HOMER MICROGRID AND HYBRID POWER | 9TH ANNUAL INTERNATIONAL

All things are not equal: energy storage capacity degradation and augmentation

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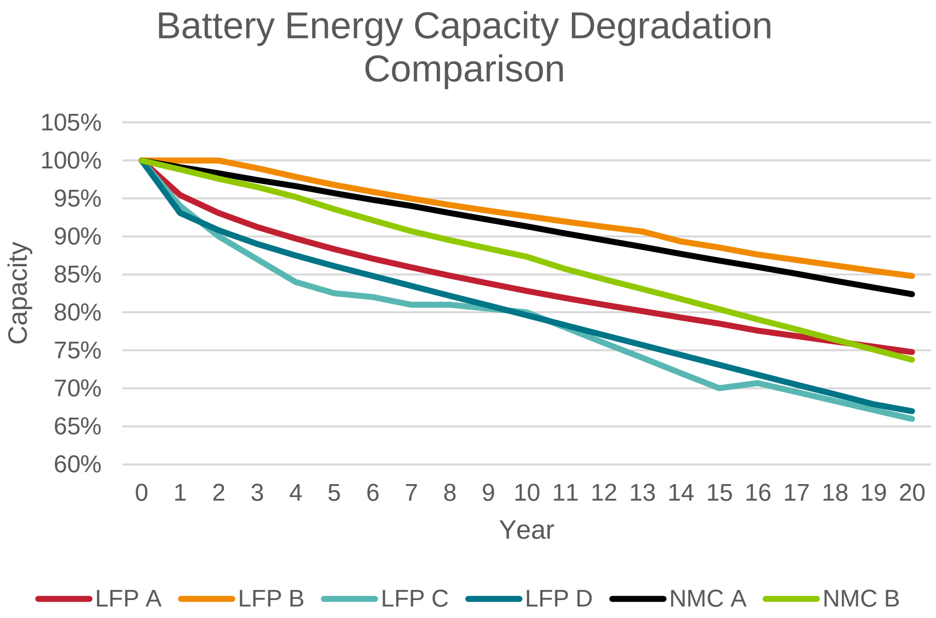
Lithium-ion batteries lose capacity

- Energy capacity inevitably decreases with time and usage
- Every successful project needs an energy capacity degradation plan
- Several approaches for mitigating battery degradation including augmentation
- Augmentation is the process of supplementing Battery Energy Storage System (BESS) capacity — “upsizing” the capacity at the outset, adding battery capacity to the project site to supplement battery capacity losses and integrating new capacity
- Augmentation maintains BESS nominal capacity
- HOMER Front models augmentation as if the whole BESS system were ‘like new’ after the augmentation event



Causes of capacity loss in lithium-ion batteries

Mechanical

- Electrode deterioration or pressure loss within the cell enclosure due to age and cycling

Growth of solid electrolyte interface (SEI)

- Layer of solid electrolyte forms on the negative electrode causing electrolyte loss, reducing free lithium for cycling, and increasing cell impedance
- Usually caused by operating at very low voltages

Lithium plating

- Metallic lithium forms on the surface of the negative electrode instead of passing into it
- Can be caused by high charge rates or below freezing temperatures
- The plated lithium will continue to react and further increase the SEI layer reducing the available lithium and electrolyte
- Plating can also lead to dendrite growth that can puncture the separator and cause a short circuit

Positive electrode decomposition

- An aging mechanism, this occurs when the positive electrode begins to dissolve into the electrolyte
- Can leave metal ions depositing on lithium particles increasing the cells resistance and can travel to the negative electrode and once again add to the SEI layer

Mitigating capacity loss in lithium-ion batteries

Cell design

- Electrolyte additives continuously developed to mitigate chemical causes of battery degradation
- New, advanced electrode materials resist certain failure modes and aging losses

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Battery usage

Battery management system control (BMS)

  - Monitors cell temperature, voltage and current; Enforces manufacturers usage rules to maximize cell performance and life

Energy management system control (EMS)

  - EMS or site controller manages specific operational parameters; Ensure performance to contract and warrantee specs

State of charge (SOC) usage

  - BMS and EMS allow operator to maintain battery system at manufacturer's stated optimal SOC range
  - Most manufacturers allow full use of batteries' SOC range, but each chemistry and manufacturer have "sweet spot"
  - Optimal SOC ranges vary, but most LFP (Lithium Iron Phosphate) and NMC (Nickel Manganese Cobalt) batteries perform best between 0 and 80% SOC

Augmentation

  - No mitigation effort will completely stop lithium batteries from losing capacity
  - Augmentation strategy accounts for future losses, ensures battery meets contract requirements throughout project life

Augmentation strategies

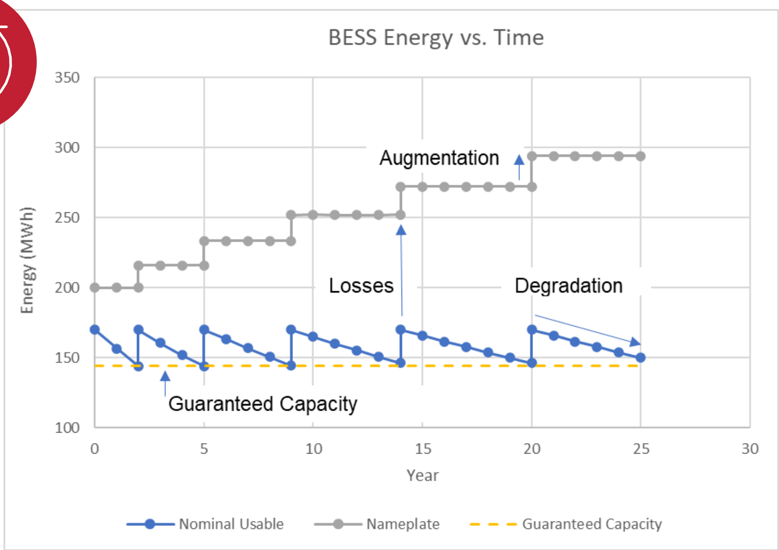
Oversizing
- Install more capacity initially to meet contract capacity at end of life
- Higher initial CAPEX for larger system
- Sizing based on anticipated degradation only does not allow use case changes

Battery replacement
- Remove old batteries, install new ones
- Labor intensive
- New batteries may not be compatible with racking, cabling, and conversion system

Rack-based augmentation
- Adding racks of new batteries alongside old
- Less costly than removing old batteries
- Allows for multiple augmentations (yearly, bi-yearly, etc.)
- Dangerous, new batteries, different internal resistances and voltage profiles

Inverter-based augmentation
- New racks or containers isolated behind own PCS or DC/DC
- Advances in EMS, can install batteries of other chemistries or manufacturers
- Requires advanced planning for additional containers, racks, wiring, etc.

Rack shifting
- Moving modules of same vintage, model, electrical, degradation from one container rack to another with empty racks
- Emptied racks populated, isolated behind own existing PCS or DC/DC
- Requires advanced planning to validate module performance, additional labor, addition of modules, wiring, etc



Original Installation

Hypothetical system of 4 inverter banks, each with 3 battery racks at date of installation.

Battery Rack-Based Augmentation

Under rack-based augmentation, a new battery rack is added at the end of battery banks.

Inverter-Based Augmentation

Under inverter-based augmentation, old racks from Inverter 1 are redistributed to banks behind Inverters 2, 3 & 4. All new racks are in one bank feeding Inverter 1.