EPRI | ELECTRIC POWER RESEARCH INSTITUTE

UNDERSTANDING USABLE ENERGY IN BATTERY ENERGY STORAGE SYSTEMS



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What's in a Kilowatt-Hour?

Battery storage is a unique electric power system asset with strengths and limitations. These systems offer grid operators flexibility to shift, balance, and smooth power flows in a variety of applications. One notable challenge to planners and operators is how to size energy storage assets with limited energy. Building too much storage can result in poor economics and building too little storage may result in insufficient energy to address the targeted applications. This brief provides various considerations for sizing the energy capacity of energy storage assets.

The energy capacity rating of a battery energy storage system (BESS) indicates the amount of electrical energy that can be stored and provided back to the grid. Many factors affect the energy capacity rating and as the battery is often the most expensive component within a BESS, its sizing can significantly impact the cost-effectiveness of any solution. Even so, the energy storage industry does not yet have a common lexicon for discussing the end use energy capacity of a storage facility.

To align expectations between a seller and a user of energy storage, it's important to have common terms and definitions. However, industry cost reports and vendor specification sheets often lack detailed descriptions of the assumed terms that support the specification. This can be misleading, or at least confusing, when engineering a new BESS or incorporating storage into grid planning. Many application-specific criteria influence the amount of energy delivered to the end use before the battery is fully discharged, such as its age, the power at which it is dispatched, its operating temperature, and auxiliary loads. The real cost and value of a BESS depends heavily on manufacturer specifications, the assumed operating conditions of those specifications, and the methods by which those specifications should be incorporated into performance and financial models.

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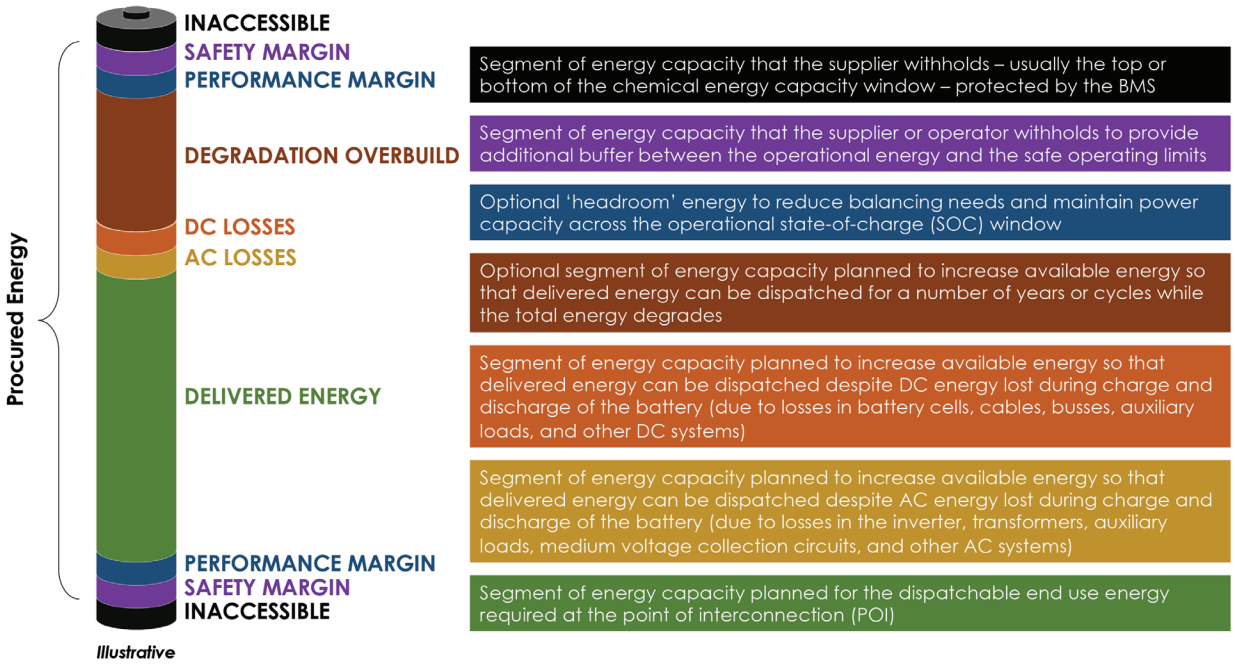

Figure 1: The energy capacity rating of a BESS can be phrased in many ways. The segments identified here capture the major categories to consider when planning BESS procurement and operation.

Segments of Energy Capacity

Many considerations factor into the capabilities of a BESS—and may change over time, with location, and by application, even for the same equipment. While a BESS may be specified as a singular numerical energy capacity rating (usually in kWh or MWh), a portion of that system may not be accessible or contribute to the end use service. To improve understanding of why this can be the case, the following sections define different segments of energy capacity, which may affect the value and appropriate energy capacity sizing of systems.

Inaccessible

Electrochemical battery cells, such as lithium ion, have maximum and minimum voltage levels which may be safely and reliably used. These limits define the highest potential electrochemical energy content inside of a battery. While some batteries can be charged beyond rated voltages, lithium ion, which represents over 90% of current BESS installations announced or under construction[1], can experience either irreversible damage or potentially catastrophic failure if pushed beyond prescribed voltage limits. These segments of energy at the edges of the State of Charge (SOC) window, considered **inaccessible**, are often excluded from a manufacturer specification, but rarely is this made explicit.

Safety Margin

The battery supplier or operator may choose to withhold additional buffer energy beyond what is inaccessible as a conservative factor of safety or to address sensor defects or battery management system (BMS) errors found in similar systems. These regions of energy capacity near the top and bottom of the SOC window—the **safety margin**—can provide an extra layer of protection.

Performance Margin

Performance deratings may result in battery storage due to multiple factors. Lithium ion batteries require reduced charge rates at the top end of the SOC window and reduced discharge rates at the bottom end due to increases in impedance and decreases in available voltage. A performance margin can help avoid these limitations. It can also help to accommodate variations in charging and discharging impedance and temperature that may disproportionately distribute energy across the pack resulting in SOC variations that require balancing.

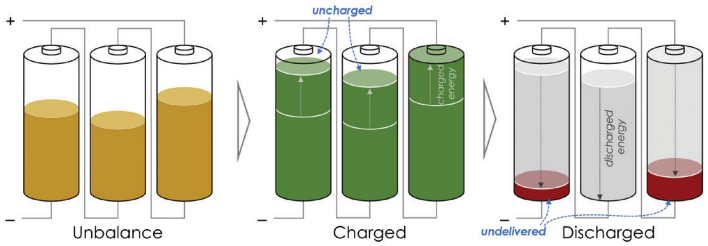

Figure 2: Unbalance between cells or modules or strings can result in reduced deliverable energy capacity if charge and discharge current is distributed evenly across them.

Additionally, mismatch between combined batteries of varying states of health can also result in lost energy capacity. One cell, module, or string may reach an SOC limit before others have, resulting in unobtainable energy until re-balancing has occurred (see Figure 2).

Degradation Overbuild

Lithium ion BESS have shorter lifetimes than conventional utility generation and transmission and distribution assets. Lifetime expectations often range from 10–20 years (as opposed to 30–50 years for conventional equipment). BESS may experience significant degradation and energy capacity loss over time with usage. Some of the most common factors contributing to degradation are:

- Chemistry – a range of cathode, anode, electrolyte, and separator materials are employed in BESS. These different chemistries have different degradation mechanisms and durability.
- Average State of Charge – a system that spends more time at higher or lower SOC may experience accelerated degradation compared to one that rests at intermediate SOC.
- Throughput – total energy charged and discharged from the system, also sometimes referred to as "cycles", contributes to degradation.
- Depth of Discharge – a larger swing in state-of-charge per cycle typically results in faster degradation

[1] Wood Mackenzie; *Global Front-of-Meter Energy Storage Projects*; 10/8/2020

- Temperature – High and low temperatures may increase degradation rates. Temperature variation within battery systems may also cause uneven wear and tear that accelerates system-level performance effects.
- Others – manufacturing defects, environmental anomalies, etc.

The BESS remaining energy capacity over time will depend on the application and should be considered when sizing the system. Degradation characteristics are typically provided by the supplier holding the system warranty and may be backed by extensive testing or operational data developed by the manufacturer.

Developers, end users, and system planners may overbuild energy capacity to make degradation invisible to the end user, enabling delivery of rated performance for longer periods of time. **Degradation overbuild** can be accomplished in different ways:

- Initial overbuild—the addition of new energy during construction.
- Augmentation—the addition of new energy in out-years of the BESS service life.
- A combination of both.
- Acceptance of the degraded performance via progressive de-rating.

Each method has different tradeoffs for the capital and operating expenses of the BESS, as well as its performance. For example, a BESS with large initial overbuild may cost more than augmentation with additional batteries procured in later years. Future cost reductions in batteries and underutilization are weighed against potential upfront policy incentives, such a tax credits applied to initial capital cost, depending on the project. On the other hand, overbuild may result in lower depth of discharge during use, which can reduce degradation rate.

The details of a performance contract also play a strong role in BESS procurement. If contracted energy is constant throughout a BESS lifetime, that may require different energy sizing than if the energy provided by the BESS facility is expected to change throughout that time. The degradation overbuild segment of energy capacity may be utilized in normal BESS operations at any time, though is intended as a buffer between the energy required for the system's end use and a decrease in available total energy capacity in its later years.

DC and AC Losses

Multiple mechanisms induce losses within a battery energy storage system. While some may independently contribute relatively little to the plant capabilities, the aggregate requires accurate representation to ensure the BESS can deliver energy as promised at the point of interconnection (POI).

DC losses result from multiple factors:

- Any DC-powered auxiliary loads such as control and data acquisition devices, lighting, and network switches or routers.
- Internal impedance within the cells from:
  - Thermodynamic effects
  - Changes to kinetic behavior
  - Material loss or degradation of the current collectors
- Impedance within DC circuits between cells, modules, racks and inverters.

Impedance losses generally result in the production of heat and may change with operational conditions, such as usage and environment. For example, lithium ion batteries often temporarily exhibit lower impedance with higher temperatures, but the associated acceleration in degradation results in higher impedance. The increase in impedance leads to a higher voltage drop when discharged and higher voltage increase when charged, reaching voltage limits more quickly and thus reducing useful energy capacity of the battery.

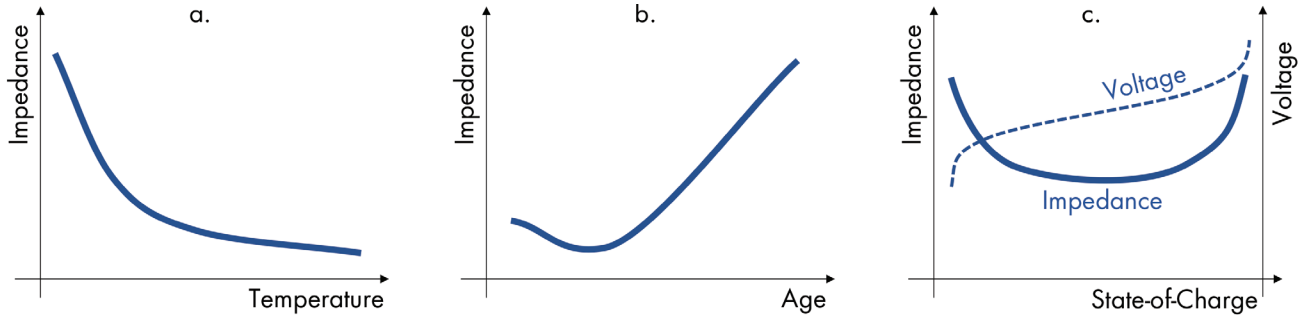

Figure 3: Typical trends of lithium ion battery impedance change as a function of temperature (a) and age (b), as well as voltage as an indicator of impedance (c)

AC losses result from power flow through and auxiliary needs to support low and medium voltage circuits within a plant between inverters and the POI. These include:

- Inverter efficiency losses
- Transformer losses
- Cable and bus impedance
- Switchgear losses

Additionally, auxiliary loads may require moderate consumption from the facility resulting in a net loss. Thermal management of a BESS, which depends on the local climate, operational use case, and the general configuration of the system, may constitute a significant proportion of auxiliary power consumption over the lifetime of a facility. In some cases, auxiliary loads may be accounted separately from efficiency losses if served by an external feed. Combined, these directly inform the total round-trip efficiency of the BESS.

Both DC losses and AC losses are typically proportional to the delivered energy.

Delivered Energy

After dividing up the pie of total energy capacity and handing out the pieces to the thieves of safety, old age, and inefficiency, the slice that remains provides actual value to the end use. The **delivered energy** is the AC energy provided at the POI, which does the work and often represents a meaningful rated energy for the facility. A delivered energy rating may include both the energy expected for use on a regular basis as well as a reserve energy capacity for use in critical events (either for backup power if the BESS supports a microgrid or to supply BESS auxiliary loads during an outage to maintain warranty conditions, or both).

Data-Driven Design

Common understanding of the constituents of BESS energy capacity can level-set expectations and support successful outcomes across the full energy storage project lifecycle. However, several questions remain unanswered, categorically:

- What are the real trends of degradation?
- What energy capacity makes sense for a given use case?
- What warranty terms offer the needed flexibility to adapt to changes in use cases?
- What is the incremental cost of each cycle?

The way in which a BESS will be used directly impacts the rate at which the system degrades and associated energy capacity loss—the duty cycle is an important driver.

Even with a well-defined application, other product-specific considerations influence the system abilities, and the outputs of performance and financial models are only as good as their inputs. Both intrinsic properties and operating conditions determine the amount of energy storage end users should procure and build. Detailed operational data at a string level (module level if possible) from similar systems can serve to verify specifications and further improve the fidelity of design and analysis tools. Recent progress in the EPRI Performance and Reliability Initiative captured these data in several utility energy storage systems (3002019781).

Accurate analysis methods validated with performance data can support robust answers to these questions and improved energy storage system management. These essential tools are needed to inform resource planning, engineering design, cost-benefit analysis, procurement decision-making, characterization during commissioning, reliable operations, and end-of-life decision-making.

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Energy Storage and Distributed Generation

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