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Techno-Economic Review of Battery Energy Storage Systems

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SUMMARY

The viability of battery energy storage systems is steadily improving as technology develops and economies of scale materialize. Evaluating batteries for power systems requires an understanding of the technical benefits of relevant applications and avenues for achieving adequate return on investment.

Energy storage systems (ESS) have made an insurgence into modern power systems, as a rapidly evolving, disruptive technology. Specifically, battery energy storage system (BESS) installations are permeating the transmission system to support large scale renewable generation projects, and home energy storage is reaching into the distribution network. Significant research and financial investments are driving down costs through economies of scale and seek to further solidify the role of energy storage in future power systems.

As batteries and other forms of energy storage begin to pick up a critical mass of viability and installations, care needs to be taken in forming the technical and economic expectations for cohesive integration with existing power systems and energy markets. Many installations are designed for specific applications that are sensitive to changes in their operating environment. Since 2015, PJM has been working to redefine its frequency regulation market after noticing conflicting operation between longer term Area Control Error signals and shorter time frame "RegD" signals sent to energy storage [1]. The resulting market changes implemented by PJM in 2017 have jeopardized the expected payback of energy storage implementations participating in the RegD market [1].

New battery energy storage projects can minimize economic risk by stacking relevant technical applications rather than focusing primarily on a single use case. For each potential application, BESS owners and investors should consider the full range of benefits available, ranging from market participation to alternative solutions. This paper provides a review of common uses for energy storage and different means of realizing financial returns, including participation in available energy markets and incorporation with other projects' technologies. A brief conclusion covers potential areas of further contribution and research.

KEYWORDS

Battery Energy Storage Systems, Non-Wires Alternatives, Energy Markets, Integrating Renewable Energy

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I. TECHNO-ECONOMIC REVIEW

Before considering the financial impacts of BESS in power systems and their corresponding markets, the technical benefits should be evaluated.

A. Review of BESS Applications

An overview of four common BESS applications are reviewed in this section. Spinning reserve and ramp control represent higher power/lower energy applications addressing stable system operation. Load/generation shifting and peak shaving tend to require higher energy density for the purpose of optimizing generation.

Spinning Reserve: Spinning reserve in a power system is the amount of capacity available for rapid response (typically in less than 10 minutes) of the online generation assets [2]. (The moniker "spinning" being derived from the rotating nature of conventional generation that has historically been used to meet the requirements for this type reserve). This system requirement exists to ensure stability in the event of unforeseen frequency deviations, such as those resulting from generator failure contingencies [3]. The ability of BESS to ramp up its power output almost instantaneously relative to conventional generation makes the technology a strong technical contender for supporting spinning reserve. A high power density Lithium-Ion battery can reach 3-4 times its energy capacity. Thus, energy set aside for spinning reserve would be able to last approximately 15-20 minutes, which is longer than the time frame needed to transition non-spinning reserves online.

In large power systems, conventional generation provides a much higher percentage of the spinning reserve requirement compared to BESS [4]. In small or isolated power systems, however, greater opportunity exists for deploying BESS for this application. Isolated grids, especially those in remote regions or islands, exhibit higher operating costs resulting from fuel prices and fewer economies of scale. This has caused a trend in deploying more renewable generation assets to offset such expenses. Renewables inherently lack the ability to provide reserve capacity (assuming the full available power is used to maximize fuel savings), and at high penetrations, energy storage becomes an operational necessity to avoid under loading generator sets. If wind and solar generation levels continue to rise in large grids, such as the mainland United States, BESS offers a promising solution to the spinning reserve problem without requiring conventional assets to run at inefficient loadings.

Ramp Control: Power system ramping refers to the rate of fluctuations in power experienced by the grid. The variable nature of renewable generation, such as wind and solar, can introduce large ramping events whenever the resources change [5]. Sharp declines or rises from load or renewable energy can lead not only to frequency deviations but also damage to equipment. For example, sudden increases in the power pushed onto the grid could cause back feeding that blows out a generator. Such situations have occurred in smaller power systems experimenting with high penetration wind and solar generation. Additionally, frequent oscillations in the effective load as seen by conventional generation can lead to mechanical stress that reduces operating lifetimes.

Energy storage, including batteries, offer a solution to mitigate system ramping issues [5]. Jamaica's major utility provider, Jamaica Public Service Ltd., is currently integrating a 24.5 MW hybrid flywheel-battery energy storage system to solve ramping and spinning reserve challenges introduced by a large wind turbine installation [6]. The fast ramping abilities of BESS (and flywheels) enable power systems to control the effective changes in power experienced by the grid.

Load/Generation Shifting: The goal of load shifting is to optimize the demand shape by leveling the power required throughout the day [7]. By reducing the daily variance in power, more efficient assets (which tend to have the least ability to increase and decrease their output) can be deployed to meet demand [8]. The concept of shifting also can be applied to uncontrollable generation resources like renewables. When a wind or solar plant is over producing (either more than the real-time load or more than economically desirable), the excess energy can be stored and redistributed at a more optimal time.

Energy shifting is accomplished by demand response activity or through energy storage. In order to accomplish this task through BESS, a high energy density is needed. The battery will likely need to absorb and discharge on the order of hours. Depending on the spread between peak demand and low load levels or the amount of over generation, a significant amount of power will conceivably be necessary.

Peak Shaving: Peak shaving seeks similar goals as shifting, although on a shorter time scale than several hours. During peak hours, load introduces congestion and stress on power systems. In turn, many utilities take measures to discourage consumers from using electricity in the form of demand charges [9]. Customers might also be penalized for short demand spikes caused by certain types of equipment (e.g. mining drills, medical scanners). Utilities must have enough power capacity available for these spikes, even though the energy sold is reduced by their brevity.

Introducing BESS can alleviate both customer demand disincentives and the negative impacts of power spikes on the conventional generation portfolio. Deploying battery to discharge whenever the power breaches a specified threshold reduces grid stress and the need for penalizing consumers.

B. Overview of BESS in Power System Markets

Due to the operation limits, namely energy capacity, BESS participation in energy markets tends to play out in day-ahead, real-time, and ancillary markets. BESS interactions with these markets are briefly covered in this section.

Day-ahead/Real-time Markets: Day-ahead and real-time markets are the final stages of the energy balancing markets. Long term contracts provide the foundation for stable pricing of energy supply, but imperfect forecasting results in imbalances in the system. As the demand period nears actualization, these balancing issues formalize and must be resolved. The day-ahead market allows qualified participants to bid/sell according to relevant forecasts. The forward looking contracts established as result are then considered financially binding. In real-time, the market is met at approximately 1-15 minute time scales.

Although structures vary, BESS can realize revenues through energy arbitrage when participating in the day-ahead and real-time markets [10]. Energy arbitrage describes the concept of purchasing power during cheaper periods and reselling it during higher value times. Efficiency becomes a crucial factor in realizing profits in this manner. Low round trip efficiencies and standby losses can hurt the financial feasibility of energy storage seeking profitability through arbitrage. BESS using modern lithium ion batteries and power electronics operate on a conversion efficiency around 80 percent (including auxiliary power consumption) [11]. When assessing the cost-benefit of purchasing, storing, and reselling electricity with BESS, the losses must be considered to reflect an accurate return on investment for participation in day-ahead and real-time markets.

Ancillary Markets: Ancillary markets exist to provide financial compensation for providing necessary grid services not realized by selling energy. This market can generally be broken up into two categories- regulation and reserves. These services help maintain power system reliability and resiliency and can include frequency regulation, reactive power support, spinning reserves, and non-spinning reserves.

Many large scale BESS installations participate in ancillary markets as a result of their inherent technical advantages and constraints. Many ESS contribute to frequency regulation with short time scales, requiring participants to respond almost instantaneously (e.g. PJM's RegD signal used for fast ACE response) [12]. BESS can also compete effectively in reserve markets, since there are no start-up costs (unlike many fast-response generators) and the cost of unused overhead or standby operation is negligible. As exemplified in the introduction, BESS profitability from ancillary service participation is highly sensitive to design, as such markets are highly competitive [1], [12]. Slight changes to ancillary market participation or operating regulations can have a devastating financial impact on ESS projects, as PJM's alterations to RegD requirements in 2017 displayed. Such sensitivities demand both prudent cost-benefit analysis for grid-tied BESS and careful consideration of market design by independent system operators.

C. Overview of BESS in Project Economics

Many BESS installations are coupled into larger projects integrating multiple types of equipment. In such projects, the BESS value is not based on stand-alone operation in an energy market but on how energy storage fulfils desired objectives in concert with other technology (e.g. wind turbines, aggregated demand response, etc.). This section reviews two project types- non-wires alternatives and renewable integration.

Non-wires Alternatives: A growing trend in transmission and distribution system planning is the consideration of non-wires alternatives (NWAs). NWAs seek the use of new technologies and incentives to address problems historically solved by constructing new lines. A planning study of NWAs might include some of the following options: distributed generation, demand response, energy efficiency programs, and ESS. Traditionally resolving congestion issues or meeting large new loads meant building new lines to support the capacity. The advancement of NWAs over recent years has allow for their amalgamation to provide another economically viable option. For example, in 2017

Bonneville Power Authority announced its plans to forgo a new transmission line along I-5 in favor of demand-side resources and batteries [13].

Improvements in battery and converter technology have played a crucial role alongside aggregated demand response to make NWAs a part of a system planner's arsenal. Declining BESS prices enable the technology to be economically deployed at the end of congested lines in order to provide alleviation. Arizona Public Service recently found it cheaper to use a four hour energy capacity BESS for a load shifting application, instead upgrading an existing subtransmission line [14]. Early BESS implementations in NWA solutions, like in Arizona, offer valuable feedback through real system data and provide greater confidence for future projects.

Renewable Integration: Integrating renewable energy in a reliable fashion is a common application for energy storage. As the permeation level of renewable generation increases in the grid, the need for offsetting its inherent variance has grown. As discussed in the application review of ramping, uncontrolled large ramp rates can lead to system stability issues, mechanical stress, and deterioration.

The intermittent nature of resources like wind and solar create a valuable space for BESS to contribute. In small power systems, like islands or remote communities, energy storage becomes an operational necessity with significant renewable installations. Such projects reasonably contain project economics favoring maximum offset of conventional fuel sources (e.g. diesel) through high penetration wind and solar generation. BESS or other energy storage subsequently become a necessity for adequate spinning reserve, ramping control, and frequency regulation. As grid interconnection requirements become more stringent, some form of ESS will likely become coupled to large renewable installations to mitigate any adverse power system impacts.

II. TECHNO-ECONOMIC APPROACH

Capacity sizing represents the major technical hurdle in assessing the financial benefits of BESS. Whether determining potential returns from energy market participation or cost savings in a project, models must consider the power and energy capabilities of the battery. One approach to solving the ESS sizing problem is through analysis of the relevant applications.

A. Application Superposition

The approach suggested can be viewed as a pseudo form of superposition. This "application superposition" takes the applications under consideration and performs a techno-economic assessment on each one. This involves modelling the technical interaction of a BESS for a particular use case to determine the benefit to the power system. Then, the benefit is mapped to economic returns. The process of tying technical benefit to financial return on investment should run through an optimization process to arrive at the ideal energy and power capacity a BESS will need to fulfil a particular application.

Operational versus Optimization Applications: When determining the energy and power requirements for a particular BESS application, the use case should be considered. A use case can be defined as either "operational" or "optimization".

An operational application is one that is necessary for supporting system stability or particular project constraints- it is needed to maintain satisfactory system operation. For example, spinning reserve or ramping control might be classified as operational applications. In an islanded grid with high penetration renewables, a BESS might be required to supply spinning reserve; especially if the system runs without conventional generation for any period of the day. Or, a large wind installation might demand energy storage for smoothing ramp rates to mitigate Area Control Error penalties. In both these situations, the economic value would likely be tied to the monetary returns offered by the renewable energy. Often times deriving the BESS capacity needs for an operational application depends on the technical constraints.

An optimization application obtains its value from the additional benefit it contributes in improving grid performance. Such applications are not required for stability but optimize the power system's operation. An example of use case is load shifting. Enough generation assets exist in a system to meet the expected peak demand for a grid, so redistributing the load from higher to lower power periods (e.g. afternoon to early morning) is not necessary to sustain operation. However, deploying a BESS for a load shifting application might optimize the generation portfolio throughout the day by avoiding costs to start-up and run peaker plants. The amount of energy and power needed to fulfill these types of use cases is determined through cost-benefit optimization.

Coincidental versus Non-coincidental Capacity: After the capacity requirements for each operational and optimization application are determined, the results are aggregated together to arrive at the final BESS sizing. However, a simple summation of the energy and power needed for each use case would likely over-estimate the actual capacity required (hence a pseudo-superposition and not a true superposition). Not all of the applications would be running simultaneously and many could "share" capacity.

Coincidental applications can be defined as the use cases where summing the energy or power requirements would be appropriate. Such applications cannot share BESS capacity simultaneously without negatively impacting the battery's ability to perform as intended. For example, in an islanded grid with high levels of renewable integration, spinning reserve and ramping control would be coincidental energy applications. If a certain amount of energy is set aside for maintaining adequate spinning reserve during diesel-off operation, then ramp rate regulation cannot use that energy without changing the amount of spinning reserve. The energy for one application is not sufficient to meet the energy for both applications.

Non-coincidental applications are those that can share energy or power capacity and still achieve the goals desired for both use cases. Consider again spinning reserve and ramping control in the electrically islanded system described above. In the case of these two applications, spinning reserve could be viewed as special case of ramping control occurring outside normal operation- a large step load change to the system. Typically, the power needed during this special contingency situation is enough to meet the normal ramping control operations. Thus, the required power capacity would simply be the power needed to support spinning reserve.

III. CONCLUSION

Carrying out a full techno-economic assessment of BESS requires a firm understanding of the technical applications and the financial avenues available for achieving a desirable return on investment. As discussed, applications can range from an operational necessity to a grid performance optimization. Understanding which category a particular use case falls into will facilitate cost-benefit calculations. Additionally, the concept of application superposition can be used to assess various applications and arrive at the required BESS capacity for a project. When stacking applications, the level of coincidence must be considered in order to effectively size the battery.

Several options exist for realizing the financial benefits of a BESS installation. These include energy market participation, non-wires alternative projects, and supporting renewable integration. The technical benefits of each application should be modelled and mapped to forecast potential monetary gains. This will allow for determining which BESS applications are worth the fiscal engagement.

As BESS continues to grow in its technical and economic capabilities, the need for quality, applicable research will increase. Clearly defining a methodology to determine the amount of coincidence between multiple applications will be critical in optimizing battery sizes. Opportunities for expanding BESS use cases in larger power systems will also arise as regulators provide definition to battery participation in energy markets. Lastly, methods need to be developed for determining the optimal location of BESS for maximizing market engagement or as part of a non-wires alternative solution.

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