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Designing Battery Energy Storage Systems for Reliability

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SUMMARY

This paper outlines a methodology for analyzing the reliability of Battery Energy Storage System (BESS) facilities. The methodology presented is scalable for different BESS facility sizes and architectures. The probability of component failures and the consequence of component failures are used to determine the expected facility capacity within a given period. Application of the methodology to a representative 5MW BESS is described and conclusions regarding the reliability of this representative system design are presented. The impact of BESS capacity fade and battery augmentation on facility reliability are discussed. Finally, a simple metric for evaluating reliability of BESS equipment groups is developed as a BESS reliability optimization tool.

KEYWORDS

Battery, Energy Storage System, ESS, Battery Energy Storage System, BESS, Lithium-ion, Reliability, Monte Carlo, Critical Power, Backup Power, Standby Power, Capacity, Energy, Augmentation, Design

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1.0 INTRODUCTION

The energy storage industry is growing rapidly and the continued large scale deployment of distributed generation will continue to drive this growth. There are several storage technologies that have solid footings in this industry, but lithium-ion battery based storage is the enabling technology behind the current surge in growth. As the energy storage industry matures, the application and use of energy storage systems by utilities and transmission operators is also maturing. Once viewed primarily as generation assets, battery energy storage systems are now being deployed as economical non-wires alternatives (NWAs) for traditional substation and distribution system upgrades, for example. Such traditional upgrades are costly, time intensive, and can be socially and politically challenging to approve, whereas battery energy storage systems can be a less costly and more expedient alternative.

BESSs are typically supplied with guarantees of facility availability, sometimes in the range of 95% to 98% for a typical commercial BESS system. Utilities and project developers combine availability guarantees with equipment warrantees to gain assurance that a given BESS may be relied upon to satisfy common use cases, including peak shaving, energy arbitrage, and wholesale market ancillary services. In general, regularly satisfying these use cases is important to project economics and revenues and these facilities are increasingly being relied upon to harden the reliability of and build resiliency for the connected power system.

Implicit in the selection and implementation of a NWA is the understanding that the reliability of the NWA is comparable to the reliability of the traditional upgrade which is being deferred. Availability of a BESS does not confer certainty that the system will be reliable when it is called upon to act. For example, a BESS availability of 97% equates to a system that is unavailable to operate approximately one day out of every month, which is well below the expected reliability of traditional transmission and distribution equipment.

Improving BESS reliability requires identifying facility components that limit reliability and either replacing those components with more reliable alternatives or changing the facility design to minimize the extent that limiting components detract from facility reliability. This paper makes use of Monte Carlo simulation for analyzing BESS reliability and identifying facility components most limiting to BESS reliability. A study case of a 5MW BESS is presented. The most likely facility output capacity is calculated for a representative facility topology and representative component reliabilities. The time dependency of facility reliability resulting from battery capacity fade is established and a simple metric for identifying reliability-limiting components is presented.

2.0 DESIGN OF A TYPICAL BESS

As described and shown below, a typical BESS is a modular assembly of many similar components configured into similar blocks, with each block consisting of battery modules, battery racks, battery enclosures, power conversion systems, and telecommunications equipment. BESS design and configuration are vendor and application specific, but the hierarchical structure shown below is generally applicable to distribution and transmission scale BESSs.

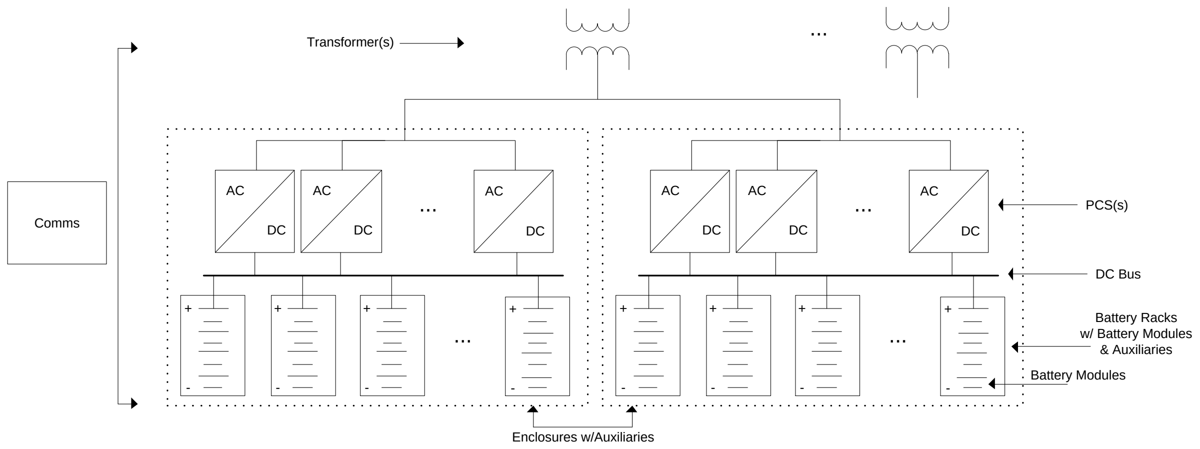

Figure 1. Typical Modular BESS

A typical battery module consists of series and/or parallel connected battery cells, mechanically packaged into rack mount modules with provisions for air or water cooling to maintain cell temperatures within vendor prescribed limits. Battery modules are series connected and physically mounted into racks or strings of batteries for connection to a common DC bus within a battery enclosure. Battery racks include auxiliary components for cooling and switch disconnect devices for connecting or removing the rack from service. A battery enclosure consists of many parallel connected battery racks, a common DC bus for interconnection to a power conversion system (PCS), provisions for controlling and maintaining enclosure temperature, communications equipment for the battery monitoring and control, and assorted system auxiliaries including control power supplies, fire protection, and emergency shutdown controls. DC/DC converters may also be connected between the PCS and battery racks or battery enclosures to match charging or discharging voltages between batteries of different health, age, or other battery-to-battery performance disparities. PCS units usually include AC and DC load disconnects and provisions for AC and DC surge protection and filtering. AC output power from the PCS is transformed via medium voltage transformers that step-up the inverter output voltage to a common facility collector circuit voltage. Medium voltage transformers may be included within a PCS enclosure or may be standalone devices with several PCSs connected to a single transformer pad mounted medium voltage transformer. Multiple medium voltage transformers are typically loop connected into a feeder which is combined with other feeders into a distribution system circuit or facility generator step-up transformer (GSU). Networking switches integrate the monitoring and controls associated with the battery management systems, facility energy management system, and associated PCS communications requirements into a control house for connection to gateways for remote facility monitoring and control.

Typical BESSs are modular and designed by assembling blocks of like equipment into configurations that satisfy project requirements. However, particular design details of components are unique, due to the technological advancements and new vendor entries in an advancing industry. Battery module design varies based on the manufacturer, the type of cell (cylinder, pouch, prismatic), the cell chemistry (LFP, NMC, etc.), and use-case requirements, but battery modules usually have 10-20 battery cells in a single module. Battery racks often consist of 20 or more battery modules, depending on the supplier and the size of the rack assembly. Battery enclosure sizes vary from as small as 10 feet long to as large as 53 feet long and may have as few as two or more than 20 battery racks. Finally, PCS units are also highly variable. A BESS project may use 50 kVA string inverters mounted inside a battery enclosure or a project could be designed to use skid mounted 3 MVA PCSs with three or more battery enclosures connected to each PCS.

3.0 RELIABILITY MODELING OF AN ESS

Reliability analysis is the study and computation of the probability of component or system success. Repairable systems, such as a BESS, typically use availability as a measure of the probability of system success. Availability is generally calculated as the ratio of equipment up-time (mean time to failure, MTTF) to the sum of MTTF and down-time (mean time to repair, or MTTR). Planned and unplanned maintenance, testing, and component failure repair times all contribute to the MTTR [1, 2]. Non-repairable or high safety significance systems use reliability as a measure of success, where reliability is a measure of the probability of success over a time interval of zero to *t*.

Traditional reliability analysis of systems and components uses three different models for approximating component failures: decreasing failure rate, increasing failure rate, or a constant failure rate. Superimposing the three failure rates produces the three well known phases of system reliability: infant mortality, useful / normal life, and wearout.

A decreasing failure rate characterizes devices with service life exceeding the time frame where manufacturing defects or infant mortality cause failures. Infant mortality failures are typically identified and resolved via factory burn-in testing or end to end endurance / commissioning testing of integrated systems of components. An increasing failure rate is used to model consumable components or components with abnormally short lifetimes in comparison to other components of the assembly. Battery capacity degradation/fade is a life-limiting facility design characteristic but is not modeled as an ‘increasing failure rate’ for this work.

Components with a constant failure rate are modeled using an exponential probability density function which uses a constant failure rate. Expressions for the reliability and failure probability of constant failure rate components are derived from [1].

Part or System Failure Rate: λ_p

Component Reliability: $R(t) = e^{(-\lambda p * t)}$ **(1)**

The above equation show that equipment failure rates must be understood to calculate system reliability.

Component Failure Rate Data

BESS components include traditional power components such as transformers, switches, cables and fuses. Comparatively newer equipment types such as batteries, battery packs, and power conversion modules are also included. Component failure rate data for most power components is available from recognized industry handbooks [3, 4, 5, 6] and published literature [7]. Additionally, vendors may provide MTTF values for their equipment, and the failure rate of a component may be calculated as the inverse of MTTF.

Mean Time to Failure, MTTF: $MTTF = 1 / \lambda_p$ **(2)**

Power Conversion System vendors, for example, often provide MTTF for their equipment that is in the vicinity of 70,000 – 175,000 hours.

Examples of component failure rate calculation are common and readily available within existing literature. Failure rates used in this work are identified but a detailed accounting of the selected and calculated failure rates is not provided.

Reliability Networks - Series, Parallel, and K-out-of-N Systems
Reliability modeling starts with converting a physical system into a reliability network model, which requires an understanding of the system operation and determination of the components that, when failed, can degrade or fail the physical system. Three common reliability networks – series, parallel, and K-out-of-N – are discussed below.

A series reliability network is any system in which all components must work for the system to operate; in these, any component that fails will result in the network failing. Assuming independent failure events, the reliability of a series reliability network, R_s, is the product of the series network constituent component reliabilities. Similarly, the failure rate of a series reliability network, R_s, is the sum of the series network constituent component failure rates.

$$R_s = R_A * R_B * \dots R_N \quad \textbf{(3)}$$
$$\lambda_p = \lambda_A + \lambda_B \quad \textbf{(4)}$$

Series reliability networks are common for developing an aggregate reliability of component networks. One example of a series reliability network used in the example that follows is the component vulnerabilities that contribute to a battery enclosure failure. A failure of the enclosure HVAC, auxiliary power, network communication, etc. will disable the entire enclosure from performing its service function.

Parallel reliability network constructs are common for developing aggregate reliabilities of redundant components networks. Assuming independent failure events, the reliability of a parallel network, R_s, improves with the number of parallel components and is represented as follows:

$$R_s(t) = 1 - \prod_{i=1}^{n}[\,1 - R_i(t)\,] \quad \textbf{(5)}$$

There are few true redundant components in a typical BESS and many single component vulnerabilities. Most components that fail have some impact on the facility output and therefore are not truly redundant from a reliability perspective. However, one example of true redundancy often exists in BESS communications equipment. Communications switches and gateways often have high consequence of failure for relatively inexpensive components, so redundancy is a cost-effective method of improving facility reliability.

K-out-of-N reliability network constructs are developed for scenarios where a subset of system components is required to satisfy the system requirements. Energy storage systems are often oversized at beginning of life, and that oversizing has the benefit of providing a measure of partial capacity redundancy. Load can be shared by ‘some of many’ batteries, which is similar to but different than the parallel reliability network construct discussed above. A K-out-of-N reliability network is used for load sharing networks designed with extra elements. For example, if a battery enclosure has five battery racks but only needs four of them to satisfy facility energy requirements, then that system would be referred to as a 4 out of 5 reliability network. Assuming independent failure events, the reliability of a K-out-of-N reliability network, R_s, with component reliabilities of R is equal to:

$$R_s = \sum_{i=k}^{n} \binom{n}{i} R^i (1-R)^{n-i} \quad \textbf{(6)}$$

The K-out-of-N reliability network requires calculating combinations. This is practical for a small number of components, but quickly becomes analytically burdensome with large numbers of combinations. For example, if a system has 100 batteries but only needs 97 of those batteries to satisfy energy requirements, there are more than 150,000 possible combinations of 97 batteries that will satisfy the energy requirements. Computation of these combinations is analytically burdensome and not practical without the use of advanced software tools.

Monte Carlo Analysis of Complicated Reliability Networks
Complex systems consisting of series, parallel, and/or hierarchical networked components with independent failure mechanisms may be analyzed using a Monte Carlo method. This method evaluates component states (i.e., in-service or failed) by comparing the component's reliability, which is the probability that a particular component's failure time is greater than its operating time interval, to a random number between one and zero.

A Monte Carlo reliability analysis can then be combined with consequences of equipment failure to evaluate impact of failures on facility capacity. Consequences of equipment failure in units of facility kW output can be assigned to components, and all failures are summed to calculate the total impact to facility output power based on expected component failures. This process is repeated through many thousands of iterations to develop a set of most likely impacts to facility output based on random component failures. Results are summarized as an aggregate most likely impact or in a histogram presentation of most likely random outcomes. A Monte Carlo analysis technique is well suited for analyzing BESS reliability.

4.0 ANALYSIS OF BESS RELAIBILITY USING MONTE CARLO METHOD

The Monte Carlo analysis method considers the likelihood of failure (reliability) and the consequence of failure to compute the most likely facility output power capacity over different reliability periods. The following process is used to analyze facility reliability:

1. Identify equipment failure consequences for the facility. An equipment failure consequence is the facility degradation in units of kW that occurs when a component fails. Failure of a battery rack, PCS, or a transformer are three equipment failures that have unique consequences to facility output. A detailed system Failure Modes and Effects Analysis (FMEA) may be developed to identify all such failure consequences. Note that many individual components may contribute to one failure consequence. A battery rack failure, for example, may occur due to a failed rack fan, failed battery cell, failed disconnect switch, or failure of other rack components. Piece part and sub-components that contribute to a failure consequence may be modeled as series, parallel, or K-out-of-N reliability networks, as applicable, to develop an overall failure rate for each failure consequence.

2. Develop a reliability network diagram for the facility. The network diagram will have a reliability network block for each possible initiation of a failure consequence identified in (1). For example, if a facility has four medium voltage step up transformers with a defined consequence of failure, then the reliability diagram should include four transformer reliability blocks.
3. Identify failure rates of each component within each reliability network block. As stated previously, failure rates are derived from industry handbooks, vendor data, and published literature. Individual component failure rates that contribute to the reliability block failure rate are aggregated into a single failure rate using the reliability methods identified above (series, parallel, K-out-of-N).
4. Select an appropriate reliability period and calculate the reliability of each network reliability block using Equation (1).
5. Assign a random number between 0 and 1 to each reliability block and compare the random number to the component reliability. If the random number is greater than the reliability, then the component is considered failed, and the failure consequence associated with the reliability network block is subtracted from the maximum facility output.
6. Determine the most likely facility output capacity in consideration of all components that are failed and compare the most likely output capacity to the facility capacity requirements.
7. Repeat steps (5) and (6) for many iterations using a scripting software package (e.g., Python, Matlab, etc.). Plot a histogram of most likely facility output capacity and continue iterating until the distribution of most likely output does not substantially change with additional iterations.
8. Repeat steps (4), (5), (6), and (7) for any additional reliability periods (i.e., 1 hour, 1 day, 1 year, etc.).

The process identified above is demonstrated for a 5MW example BESS in the sections that follow. Although not explicitly identified above, it is noted that understanding the sensitivity of analysis results to analysis inputs is an important part of any analysis. Sensitivity studies of inputs may be performed by parametrically studying failure rates in Step (3) and observing the impact to analysis outputs. This type of sensitivity study will help the BESS designer understand the variability and limitations of the reliability analysis.

5.0 RELIABILITY ANALYSIS OF A REPRESENTATIVE 5 MW / 20 MWH BESS

This section includes a worked example of a 5MW BESS capable of charging or discharging its energy capacity of 20MWH in a four hour period (5MW / 20MWH BESS). The facility is specified in Table 1 with subsequent sections following the process identified above.

The BESS facility has four battery enclosures with 18 battery racks and 15 string inverter type PCSs housed within the battery enclosure. There are two battery containers connected to each medium voltage transformer, and two medium voltage transformers on a single feeder that connect to a distribution level facility POI. The facility has an 8% battery energy overbuild to allow for battery capacity fade. Auxiliary power is supplied to each component via a separate auxiliary power transformer and the facility output is controller limited to a maximum 5MW output.

Equipment ratings and quantities identified in Table 1 are notional and not representative of a particular vendor or manufacturer. Component losses and facility efficiency are omitted for simplicity, but could be considered for a more accurate implementation of this method.

Table 1. Specification of 5MW / 20MWH BESS Facility

Equipment / Facility Ratings			
Facility Power Rating (MW)	5.0	PCS Transformer (kVA)	2750
Facility Energy (MWH)	20	PCS Rating (kVA)	90
Rack Energy (kWH)	300	C Rate	0.25[1]
Facility Design			
Number of Feeders	1	BOL Energy (kWH)	21600
Battery Cells / Module	17	BOL MFO (kW)	5400
Modules / Rack	18	PCS / Enclosure	15
Rack Power (kW)	75	Total Number of PCS	60
Racks / Enclosure	18	Number of Transformers	2
Enclosure Energy (kWH)	5400	Number of Feeders	1
Number of Enclosures	4		

[1] Facility C-Rate is the ratio of the rated facility output power (5MW) and the battery energy capacity (20MWH).

Facility Failure Consequencess (Step 1)
The facility specified in Table 1 has five different failure consequence categories.

The first failure consequence is defined as the failure of a battery rack. A failed battery rack has a consequence of 300 kWH of lost energy which is 75 kW of lost power at a C-Rate of 0.25. Note that this failure consequence is a function of battery capacity and fade, so the consequence of this failure depends on when the failure occurs relative to equipment life. Components that contribute to the failure rate of this failure consequence include battery cells, battery module fans, battery rack fans, battery rack disconnects, and rack level Ethernet communication equipment. Failure of any of these components renders the rack degraded and requires its removal from service. Accordingly, these components are modeled as series reliability networks.

The second failure consequence is defined as the failure of a PCS. A failed PCS has a consequence of 90 kVA of lost power generation. Components that contribute to the PCS failure rate include IGBTs, RLC filter components, AC and DC disconnects, and Ethernet control and communication circuitry. Failure of any of these components renders the PCS degraded and requires its removal from service. Accordingly, these components are modeled as series reliability networks.

The third failure consequence is defined as the failure of a battery enclosure. A failed enclosure has 18 battery racks and 15 PCSs, so the failure consequence of 1350 kW is the lesser of the combined capacities of the racks (1350 kW at Beginning of Life, BOL) and the combined capacities of the PCSs (1350 kVA). Components that contribute to the failure rate of this failure consequence include HVAC systems, auxiliary power transformer(s), auxiliary power supplies, fire suppression systems, container level communications switches, and any container level collector system components (breakers, disconnects, cables, etc.). In addition to single component vulnerabilities (series reliability networks), fire protection systems are often configured with 2-out-of-3 redundancy and telecommunications equipment is often fully redundant. Accordingly, series, parallel, and K-out-of-N reliability networks may apply to container subcomponents.

The fourth failure consequence is defined as the failure of a collector system transformer. A failed medium voltage collector transformer has a consequence of 2750 kW which is two battery enclosures of lost capacity.

The fifth and final failure is defined as the failure of the entire facility. A failed site communication gateway, Ethernet switch, or auxiliary power transformer may lead to a loss of the entire facility capacity. High consequence equipment failures such as these often have full redundancy.

Equipment failure consequence categories are summarized in Table 2.

Table 2. Summary of Equipment Failure Categories

Category	Description	Consequence at BOL
1	Failed Battery Rack	75 kW
2	Failed PCS	90 kW
3	Failed Container	1350 kW
4	Failed Transformer	2700 kW
5	Failed Site Ethernet	Entire Facility Capacity

Facility Reliability Diagram (Step 2)

The reliability network diagram for this facility is shown in Figure 2. The facility reliability network block is shown to the far right and has two subordinate transformer reliability network blocks. Each transformer reliability block has two subordinate battery enclosure reliability blocks and each battery enclosure has 15 PCS and 18 battery rack subordinate reliability blocks. Note that PCS and enclosure reliability blocks are shown only once for simplicity. The complete facility reliability diagram has 1 facility reliability block, 2 transformer reliability blocks, 4 enclosure reliability blocks, 60 PCS reliability blocks, and 72 battery rack reliability blocks for a total of 139 reliability blocks.

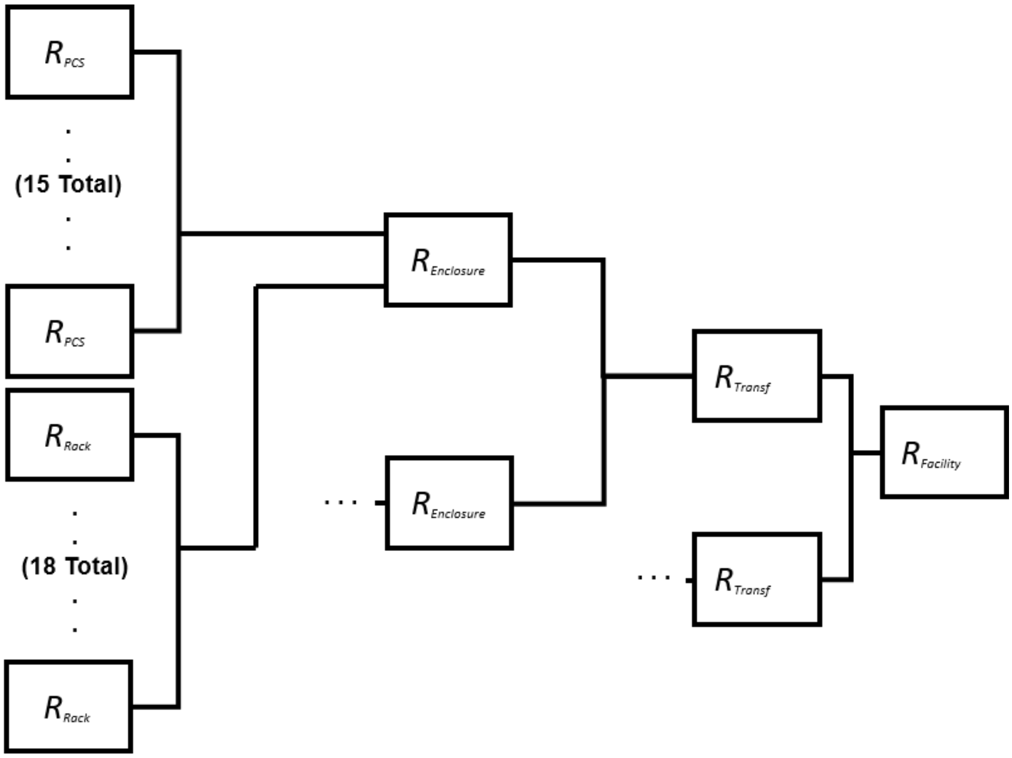

Figure 2. Reliability Network Diagram For 5 MW / 20 MWH BESS

Understanding component hierarchy is important when considering expected equipment failures and their aggregate impact to facility capacity. If a senior component and a subordinate component are both expected to fail, then the total consequence of equipment failure is equal to the consequence of the senior component. For example, if a transformer is expected to fail and one of its subordinate battery enclosures is also expected to fail, the aggregate consequence of these failures is equal to the transformer failure consequence, not the sum of the transformer and container failure consequences.

Reliability Network Block Failure Rates and Reliabilities (Steps 3 and 4)
A detailed FMEA may be performed to identify components that contribute to the aggregate failure rate of each reliability block and, as stated previously, a detailed construction of applicable failure rates is not presented in this paper. The reliability block failure rates used in this worked example are summarized in Table 3. Reliabilities for durations of 8 hours and 1 week are calculated using Equation (1) and are also summarized in Table 3.

Table 3. Worked Example Reliability Block Failure Rates and Reliabilities

Equipment Group	**Failure Rate (Failures/10^6 Hours)**	**Reliability**	
		8 Hour	**1 Week**
Battery Rack	200.0	0.9984	0.967
String PCS	7.0	0.9994	0.9875
Battery Enclosure	75.0	0.9999	0.9988
Transformer	1.0	1	0.9998
Facility	5.0	1	0.9992

Monte Carlo Analysis of Reliability Diagram (Steps 5, 6, and 7)
The Monte Carlo analysis of the BESS reliability diagram is performed by assigning a random number between 0 and 1 to each reliability block and comparing that random number to the calculated reliability summarized in Table 3. The reliability network diagram is then reviewed from right to left and the consequences of failed components are subtracted from the maximum facility output capacity. Note that subordinate equipment to a failed senior component may be ignored, as the consequence of failure to the facility output capacity is equal to the failure consequence of the senior components. This review process is well suited for automation with scripting tools such as Matlab or Python and may be easily implemented with nested if/then/else commands.

The Monte Carlo simulation described above develops a most likely facility output capacity that is less than or equal to the maximum possible output capacity. This process is then repeated for thousands of iterations and the set of output capacities can be plotted in a histogram.

Figure 3 shows histograms for 8 hour and 1 week reliability of the 5MW BESS at Beginning of Life (BOL), simulated for 20,000 iterations. Capacity degradation associated with battery fade is not considered in the results shown in Figure 3 because the analysis is performed at BOL. Simulation results are grouped into 2.5 MW bins to show the distribution of most likely facility output capacity. The histograms include red vertical lines showing the average facility most likely output capacity from the Monte Carlo analysis and black vertical lines showing facility output capacity requirement.

The histograms show that the distribution of most likely facility output for the 1 week reliability is lower and more uncertain than the 8 hour reliability, which is expected. Additionally, the histograms show that the distribution of most likely capacity is irregular and varies based on the reliability duration.

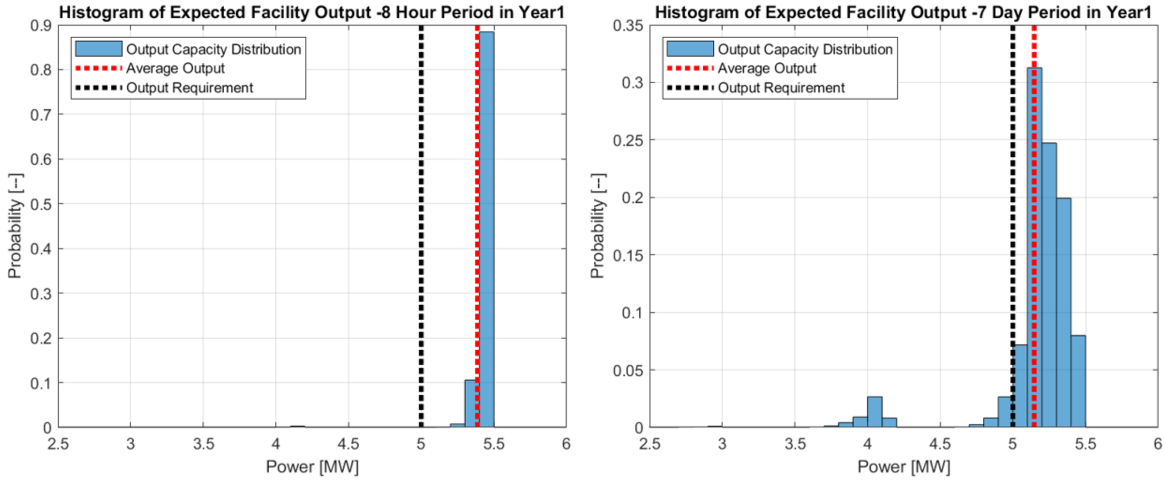

Figure 3. Histogram Of Most Likely Facility Output for 8 Hour and 1 Week Reliabilities

6.0 REVIEW OF MONTE CARLO RELIABILITY ANALYSIS

The histograms of most likely facility output provide a general overview of most likely facility output, but additional analysis provides insight into the facility reliability and its design. The average most likely output capacities are 5.39 MW and 5.15 MW for the 8 hour and 1 week reliabilities, respectively. Accordingly, the BESS is expected to satisfy the average output requirement of 5MW for both reliability durations.

The expected frequency of not satisfying the facility requirement of 5MW is also of interest, as BESS power purchase agreements are typically structured to penalize deficient capacity and do not incentivize excess capacity. The likelihood of the average most likely output capacity exceeding the output requirement of 5MW is 99.7% and 91.9% for the 8 hour and 1 week reliabilities, respectively. A longer BESS reliability requirement has a lower most likely facility output capacity and a higher likelihood of not satisfying the output requirement, exposing a BESS to lost revenue and performance penalties.

Examination of the most likely equipment failures for a one week reliability reveals the BESS equipment that are driving the overall facility reliability. A summary of the expected equipment failures is shown in Table 4. This table summarizes the number of equipment reliability blocks, the expected number of failures of each reliability block type, and the consequence of failure for each equipment. This table also shows that the battery enclosure and the battery racks are the largest contributors toward facility output capacity degradation.

Table 4. Summary of Equipment Group Contributions to BESS Expected Output Degradation

Equipment	Number of Reliability Blocks	Most Likely Number of Failures	Consequence of Failure	Contribution to Facility Output Capacity Degradation
Facility	1	0.0011	5000 kW	5.5 kW
Transformer	2	0.0005	2500 kW	1.3 kW
Enclosure	4	0.04855	1250 kW	60.7 kW
PCS	60	0.06925	90 kW	6.2 kW
Battery Rack	72	2.31135	75 kW	173 kW

This summary of expected failures and calculation of average contribution to facility output capacity degradation is a simple tool that identifies the BESS reliability limiting equipment. A summary similar to that provided in Table 4 may be used as a tool to optimize the designed reliability of a BESS. A system with an optimized reliability design has equal contributions to facility capacity degradation for all equipment.

For this worked example of a 5MW BESS, the battery racks and battery enclosure are the reliability limiting equipment. Facility reliability may be improved by selecting higher reliability equipment, adding design redundancy to components, or adding additional capacity overbuild for the battery racks.

Similarly, the above summary also shows that the facility, transformer, and PCS equipment contribute substantially less to facility reliability than the enclosure and battery rack equipment. BESS cost may be reduced by removing redundancy from this equipment or selecting lower cost, lower reliability components without substantially impacting the overall facility reliability.

7.0 TIME DEPENDENCY OF EXPECTED FACILITY CAPACITY

Battery capacity fade is a characteristic of BESS facilities. Capacity fade is considered in facility design by oversizing the beginning of life capacity and augmenting the BESS with additional battery racks during the life of the system. Most BESS facility capacity projections show a decreasing trend with prompt increases in battery capacity. These prompt capacity increases are a result of battery augmentation. A battery degradation curve for the representative 5MW system is shown in **Figure 4**.

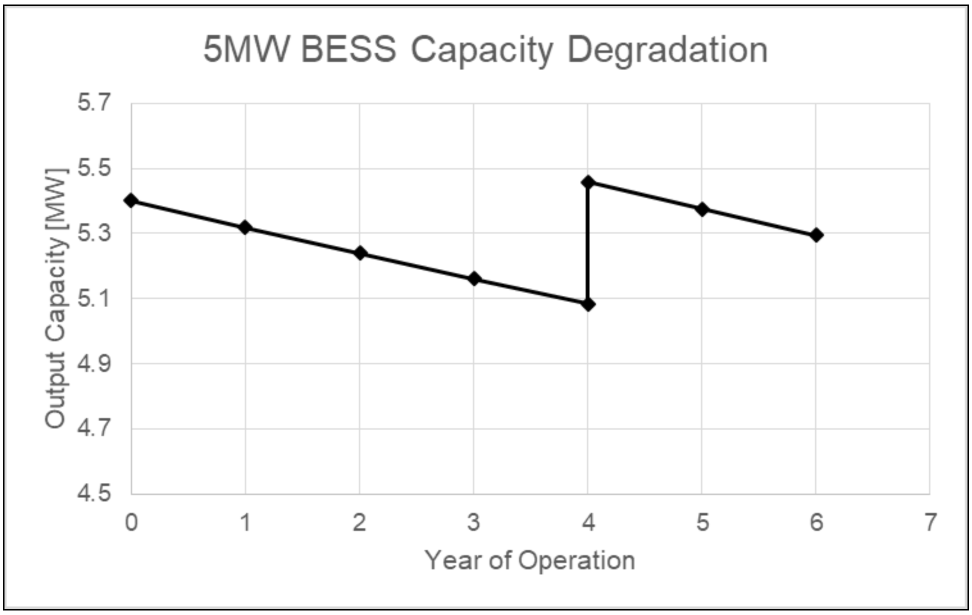

Figure 4. Representative Capacity Degradation of 5MW BESS

The Monte Carlo reliability analysis presented in the preceding sections subtracts the consequence of failed equipment from the maximum facility capacity, not the maximum facility output requirement. The facility overbuild at beginning of life provides capacity margin that allows for some equipment failures while still satisfying obligations for supplied capacity at the point of interconnection.

BESS facility capacity is most vulnerable to equipment failures when there is the least margin to output capacity requirements. The 5MW BESS capacity degradation plot shown in **Figure 4** shows that the BESS has the least capacity margin immediately preceding battery augmentation in Year 4. Histograms of most likely BESS facility capacity in year four are presented in Figure 5.

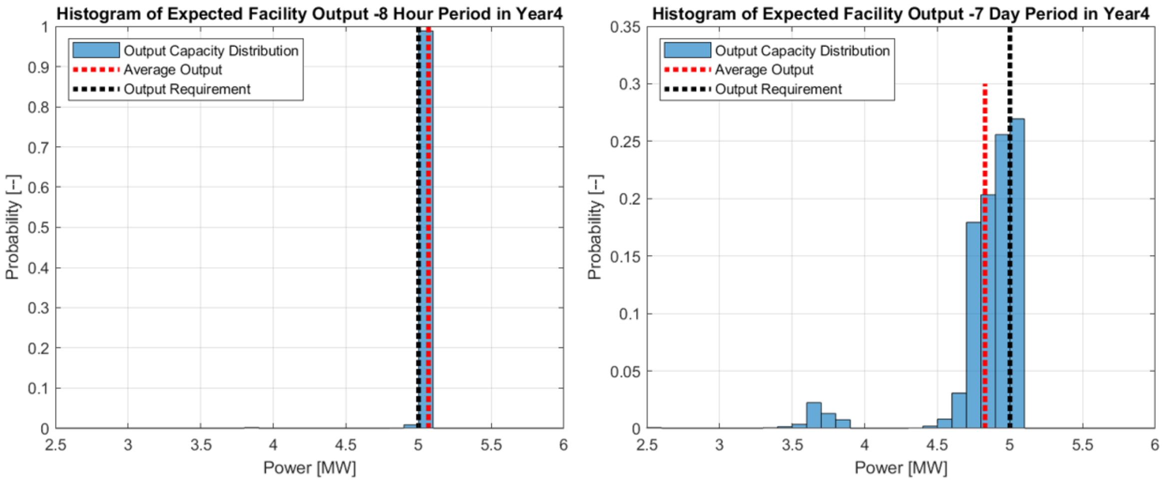

Figure 5. Histogram Of Most Likely Facility Output for 8 Hour and 1 Week Reliabilities (Year 4)

The average most likely output capacities are 5.1 MW and 4.8 MW for the 8 hour and 1 week reliabilities, respectively. The calculated most likely capacity degradation from Year 1 matches the natural intuition that the most likely facility capacity in Year 4 is less than Year 1. However, the expected frequency of not satisfying the facility requirement of 5MW is less intuitive and once again of interest. The likelihood of the average most likely output capacity exceeding the output requirement of 5MW is 98.8% and 26.7% for the 8 hour and 1 week reliabilities, respectively.

The histograms of most likely output and the performance summaries demonstrate the impact of battery capacity fade on most likely BESS facility output capacity. BESS facilities with longer duration reliability requirements such as those in critical power applications require particular consideration of BESS facility design and performance guarantees to satisfy output capacity obligations and avoid performance penalties.

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