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Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications

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Abstract

Purpose of Review The need for energy storage in the electrical grid has grown in recent years in response to a reduced reliance on fossil fuel baseload power, added intermittent renewable investment, and expanded adoption of distributed energy resources. While the methods and models for valuing storage use cases have advanced significantly in recent years, the value of enhanced resilience remains an open research question.

Recent Findings The findings of the recent research indicate that energy storage provides significant value to the grid, with median benefit values for specific use cases ranging from under $10/kW-year for voltage support to roughly $100/kW-year for capacity and frequency regulation services. While the value of lost load is used widely to estimate the benefits of mitigating short-duration outages, reaching as high as $719/kilowatt-year, there is no consensus when it comes to monetizing the value of improving grid resilience.

Summary This paper presents a use case taxonomy for energy storage and uses the taxonomy to conduct a meta-analysis of an extensive set of energy storage valuation studies. It reviews several approaches for monetizing reliability and resiliency services and presents a proposed approach for valuing resiliency for energy storage investments.

Keywords Energy storage · Energy economics · Storage valuation

Introduction

Across the USA, utilities, public utility commissions, and legislatures continue to adopt policies to address the needs of a rapidly evolving electrical power grid. Renewable portfolio standards have been established in 29 states plus the District of Columbia and a small number of states (e.g., California, Oregon) have established energy storage targets or mandates. California adopted the first energy storage mandate in the USA when, in 2013, the California Public Utilities Commission set an energy storage procurement target of 1.325 GW by 2020. Since then, energy storage targets, mandates, and goals have been established in Massachusetts, Nevada, New Jersey, New York, Oregon, and Virginia [1].

While the need for storage continues to grow in response to our reduced reliance on fossil fuel–based baseload power, added renewable investments, which are intermittent, and expanded adoption of distributed energy resources, industry stakeholders struggle to understand the full range of use cases and the evolving costs of energy storage resources. In the absence of clear understanding of energy storage use case values and cost drivers, financial returns on storage projects often fail to meet industry expectations. While the methods and models for valuing storage use cases have advanced significantly in recent years, a very important benefit remains elusive: resilience.

This report first references a use case valuation taxonomy and then outlines recent results from several energy storage valuation studies. It reviews several recent studies that assign value to use cases that are designed to address reliability or resilience considerations but fail to fully address the benefits of resilience. Finally, it reviews current approaches for monetizing resilience and presents the foundation of a proposed resilience valuation approach.

This article is part of the Topical Collection on *Energy Storage*

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For this paper, reliability costs are defined as those experienced by customers due to more frequent, shorter-duration (<24 h) outages. Resiliency questions are those tied to hardening the grid in a manner that will reduce the probability of less frequent, longer-duration (>24 h) outages. These long-duration outages occur due to more catastrophic events, such as wildfires in California or hurricanes in Louisiana or Florida. In addition to customer interruption costs, these events can have societal costs associated with injury, property damage, and perhaps loss of life that would not typically be a factor in the short-term reliability events.

Energy Storage Benefits

Energy storage is a unique asset capable of providing tremendous value and flexibility to the electrical grid. Battery energy storage systems (BESSs) can be used to provide services at the bulk energy or transmission levels while simultaneously providing localized benefits unattainable for traditional generation capacity; capacity that is larger and therefore not as scalable, not as flexible or responsive as energy storage, and incapable of being deployed down in the distribution system near load pockets. The technology has the potential to be integrated at multiple levels of the grid from small, behind-the-meter (BTM) applications up to the transmission-level with various power and energy capacities. The power capacity of other forms of energy storage, such as pumped-storage hydro (PSH), can exceed 1 gigawatt (GW). Each of these technologies offers a range of benefits that together can bring balance and resiliency to the grid.

Balducci et al. (2018) presented a taxonomy of services for energy storage valuation that were stratified according to five major categories: bulk energy-based, ancillary-based, transmission-based, distribution-based, and customer-based services [2••]. The taxonomy presented in [2••] was built on a foundation established in [3•]. Energy storage systems (ESSs) deployed at different levels of the electrical grid serve different functions. For example, a BESS located at a distribution substation may offer both ancillary-based and distribution-based benefits. A key component to proper valuation is knowing that benefit streams are often subject to constraints such as market area, ownership, and technical capabilities and limitations of the storage system. In order to effectively stack values, it is essential to factor in co-optimization of services when conducting valuation. There is multidimensional competition for energy stored within the ESS. If the ESS provides a service in one time period, less energy is available in the next. Also, an ESS cannot meet the requirements of all services simultaneously.

Figure 1 presents the findings of several recent energy storage valuation studies. The results in Fig. 1 were initially derived first through [2••] but expanded with additional literature reviewed for this article. Results are presented in terms of \$/kilowatt (kW)-year, which is a metric tied to the power capacity of the ESS. Thus, a 1 megawatt (MW)/4 megawatt-hour (MWh) BESS that generates \$10,000 annually in arbitrage revenue would yield a \$10/kW-year value. Value, as reported in the literature, can be tied to compensation earned through participation in Independent System Operator (ISO), Regional Transmission Organization (RTO), or other energy markets. Alternatively, they can be tied to bilateral contacts or through avoided cost measures. Note also that the box and whisker plots identify the 25 percentile, 75 percentile, maximum, and minimum values.

Value by Use Case

Balducci et al.'s work [2••], which forms the basis of the literature review that has been updated for this paper, provides documentation of numerous energy storage valuation studies and their results. Updates to this dataset include research published in 2018–2020 and studies focused on storage technologies other than BESSs, including PSH.

Updates to the dataset include the following analyses: modular PSH for Shell Energy North America across multiple locations [4•], four utility-scale batteries in the Pacific Northwest [5–7], and additional battery analyses conducted by various research teams within the California Independent System Operator (CAISO) area and the Independent System Operator – New England (ISONE) area [8–12].

A few key takeaways can be established from these updated values:

- Almost all values fall under \$400/kW-year and a majority are under \$200/kW-year. Outliers do exist. For example, a battery system deployed in the Pacific Northwest by Avista measured an outage mitigation value of \$719/kW-year due to a large industrial customer that faced costly power outages caused by voltage sags [6]. The median value for this use case was measured at \$71/kW-year.
- While some values are more prevalent across projects and the literature (e.g., regulation, arbitrage, capacity), others are not as common or very rare with just one or two datapoints (e.g., voltage support, black start, and frequency response). Limited insight can be gained from these examples until more datapoints are acquired.
- The range of \$/kW-year within each use case can vary widely. Regulation, for example, has some of the highest and the lowest \$/kW-year values in the dataset.
- Arbitrage, which is a use case often attributed to energy storage, has been well-researched with estimates registering at a low medium value of only \$32/kW-year.
- Use cases with a localized focus such as outage mitigation, distribution, or transmission deferral yield values that vary

Fig. 1 Findings of research into the value of energy storage

significantly between projects, with a small number of projects generating very large values.

Overall, the data presented in Fig. 1 provides values generated by use case as estimated for ESSs throughout the USA, and identifies which values have shown the greatest benefit. While outage mitigation addresses a reliability question and other benefit streams, including distribution deferral, it can be tied to projects designed to enhance grid resilience. The value of enhanced resilience remains an open research question which, if solved, would greatly enhance the economic attractiveness of energy storage.

Efforts to Monetize Reliability and Resiliency

Energy storage valuation studies walk cautiously around questions relating to the costs associated with power disruptions. They tend to focus more, if not entirely, on reliability questions rather than addressing the value of resiliency.

There are a number of techniques used to monetize the value of power reliability and grid resilience, all with various benefits and drawbacks. This section summarizes several of the most common approaches and presents the results of several studies using these techniques.

Customer Damage Functions and Value of Lost Load

The most common method for estimating interruption costs is the customer damage function (CDF), which establishes a relationship between costs to a customer and interruption duration. Every study yielding a power reliability value presented in Fig. 1 relied on the CDF as expressed in terms of value of lost load (VOLL).

In [6], the BESS demonstrated the capabilities to effectively operate in an islanded model for the customers in the downtown area of Glacier, Washington. This operation results in benefits accruing to Puget Sound Energy customers located in the islanded area, and were monetized in terms of VOLL.

Using historic outage data, the research team constructed a statistically average outage year. Outages were then randomly selected and scaled to reach the average outage duration for the year. The outages were then built into an optimization tool, assuming no event foreknowledge, and the energy on-hand at the moment each outage struck was then used to mitigate the outage. The with and without BESS conditions were then compared to determine the change in the number of outages and outage duration. The savings to customers were estimated at $310,000 or $310/kW-year for the 1 MW/2.2 MWh Glacier BESS. The basis of the estimated VOLL was the interruption cost estimates presented in [13••].

The economic benefits of a combustion turbine generator (CTG) with a temperature-dependent maximum capacity of 16 MW and a 6 MW/48 MWh Tesla lithium-ion BESS deployed on Nantucket Island, Massachusetts, were provided in [14•]. The study evaluated 704 outages that occurred over 11 years. The Nantucket Island analysis was more comprehensive than [6] because the research team had developed a distribution system model for the island in GridLAB-D and OpenDSS. Furthermore, any outages listed as secondary/service, transformer, or fused branch in the description were eliminated because the BESS + CTG could not address them. The remaining outages were simulated in the distribution system model, and the change in VOLL to customers was estimated based on the with and without BESS + CTG conditions. The model simulated multiple scenarios with and without distribution system investments (i.e., reconductoring and automated feeder switching), yielding $780 thousand to $1.0 million in annual avoided costs [14•].

The Nantucket Island study also illuminated the practice in energy storage valuation assessments where reliability is monetized in an indirect manner, in this case as a transmission deferral benefit. Based on an extensive analysis of load growth on the island, the load will be expected to exceed the capacity of the island grid during certain days in the summer if an N-1 contingency is triggered by the failure of one of the submarine transmission cables connecting the island to mainland Massachusetts. Rather than making an investment in a third transmission cable with a cost that could exceed $200 million, the National Grid elected to invest in the CTG and BESS. Transmission deferral in this case effectively serves as a proxy for reliability, the benefit of which was estimated at nearly $110 million [14•].

Individual CDFs often serve as the basis of monetizing outage mitigation. The Avista Utilities in Washington State deployed a 1 MW/3.2 MWh vanadium flow battery system that was developed by UniEnergy Technologies [6]. Avista's battery system was located on the campus of Schweitzer Engineering Laboratories (SEL), which is powered by two redundant feeders (regular feeder TUR117 and alternate feeder TUR116) from Avista's Turner substation located nearby. The SEL facility contains sensitive manufacturing processes that are prone to power quality disturbances, such as voltage sags.

The research team analyzed voltage sag data from 2014 to 2017 provided by SEL. Applying the Computer Business Equipment Manufacturers Association (CBEMA)–defined power quality curve, over 40 voltage sag events (<70% in voltage magnitude, >20 ms in duration) were identified. The results matched the finding of SEL's power quality monitoring system. SEL indicated that each voltage sag event of sufficient magnitude and duration caused equipment to shut down for a minimum of 3 h at a cost of $150,000 per hour in lost productivity [6]. With an energy storage system on-site, a solution was devised to engage the fast real and reactive power control capability of its power electronic converters to mitigate the voltage sags and avoid interruptions.

By reviewing the BESS inverter reactive current profiles during voltage sag events, it was determined that the response time of a reactive current would be lower than the time criteria (>20 mSec) for defining voltage sag using the CBEMA curve. However, the magnitude of improvement by reactive power would depend on the voltage sensitivity. An additional analysis performed by the Washington State University showed voltage improvement for scenarios where base case voltage (i.e., without reactive power support) did not sag below 95%, which is higher than the voltage sag definition criterion (<70% of nominal voltage).

Overall, due to the extensive down time caused by each outage of a minimum of 3 h, the benefits from voltage sag mitigation are substantial. Over the course of the 20-year battery life, the present value benefit from this use case was estimated at nearly $10 million [6]. It is important to note that the battery system became non-operational and was removed from the facility prior to the end of its promised/anticipated life. Therefore, the results presented in [6] represented the potential benefits that could have been derived had the battery operated as tested and remained in place for its entire usable life.

The CDF method, while perhaps the most direct and extensively applied, does have drawbacks. Residential customers, for example, experience very few direct economic costs associated with short-duration outages, yet might be willing to pay more to avoid the discomfort or uncertainty associated with unplanned service interruptions. These studies often fail to statistically control for cognitive bias in the respondent. CDF or VOLL-based estimates generally do not extend to outages registering longer than 24 h [15••].

Stated Preference Techniques

To address some of the shortcomings associated with CDF studies, contingent value (CV) studies use interview and bidding techniques to elicit a customer's willingness to pay (WTP) to avoid service interruptions. In [15••], a research team defined an approach for estimating the WTP on the part of residential customers to avoid a 24-h outage. The study found that the expressed WTP, presented in terms of cost per kWh, for low amperage backup service was much higher than for full service, and that WTP grew as respondents' knowledge of the outage characteristics and consequences improved [15••].

This technique was employed in a survey of electric service customers in Allegheny County, Pennsylvania. Face-to-face interviews taking 1 h on average were conducted with 73 customers in 2015. The findings of the study indicate that higher priority backup services were more highly valued than lower priority ones ($0.75/kWh vs. $0.51/kWh), and when given more information regarding the ability to provide partial (20 Amps) services, the difference between the two values grew to $1.2/kWh vs. $0.35/kWh [15••].

There are several challenges associated with implementing the CV method, not least of which are several biases that could be introduced during the interview process. Anchoring bias occurs when the value provided by the respondent depends on the first bid presented. Information bias is evident when the information presented by the interviewer influences the response. Hypothetical bias exists if the context is not viewed as realistic by the respondent. The CV method also fails to address broader macroeconomic effects of long-duration outages, and societal or community effects associated with personal injury, loss of life, or property damage. Like the CDF, nearly all CV studies elicit WTP values for outages defined as under one day [15••]. Finally, extending WTP surveys to other regions and customer types can yield implausible results.

Discreet choice experiments (DCEs) are an approach to overcome some of the theoretical problems associated with the CV method. DCEs attempt to elicit more precise estimates of WTP by offering respondents choices between two and more discreet alternatives. The DCE alternatives are varied in a manner that allows researchers to extract information from respondents that leads to an indirect value estimate for resilience [15••].

Macroeconomic Models

To address the broader economic impacts of service disruptions, some studies employ input-output (I-O) and computable general equilibrium (CGE) models. An I-O model captures inter-industry relationships within an economic system in order to determine how an impact on one industry cascades throughout an economy. In addition to direct economic impacts, I-O models also measure indirect and induced effects. Indirect effects include those relating to purchases of goods and services from companies in the supply chain, while induced effects are those tied to household spending of income earned through business operations. CGE models expand on the theoretical underpinnings of I-O analysis by eliminating the fixed-coefficient character of I-O models, enabling sectors and households to respond to relative factor prices. The CGE model is more dynamic than the I-O model and capable of evaluating substitution effects and changes in consumer spending in response to rising prices caused by scarcity.

A simplified CGE model was developed to evaluate the economic impact of a 2-week outage on the San Francisco Bay Area. The study found that in the absence of substitution responses and mitigation efforts tied to investments in backup energy infrastructure, economy-wide net costs reach $1 billion. Substitution responses reduce the impact to $123–$644 million, while investments in backup infrastructure investments further reduce economic costs to $19–$30 million. Note that this estimate excludes the costs to residential customers, which using [13••] would cost nearly $1.5 billion [15••].

While macroeconomic models capture a more complete picture of resiliency, they do not include power flow simulations or model the physical characteristics of an electrical grid. Applying them to specific energy storage investments is very challenging. CGE models are extremely data-intensive and require significant skill and knowledge to build. Finally, these models would not capture any societal or community effects associated with loss of life, injuries, and infrastructure or property damage.

Proposed Framework for Monetizing Resiliency

Weimar et al. (2018) develop a framework for valuing resilience [16••]. In this article, the framework provides a monetary value of resilience focused on electricity and can help provide the financial justification for resilience investment decisions. The probabilistic approach goes beyond the reliability calculation to provide a value for high-impact, low frequency events associated with changing weather patterns, other natural hazards, and human threats.

Resilience can be defined by four R's: resourcefulness, redundancy, robustness, and recovery. Resourcefulness requires the ability to prepare, respond, and manage a disruption. Redundancy provides for backup resources such as energy storage and microgrids. Robustness means the system maintains operations during a long-term outage. Recovery indicates the ability to return to normal operations quickly. Resilient systems prevent or reduce disruption times caused by hazards or threats.

Equation 1 provides a mathematical representation of the approach to calculating value at risk or resilience value. The framework introduces resistance and damage to the standard approach to calculating values at risk where resistance and damage would be standardly called vulnerability. The characteristics of equipment and other assets include the materials, engineering, maintenance level, and climate zone to determine the resistance value for each type of asset. The probability of the failure given those characteristics is damage. The loss is the value of the damage including the VOLL that occurs. Equation 1 provides the mathematical definition of the value at risk. Note in the equation, the hazard is conditioned upon the site; the resistance is conditioned on the hazard; the damage conditioned on the resistance of the assets in question; and the loss is conditioned on the damage to the assets.

$$V = \Pr(H \mid S) * \Pr\left(R \mid \underline{H}\right) * \Pr(D \mid R) * \Pr(L \mid D) \tag{1}$$

where V is the value at risk, Pr is the probability, H is the hazard, S is the site, R is the resistance to indicated hazard, D is the damage that occurs to the asset, and L is the dollar value of the loss that occurs due to damage.

The probabilistic approach requires the ability to collect data on hazards, vulnerabilities (in terms of resistance and damage), and the losses associated with the value of lost load, revenue losses, and asset restoration for energy measures. The framework calculates the probability of the hazard multiplied by the probability of the resistance multiplied by the probability of damage multiplied by the probability of loss values to determine the value of asset damage, repair costs, and restoration time.

Restoration time supplies the basis for lost load time and thus becomes the kilowatt-hour basis for calculating the value of the lost load. Comparison of the baseline resilience value with the resilience value associated with the resilience solution alternatives reveals, by measuring the difference, the resilience value that the alternative provides.

Equation 1 and Fig. 2 simplify the value at risk as there may be many significant hazards and many asset types at risk. Each hazard and asset must be evaluated through an all-hazards approach. Care must be taken to assure independence and interdependence are accounted for in the calculation of the value at risk. Using Puerto Rico as an example, the island faces both hurricane and earthquake hazards. Hurricanes are associated with flooding both from rainfall and from storm surge. Earthquakes and tsunamis can occur together, but earthquakes in one area may cause tsunamis in another. The hurricane and earthquake can be assumed to be independent events. However, hurricane winds and flooding are interdependent. Earthquakes and tsunamis are also interdependent events.

The probabilities of each hazard need to be carefully determined. Thus, hurricane damages are not just the loss of electric poles due to high wind but may also include damage to substations and the conductors as a combination of wind, flooding, and storm surge but the probabilities may differ for a given site. In addition, hazards often damage the assets of an entire site. The cumulative losses associated with each of the assets damaged for all hazards and associated probabilities provide the calculated resilience value. Furthermore, each hazard has different intensities and probabilities for each and will have a different impact on the damage and loss probabilities. Therefore, the value at risk is the sum of the different hazards and hazard intensities, resistance, damage to all assets, and loss probabilities. Furthermore, note that this is a simplified version of the value at risk equation, and each term includes a quantification of its associated probability as well as the cumulative associated outcome. For example, the loss term (L) includes both the cumulative probability of a loss at a given level of damage and the cumulative dollar loss value.

Thus, the damage function provides the cumulative probability of loss to each of the asset types as a combination of the resistance and hazard intensity probabilities. The value at risk is determined by calculating the time and cost of restoring the electricity to accommodate the load. The forecast duration determines the amount of lost load (outage duration) and in turn can be used value the kilowatt-hour (kWh) lost or the value of water forgone as a result of the hazard and vulnerability. The outage time is calculated by determining the amount of time required to restore each component of load.

Conclusions

Today's publications typically discuss various value streams or cost goals and projections of Fig. 1, but the value assessment of avoiding service disruptions and improving grid resilience are commonly excluded. While the value of increased reliability associated with avoiding more frequent, limited-duration outages is well-documented, the value of energy storage to improving grid resilience remains an open research question, which deserves similar definition.

The following are some of the key conclusions found in this analysis:

- Energy storage provides significant value to the grid, with median benefit values by use case ranging from under \$10/kW-year for voltage support to roughly \$100/kW-year for capacity and frequency regulation services.

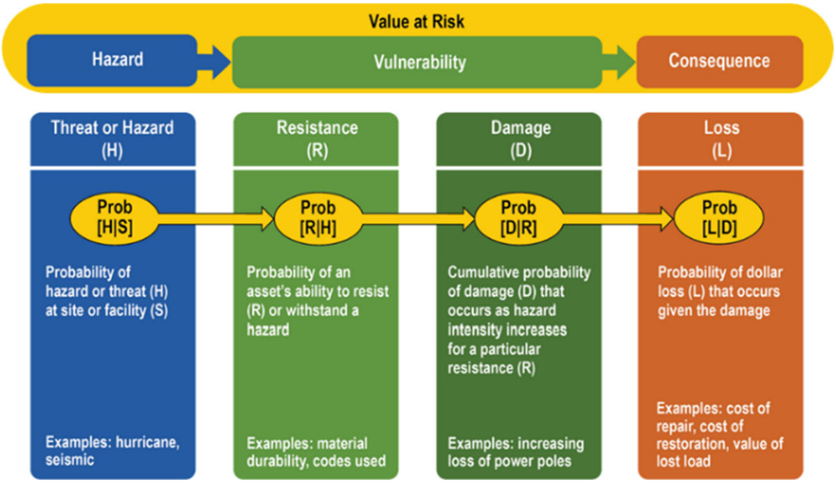

Fig. 2 Pictorial approach to value risk assessment and resilience valuation

- Use cases with a localized focus, such as outage mitigation, distribution, or transmission deferral, yield values that vary significantly across projects, with a small number of projects generating very large values.
- While the value of lost load is used widely to estimate the benefits of mitigating short-duration outages, reaching as high as $719/kW-year, there is no consensus when it comes to monetizing the value of improving grid resilience.

Energy storage is an asset with unique capabilities that make it capable of greatly enhancing grid stability. Inclusion of the values tied to reliability improvements and enhanced resilience will be critical to unlocking the full value of storage and enhancing the ability of developers and utilities to demonstrate positive returns to regulators, third party investors, and other partners.

Declarations

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest Patrick Balducci, Kendall Mongird, and Mark Weimar declare that they have no conflict of interest.

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