative to these other sources of value. However, it is important to highlight that the avoided T&D capacity costs are averages across the system; there are possibly specific locations on the grid where T&D deferral value would be significantly higher than this (and vice versa).[29]

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[27] Derived from assumptions in the CPUC's resource planning process, which are based on Lazard's Levelized Cost of Storage 2.0 study. Cited estimates are for 4-hour duration batteries, which aligns with the assumptions in our study. Costs will vary depending on technology type and configuration. See CPUC Energy Division, "Preliminary RESOLVE Modeling Results for Integrated Resource Planning at the CPUC," July 19, 2017, page 33. The CPUC presented costs ranging from $2,000/kW to $4,500/kW in 2016, decreasing to $2,000/kW to $3,000/kW by 2030. We levelized the costs over an assumed life of 15 years using a discount rate of 8%.

[28] McKinsey & Company, "Electrifying Insights: How Automakers Can Drive Electrified Vehicle Sales and Profitability," January 2017.

[29] It is also the case that T&D capacity costs will account for a proportionally larger share of the total value when marginal generation capacity costs are assumed to be closer to the lower resource adequacy payments that are being given to existing generators in California.

When quantified in isolation, the individual value streams are significantly lower than the combined estimates of total value. Pursuing resource adequacy value or frequency regulation in isolation, for instance, would only produce around $100/kW-year of benefits with perfect foresight. This contrast highlights the significant potential value in being able to dispatch the battery to capture multiple value streams.

Some sources of value will need to be forgone in order to pursue higher sources of value (e.g., not maximizing energy market value in order to ensure sufficient energy is available to provide capacity value). The individual value streams are not purely additive. However, it is noteworthy that the "stacked" value of energy storage is only 6% less than the sum of the individual value streams.[30] In other words, relatively little value is foregone by pursuing multiple value streams simultaneously.[31]

Given the value in stacking the benefits of battery storage, one might ask why there are not more instances of batteries being used to capture these multiple value streams. Currently, technical barriers pose a constraint. The algorithms and software that are required to manage the battery's operation across multiple markets and price signals need to be developed further in order to capture these benefits. Additionally, in some instances, regulatory and market design barriers prohibit batteries from being used to comprehensively capture this value. Those issues are discussed in Section IV of this report.

Figure 7 summarizes the Base Case battery value estimates.

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[30] These are the results for the San Diego market under the Perfect Foresight case.

[31] It is possible that more detailed modeling of the timing of T&D system peaks could reduce this value, to the extent that those peaks are less coincident with the system peak than we have accounted for in this study. More granular data would be needed to conduct that analysis.

Figure 7: Battery Value for Individual Use Cases and Stacked Benefits
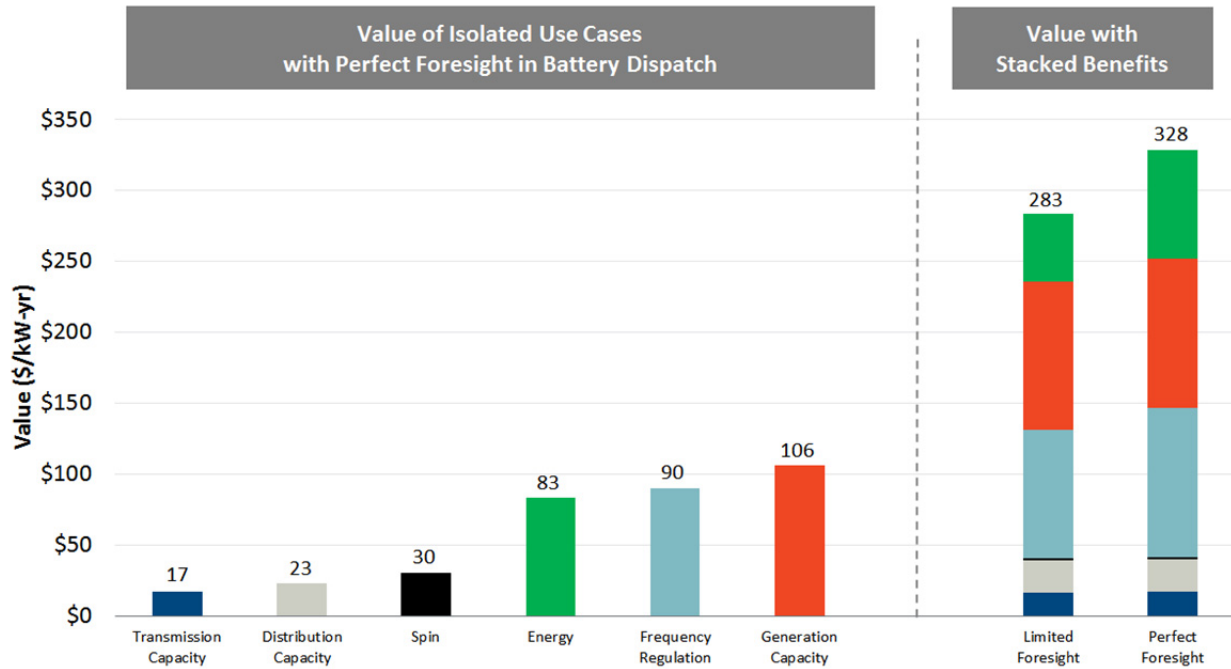
Note: Results shown for San Diego. Value in other California locations is assessed through sensitivity analysis. Energy and ancillary services value is an average across market conditions between 2013 and 2016.

In our simulations, as expected, the battery is generally discharged on the energy market when prices are high (between 4 and 9 pm) and charged when prices are low (mostly midnight to 4 am). Figure 8 illustrates the average dispatch of the battery across hours of the day. Of course, the dispatch pattern could look different that this average profile on any individual day, depending on the prices on that specific day.

Figure 8: Average Battery Operation (Summer 2016)
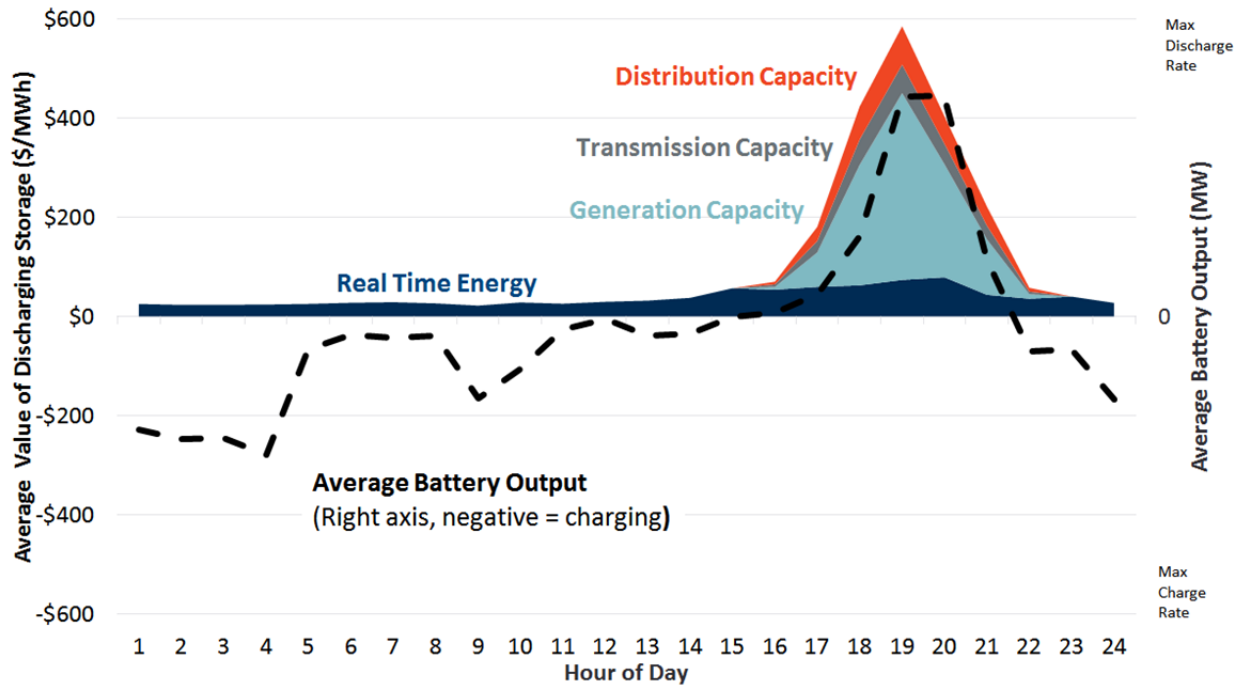
Notes: Results shown for San Diego. For simplicity, the figure only accounts for participation in the DA and RT energy market and does not illustrate provision of regulation or spinning reserves.

SENSITIVITY CASES

Market conditions can vary significantly by location and over time. As discussed in Section II of this report, there is uncertainty associated with some of the assumptions in the analysis. We developed several sensitivity cases to address this uncertainty. Specifically, we tested sensitivity of the value estimates to assumptions regarding (1) marginal generation capacity costs, (2) the historical basis for market prices, (3) the amount of notification provided in advance of a resource adequacy event, (4) the marginal cost of distribution capacity, (5) the need for frequency regulation, and (6) the battery's location within the CAISO transmission system. Each of the sensitivity cases assumes limited foresight (as described above) and co-optimizes the battery's dispatch across all available value streams. Table 1 summarizes the upper- and lower-bound assumptions for each of these sensitivity cases.

Table 1: Description of the Sensitivity Cases

Sensitivity Case	Lower Bound	Upper Bound
Generation capacity cost	RA payment for existing resources ($33/kW-yr)	Base assumption ($113/kW-yr)
Years	Lowest value from model runs for individual years	Highest value from model runs for individual years
Event notification	1 hour notification of resource adequacy event	Base assumption (24 hour notification)
Distribution capacity cost	$0/kW-yr	$57/kW-yr (highest value from range of values in CPUC marginal cost calculator)
Frequency regulation	No market opportunity to provide frequency regulation	Base assumption (full market access without price impact)
Location	Lowest average annual value from studied locations (NP15)	Highest average annual value from studied locations (SDG&E)

Notes: Assumptions that vary by location include power prices and the distribution of capacity events

The battery's value is highly sensitive to the marginal price of generation capacity. In the longer term, or in locations where there is a need for new peaking capacity, the battery's capacity value is significant (as illustrated in the Base Case). Alternatively, if the need for new generation capacity is considered to be smaller than the Base Case estimate – a near-term view shared by many in the California market – then the total value of the battery could be less than half of the Base Case estimate.

The Base Case value estimate is less sensitive to changes in assumptions other than the value of generation capacity. Variation in value estimates across historical study years is fairly material, highlighting revenue volatility that could be faced by battery owners participating in wholesale markets. Figure 9 summarizes the results of the sensitivity analysis.

Figure 9: Results of the Sensitivity Cases
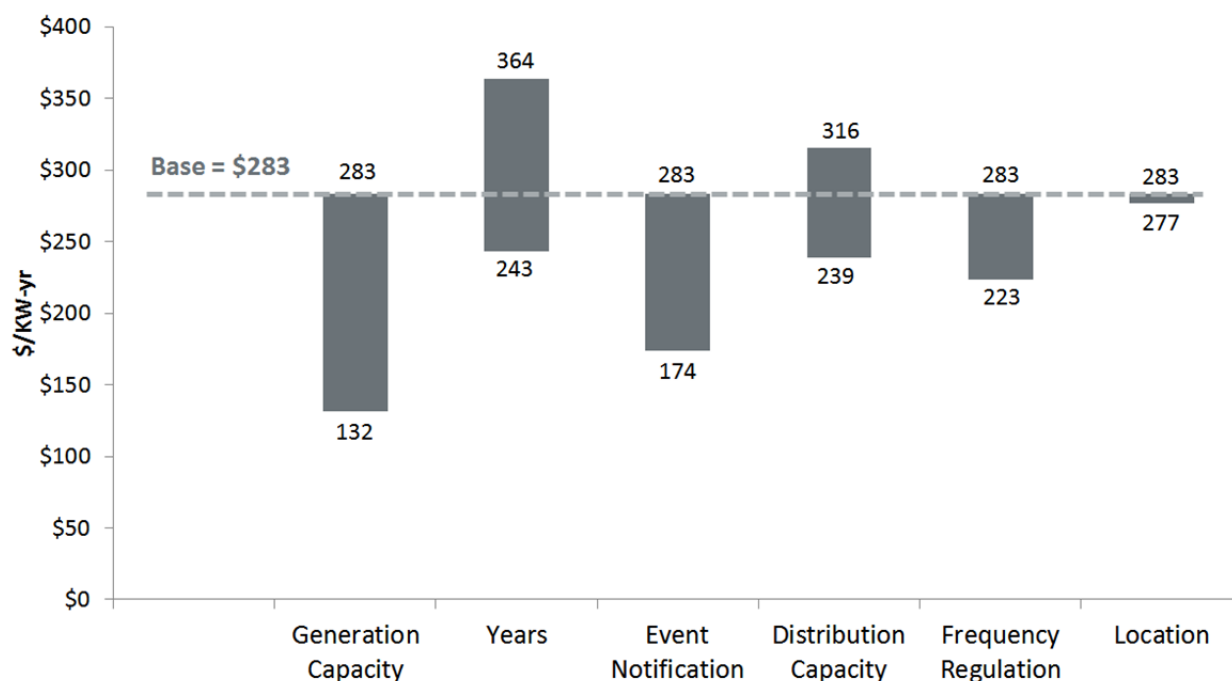
Notes: Average 2013-2016 value for Limited Foresight case in SDG&E location, unless otherwise specified. "Location" sensitivity only includes variation in energy and ancillary service prices; it does not include variation in marginal capacity costs.

While our assessment captures some historical variation in market price drivers such as the power supply mix, fuel prices, and ancillary services and capacity needs, these are factors that could change further in the future. Changes to the price of natural gas in particular can have a significant impact on the energy price arbitrage and ancillary services value of battery storage, since natural gas and renewables are the marginal sources of generation in California. The expected addition of increasing amounts of renewable generation will also have a significant, and likely positive, impact on the value of energy storage.[32] Further assessment of the sensitivity of battery storage value to changes in the price of natural gas and the market share of renewables would be a valuable research activity.

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[32]   For instance, we separately assessed how the energy value of the battery would change if it were being dispatched against projected 2030 hourly day ahead prices in Southern California, assuming the California meets its aggressive renewable portfolio standard (RPS) requirements. As an isolated use case, the energy value of the battery increased by a factor of five.

Over time, a battery's useful energy storage capacity is affected by its operations. Cycling a battery (i.e., charging and discharging) leads to reduction in its storage capability. The extent to which this capacity degradation occurs can vary significantly from one technology to the next. Regardless, due to cycling limitations or other considerations like variable O&M costs, battery operators may wish to restrict dispatch of the battery to its highest-value uses.

We conducted analysis to understand the extent to which the value of battery modeled in this study would be sensitive to cycling restrictions. Specifically, we optimized the battery's operation subject to additional constraints on the number of cycles.[33]

Our analysis suggests that total value is relatively insensitive to restrictions on the number of charging cycles. This is because capacity and ancillary services are the primary drivers of value, and capturing these value streams does not require frequent discharging of significant amounts of energy. Energy price arbitrage, which requires frequent charging and discharging of the battery, is somewhat sensitive to the cycling restriction but only accounts for a modest portion of total value. In fact, a significant fraction of the energy arbitrage value is made up through discharging during infrequent, large price spikes rather than cycling to arbitrage daily price patterns. Figure 10 illustrates the total value as a function of the number of full charging cycles per year.[34]

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[33]   This was effectively modeled by imposing an artificial variable O&M cost. The impact of the variable O&M cost was only reflected in the battery's dispatch; it was not included as a cost when calculating total benefits.

[34]   The number of full charging cycles is calculated as the total MWh of annual discharge divided by the MWh of energy storage capacity.

Figure 10: Total Battery Value vs Number of Full Charging Cycles per Year
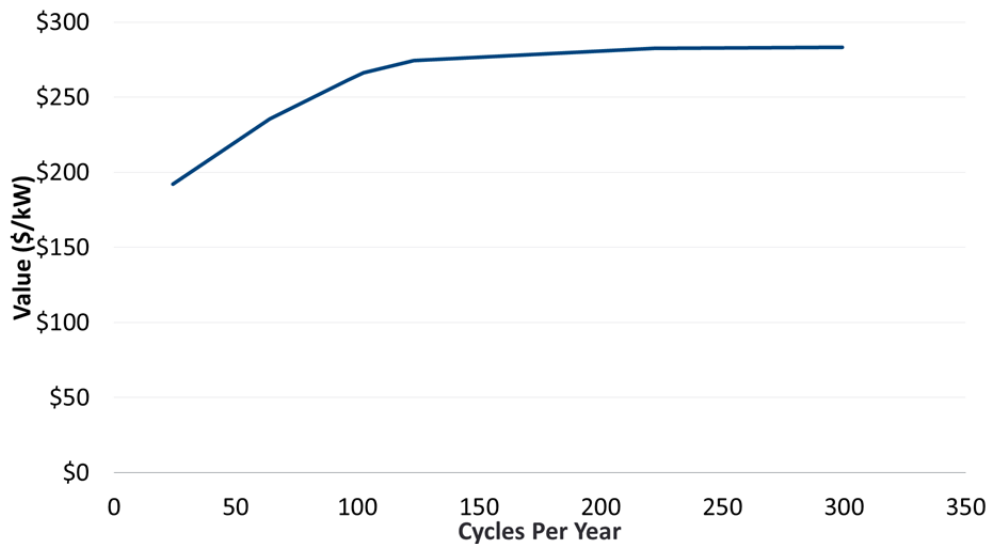
Notes: Cycles per year calculated as MWh of annual discharge divided by MWh of battery capacity. Calculation assumes no cycling for frequency regulation, which is provided every hour.

COMPARISON TO OTHER STUDIES

We reviewed prior studies on the value of energy storage to add context to our findings. Some studies were California-specific while others focused on other regions of the U.S. The studies typically quantify on only a subset of the value streams that are estimated in our analysis. However, it is still possible to benchmark the results of our study by making comparisons specifically for the subset of relevant value streams.

California-specific studies included reports by NREL (2015)[35] and LLNL (2014 and 2017)[36]. For findings from other regions, we relied on a 2015 RMI study[37] which surveyed analyses conducted by seven different organizations.

Figure 11 summarizes how our value estimates compare to the range observed in the other studies. The estimates of comparable value streams in our study are within the range of findings

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[35] Eichman, Josh, et al., "Operational Benefits of Meeting California's Energy Storage Targets," National Renewable Energy Laboratory, December 2015.

[36] Edmunds, Thomas, et al., "The Value of Energy Storage and Demand Response for Renewable Integration in California," Prepared for the California Energy Commission by Lawrence Livermore National Laboratory, June 2013.

[37] Edmunds, Thomas, et al., "The Value of Energy Storage and Demand Response for Renewable Integration in California," Lawrence Livermore National Laboratory, February 2017.

of the prior studies. While this benchmarking exercise helps to put our findings in context, there are limitations on its usefulness due to the wide range of assumptions and modeling approaches that are used across the analyses.

Figure 11: Energy Storage Value Estimates from Recent Studies
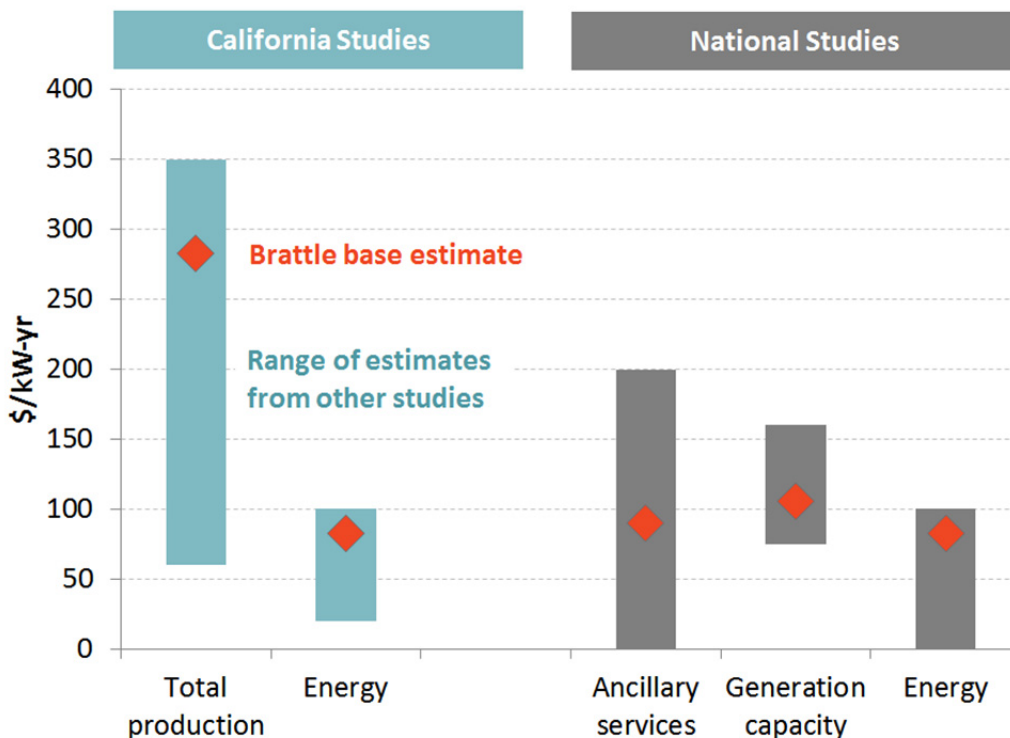
Notes: All values shown are approximate. See bibliography for a complete list of reviewed studies on energy storage value.

SUMMARY

Our analysis suggests that, in many cases, the "stacked" benefits of battery storage compare favorably to recent estimates of new battery costs. This finding is sensitive to the marginal cost of generation capacity but is otherwise robust across the sensitivity cases we analyzed. The quantified benefits appear to be in line with those in other studies. The following is a summary of the important observations from this assessment of the value of battery storage in California:

- Even with limited foresight in LMP forecasting, our Base Case findings suggest that the total value of one kilowatt / four kilowatt-hours of energy storage in California could be around $280/kW-year. By comparison, recent estimates of battery costs have been in the

range of $200 to $500/kW-year (though they vary significantly by technology type and configuration).[38]

- Accounting for the "stacked" benefits of battery storage by optimizing its dispatch across all analyzed value streams significantly increases the total value of the battery relative to any individual value stream (i.e., by a factor of 2x to 3x over the most lucrative individual uses cases).

- Multiple value streams can be captured without significantly sacrificing the benefits of any given individual value stream.

- Improved price forecasting capability (i.e., market foresight) could further increase the estimated value of the battery, but only to a limited degree.

- Avoided generation capacity, frequency regulation, and energy price arbitrage are the largest sources of quantified value. However, the "depth" of each market should be taken into consideration when valuing large quantities of energy storage in a given market. Frequency regulation in particular is a highly valuable service with a very limited need. At the same time, the need for frequency regulation is likely to increase with greater renewable resource deployment. This consideration is particularly relevant in the California market, as the state approaches its 50% renewable energy target.

- Sensitivity cases suggest that uncertainty about the capacity value of storage could significantly impact estimates of total value. In the short run, excess supply means that the capacity value of energy storage in California will be modest unless there are local needs for resource adequacy. In the longer term, as planning reserve margins tighten, system-wide capacity value could approach the levels quantified in this study.

- Aside from sensitivity to generation capacity cost assumptions, the Base Case results are otherwise fairly robust across a range of assumptions about T&D capacity costs, location, and study year, ranging roughly from $200 to $300/kW-year. Total value exceeds $200/kW-year even the case where there is assumed to be no market opportunity to provide frequency regulation.

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[38] Derived from assumptions in the CPUC's resource planning process, which are based on Lazard's Levelized Cost of Storage 2.0 study. See footnote 30 for further discussion.

IV. Policy Considerations

In this study, we have quantified the potential value of battery storage regardless of regulatory, market, or other barriers which may otherwise prevent this potential value from being fully realized. The presence of such barriers can vary dramatically by region of the U.S.

California is broadly considered to be a leader among U.S. markets in facilitating energy storage adoption. Noteworthy energy storage initiatives in California include:

- An aggressive storage procurement mandate for the investor-owned utilities (IOUs);
- The Self Generation Incentive Program (SGIP), which provides incentive payments to behind-the-meter storage;
- Ongoing enhancements to CAISO's energy and ancillary services markets to support the participation of storage;[39]
- CAISO's Energy Storage and Distributed Energy Storage (ESDER) stakeholder group, which works to enhance the market participation of grid-connected storage;
- CAISO's implementation of new wholesale market products that are amenable to storage, such as the flexible ramping product;
- Ongoing CPUC proceedings related to identifying the locational value of distributed energy resources; and
- The CPUC requirement that load serving entities contract for sufficient flexible capacity, which storage is eligible to provide.

While these efforts have aggressively promoted the adoption of energy storage in California, there may be additional opportunities to remove barriers and more fully capture its economic value. A comprehensive barriers assessment was not within the scope of this study and would be a valuable future research activity. However, we have reviewed industry reports and stakeholder comments in recent regulatory proceedings in order to develop a preliminary sense of the challenges to fully capturing the value of distributed energy storage.

BARRIERS

Our literature review identified a few challenges to monetizing the full "stacked" value of battery storage in California.

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[39] CAISO requires distributed resources to be aggregated above a minimum size threshold, and participation eligibility differs between Non-Generator Resource and Proxy Demand Resource participation model.

Capturing energy and ancillary services value

Energy storage currently has the ability to participate in CAISO's energy and ancillary services markets. CAISO has established multiple participation models for storage, to accommodate a variety of physical characteristics and desired participation strategies. For example, the Non-Generator Resource (NGR) model has been established for smaller, energy-constrained resources that are able to provide energy, regulation, and operating reserves. The Proxy Demand Resource (PDR) model is designed for storage resources that exist behind the meter and can provide load curtailment (but not inject power onto the grid).[40]

Stakeholder views on barriers to capturing energy and ancillary services value in California have generally related to the need to clarify and streamline market rules and regulatory processes. Areas in which stakeholders have previously identified a need for clarification include: (1) aggregation requirements for wholesale market participation, (2) limits on net exports of energy from customers to the grid and the regulatory treatment of distributed resources which export energy to the distribution system, and (3) prioritizing dispatch control in cases when the battery is being operated to provide multiple sources of value.[41] The latter point on dispatch control would address confusion around which entity has priority to dispatch a battery when it is utilized for more than one purpose by multiple parties.

Capturing flexibility value

CAISO and the CPUC have recently implemented reforms to enhance incentives for flexible resources. This includes the recent CPUC requirement that utilities procure sufficient flexible capacity, and the addition of a new CAISO flexible ramping ancillary service product. Storage can provide both of those services. However, it is not clear if the current products are sufficient to attract adequate flexibility or if additional market products are needed. An ongoing CAISO stakeholder process is exploring further enhancements to increase system flexibility and enable storage to provide flexible capacity, but no solutions have yet been finalized.

Capturing transmission and distribution value

In California, the IOUs are in the process of developing Distribution Resource Plans (DRPs). These DRPs are intended in part to provide an indication of locations where distributed energy resources, including distributed storage, could be used as a cheaper alternative to distribution system capacity upgrades. Related to this activity, stakeholders are establishing protocols for "locational net benefits assessments," which would lead to a uniform methodology for

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[40]   California ISO, "Response of the California Independent System Operator Corporation to Data Request", FERC Docket No. AD16-20-000, May 16, 2016.

[41]   California ISO, "Draft Energy Storage Roadmap for California," October 8, 2014.

quantifying the benefits of distributed energy resources. While these initiatives are ongoing, they have not yet produced a well-defined and accepted methodology.[42]

Capturing generation capacity value

There is no centralized capacity market in California. That is in contrast to several other organized markets in the U.S., such as ISO New England, the Midwest ISO, the New York ISO, and PJM. In California, capacity resources are procured by utilities through bilateral contracts. Analysts and some stakeholders have indicated that this bilateral process can be a less transparent and more administratively cumbersome approach than working through a wholesale capacity market with well-defined rules and clear outcomes.[43,44] While a centralized capacity market is not necessary for storage to participate in providing resource adequacy, the absence of a capacity market results in the lack of a transparent price signal. This presents a challenge for significant deployment of storage outside of the state's storage procurement process.

Other issues

While California IOUs have a mandate to procure a significant amount of energy storage,[45] it is not entirely clear to what extent the utilities will be able to operate the storage technology to maximize its total potential value. In many regions of the U.S., utilities are not incentivized – and are often even prohibited – from using storage to maximize total system benefits. This restriction is generally due to concerns about regulated monopolies operating assets to compete in unregulated markets. As a result, utilities can be limited to operating the battery only to capture its distribution value, while leaving energy, ancillary services, and resource adequacy value on the table.[46]

ADDRESSING BARRIERS AT THE RETAIL LEVEL

There is a variety of ways in which to address barriers to monetizing the full value of battery storage. Many of the options for addressing the barriers are at the wholesale market level, along the lines of the various ongoing initiatives in California that are described above. Wholesale market barriers are being resolved by CAISO and FERC in concert with other CPUC efforts.

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[42]   Trabish, Herman, "Have California's efforts to value distributed resources hit a roadblock?" Utility Dive, March 21, 2017.

[43]   Pfeifenberger, Johannes, Kathleen Spees, and Sam Newell, "Resource Adequacy in California: Options for Improving Efficiency and Effectiveness," prepared for Calpine by The Brattle Group, October 2012.

[44]   Fitzgerald, Garrett, et al., "The Economics of Battery Storage," Rocky Mountain Institute, 2015.

[45]   See the CPUC's storage mandate docket (R.15-03-011).

[46]   Bade, Gavin, "Who Should Operate the Distribution Grid," Utility Dive, March 19, 2015.

Generally, there has been a heavy focus in California on addressing energy storage participation barriers in wholesale markets.

While we have not quantitatively analyzed the customer-side economics of battery ownership and utilization, there are also clear options for addressing barriers to distributed storage adoption at the retail level. To this end, our scope for this study specifically called for an exploration of opportunities to facilitate storage adoption through retail rate reform. It would be a valuable future research activity to comprehensively evaluate opportunities to address barriers at both the retail and wholesale levels.

Better alignment of the retail rate design with the underlying structure of system costs can incentivize customers to adopt battery storage and use it in a way that produces system benefits.[47] In some instances, current rates have flat volumetric charges that do not vary by time of day, and/or demand charges that do not reflect the full cost of capacity. These rates do not fully convey the underlying costs which could be avoided through optimal utilization of the battery. A more granular, cost-based rate design that accounts for the operational characteristics of battery storage would incentivize customers to operate behind-the-meter battery installations in a way that would increase the overall system value of the battery.

Generally, rates with the following characteristics will most fully capture the benefits associated with the significant operational flexibility of battery storage:

- Significant price granularity and temporal variation
- Strong price signals that fully reflect the time-dependent nature of capacity costs
- High-price events that are limited in duration but still sufficient to capture the drivers of the underlying costs

THE STATE OF RATE DESIGN FOR STORAGE IN CALIFORNIA

In California, there currently are retail rate designs that satisfy the criteria for storage-friendly rates to at least some degree. These rate offerings appear to be more prominent for commercial and industrial (C&I) customers than for residential customers. For instance, most C&I customers have access to a three-part rate with a demand charge (this concept is discussed in further detail below).[48] C&I customers also have access to a rate with hourly variation in the generation

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[47] Of course, with the introduction of any new rate design, it is necessary to consider the rate's broader implications, including distributional effects on customer bills and implications for the utility's ability to fully recover its costs.

[48] See, for instance, SCE's "General Service – Demand" tariff: https://www.sce.com/NR/sc3/tm2/pdf/ce30-12.pdf.

charge.[49]   For these customers, important future rate design considerations from an energy storage standpoint include (1) whether or not the demand charge and time-varying volumetric charges fully reflect marginal (i.e., avoidable) capacity costs, and (2) if time-varying charges can be tied to system costs in a more dynamic manner, as opposed to a pre-published hourly price schedule.

Storage-friendly rates for residential customers in California also exist to a certain degree, though the options are more limited. All residential customers have access to a static time-of-use rate, with higher prices during peak hours of each day and discounted prices during all other hours.[50] Depending on their utility, residential customers also typically have access to either a critical peak pricing (CPP) rate[51], which provides the higher peak period price signal on a day-ahead basis during a limited number of events per year, or a peak time rebate (PTR) which provides payments for peak load reductions below an estimated baseline level of "normal" energy consumption[52]. Further price granularity in these rate offerings could enhance the incentive for behind-the-meter storage to provide system value.

Regulatory proceedings are underway in California to develop optional tariffs that are specifically designed for customers with distributed energy resources such as rooftop solar PV, energy storage, or smart appliances.[53] The overarching objective of this initiative will be to move beyond the current rate offerings and provide rate options with enhanced price granularity and cost-reflectivity. Along these lines, we have identified two rate design innovations that could provide particularly significant opportunities for monetizing the value of behind-the-meter energy storage. Those options are a "three-part rate" and a "smart home/business rate".

TWO NEW RATE DESIGNS FOR CAPTURING STORAGE VALUE

Three-part rate

Three-part rates consist of three charges, each of which is designed to recover different types of costs. A demand charge ($/kW) would recover the utility's distribution capacity costs, and

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[49]   See, for instance, SCE's "Real Time Pricing" rate schedule for Small General Service customers: https://www.sce.com/NR/sc3/tm2/pdf/CE330.pdf.

[50]   Further, static TOU rates are expected to become the default residential rate offering in 2019.

[51]   See, for instance, PG&E's SmartRate: https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/smart-rate-add-on/smart-rate-add-on.page.

[52]   See, for instance, SCE's Domestic Summer Discount Plan: https://www.sce.com/NR/sc3/tm2/pdf/ce342.pdf.

[53]   Jeff St. John, "California Solar Industry and Utilities Unveil Dueling Solar-Storage Tariffs," Greentech Media, March 17, 2017.

possibly also some portion of transmission and generation capacity costs.[54]   A time-varying volumetric charge ($/kWh) would recover energy costs. The peak period of the energy charge could also recover some portion of generation capacity costs, if those are not already being recovered through the demand charge. A fixed charge would recover fixed customer costs, such as metering and billing.

Demand charges provide a strong, cost-based price signal for recovering capacity costs. Further, the short duration of the demand charge measurement (typically anywhere from 15- to 60-minutes) makes it avoidable through the dispatch of many configurations of battery storage. The addition of a time-varying volumetric charge further enhances the actionable price signal in a three-part rate.

In California, the introduction of three-part rates would be an opportunity particularly for residential customers with storage. Three-part rates are already offered on an optional basis to small commercial and industrial customers and appear to be a standard feature of rates for larger customers. However, three-part rates are not currently offered to the residential class. The California utilities have proposed the introduction of residential demand charges in prior rate cases, but those proposals have not been adopted due to stakeholder opposition.

Demand charge avoidance has become a viable business model for energy storage companies, including developers of both battery storage and thermal energy storage technology. The Energy Storage Association, for instance, highlights the opportunities in demand charge avoidance on its website.[55]   Many storage developers advertise the opportunities presented by demand charges. Recent research has quantified the opportunity that demand charges can present for customers with behind-the-meter storage.[56]

Smart home/business rate

A smart home/business rate is a form of real-time pricing in which all energy and capacity costs vary on an hourly or even sub-hourly basis. Energy costs are recovered through an hourly price tied directly to the wholesale energy market (or to the marginal cost of energy where there is no wholesale market). Capacity costs are allocated to hours of the year proportional to the risk that each hour presents in terms of reliability and capacity shortages.

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[54] For further discussion, see Hledik, Ryan, "Rediscovering Residential Demand Charges," *The Electricity Journal*, August/September 2014.

[55] Energy Storage Association Website (accessed June 2017): http://energystorage.org/energy-storage/case-studies/peak-shaving-and-demand-charge-avoidance-prudent-energy-vanadium-redox.

[56] Hledik, Ryan and Gus Greenstein, "The Distributional Impacts of Residential Demand Charges," *The Electricity Journal*, 2016.

If sufficient information, infrastructure, and capabilities are available, the prices in a smart home/business rate may also vary geographically to reflect local system constraints. While geographic price variation is not currently implemented at the retail level, there has been emerging interest among some industry stakeholders in extending the wholesale market concept of locational marginal pricing (LMPs) down to the distribution network. Whether this can be practically implemented remains to be seen.

Rates with hourly energy price variation are commonly available for commercial & industrial customers. However, it is typically only the energy price that varies by hour in these rates. In California, hourly energy pricing is offered as an option to even the smallest commercial customers, though the prices are based on a predetermined, published rate schedule rather than being based on real-time market fluctuations. Residential customers generally do not have access to hourly or sub-hourly pricing, but there is emerging interest in the concept of an optional smart home rate for customers with various home energy management technologies.[57]

What makes smart home/business rate offerings distinct from prior rate offerings is the hourly allocation of capacity costs across hours. This is a new concept that is largely untested but is expected to begin to receive consideration in pricing pilots over the next couple of years.[58] The hourly variation in capacity costs creates opportunities for the battery operator not only to capture fluctuations in energy value, but to provide resource adequacy in a price-based manner that is tied directly to the underlying drivers of capacity needs.

Important rate design considerations

The overarching goal of rate design is to develop rates that are cost-based. While tradeoffs must always be made in rate design, rates should not be created with the sole objective of creating financial opportunities for any individual technology (including storage) if doing so means dramatically departing from the principle of cost-causation. If there is a policy objective of subsidizing certain emerging technologies, it is most economically efficient to do that outside of the rate design, such as through rebates or other incentives.

If carefully designed, the two rate options discussed in this report can be developed in a manner that satisfies the objective of cost causation while still providing price signals that are tailored to the specific operating characteristics of energy storage technologies. Important challenges to be overcome when developing these rates include:

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[57] See, for instance, Devi Glick, Matt Lehrman, and Owen Smith, "Rate Design for the Distribution Edge," Rocky Mountain Institute report, August 2014.

[58] For instance, this concept is being explored by at least one utility in New York.

- Aligning the avoidable charges in the new rate (e.g., the demand charge) with marginal costs. This ensures that avoidance of the charges through dispatch of the battery is accompanied by a commensurate reduction in the utility's long-run costs.

- Addressing the location-specific nature of transmission and distribution capacity costs. To closely align price signals with the marginal cost of transmission and/or distribution capacity, it would be necessary to introduce price variation on a geographic basis within a utility's system. It will be important to consider whether that can be practically achieved through rate design, or if it is better achieved through geographically-targeted incentive-based demand response programs in which distributed storage could participate.

- Providing rate-based incentives to capture multiple storage value streams while limiting the complexity of the rate design to a level that is acceptable to customers. Due to complexity, ancillary services and day-ahead / real-time price arbitrage opportunities would likely need to be addressed at the retail level outside of the rate design, through a separate program with an aggregator or utility.

CONCLUSION

Operating batteries to capture "stacked" benefits could unlock significantly more value than using batteries to pursue individual value streams in isolation. This finding is fairly robust across a range of sensitivity cases conducted in this study.

However, challenges to fully capturing the value in stacked benefits remain. Some of the barriers are technical in nature, and may be overcome as new battery management algorithms and software are developed. Other barriers may be overcome through new policy initiatives. Offering new or revised rate designs which more fully reflect the time-varying nature of the cost of generating and delivering electricity is one of many possibilities. Costs of energy storage are expected to continue to decline, and market adoption is likely to increase as a result. In this scenario, considerations at both the retail and wholesale level will play an increasingly important role in the formation of energy storage policy initiatives.

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