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Energy Storage Systems as a Reliable Alternative to Diesel Generators for Critical Power Applications

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SUMMARY

In this paper, a reliability model for an Energy Storage System (ESS) is developed. The model is used to calculate total system availability for a representative ESS. Parametric studies are performed to evaluate the effect of capacity oversizing and energy market participation on the overall system availability. The results show that ESS can meet and exceed typical required availability of 95% for critical applications. Further studies can optimize energy market participation to generate revenue, potentially offsetting the total cost of the ESS.

KEYWORDS

Energy Storage System, ESS, Battery Energy Storage System, BESS, Lithium-ion, Diesel Generator, Reliability, Critical Power, Backup Power, Standby Power, Energy Market Participation, Capacity Market

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INTRODUCTION

Stationary Energy Storage Systems (ESS) represent an unprecedented opportunity to provide reliable, emissions-free backup power for critical applications. Current political and social trends are resulting in diesel generators (DGs) becoming less desirable as the primary source of backup power for such applications. ESS can provide a similar, if not better, level of reliability in critical power applications, as well as provide significant environmental benefits due to the elimination of harmful greenhouse gas (GHG), NOx, and SOx emissions. Although the initial cost of an ESS may be greater than an equivalent DG, the total cost of ownership may be offset by lower operations and maintenance (O&M) costs as well as from revenue that is received from participation in the energy markets.

Some jurisdictions are restricting the ability to permit DGs for extended run times, severely limiting the use cases in which DGs can be deployed. In some cases, a hybrid solution may be employed to limit the emission of GHGs. However, hybrid solutions come with only limited reduction in environmental impact and do little to mitigate the O&M costs aside from a reduction in fuel costs. For applications where permitting DGs is difficult or impossible, battery energy storage systems (BESS) can be a viable alternative solution, provided the resulting system is designed appropriately to achieve the necessary level of reliability.

This paper considers a generic energy storage system. Some common energy storage systems include lithium ion battery energy storage systems (Li-BESS) as well as flow battery energy storage systems. Energy storage systems can be modeled generally as a combination of sub-systems interacting with one another, as shown in Figure 1. The system can be either water cooled or air cooled, but generally always contains an energy storage component, a thermal management component, a power conversion component (inverter), and an energy management control system.

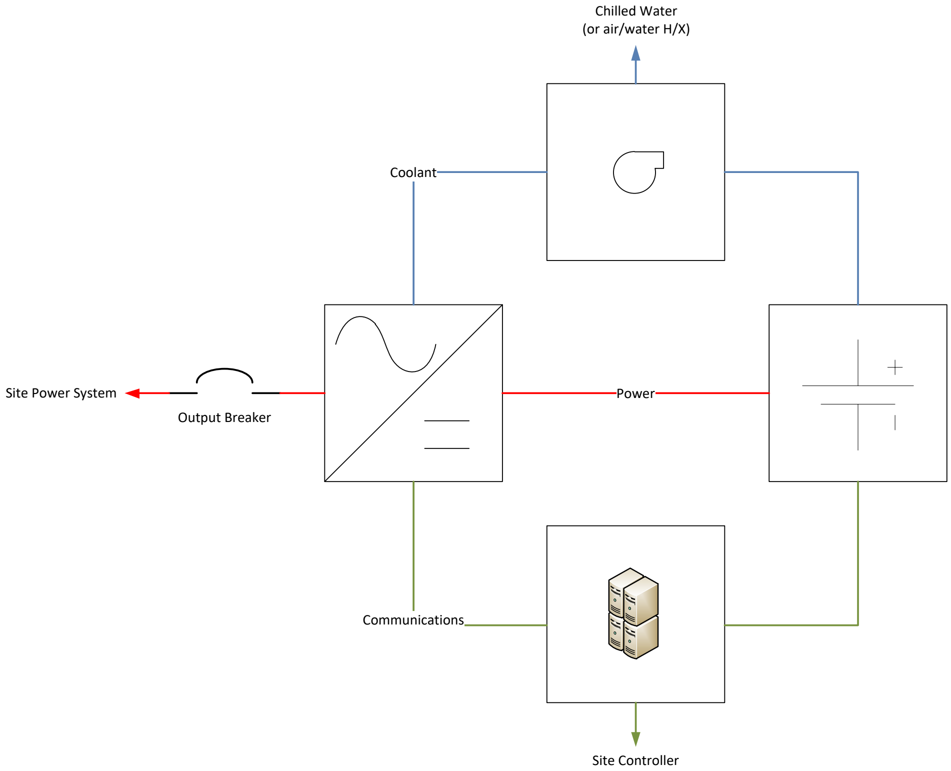

Figure 1 – Typical Energy Storage System

DIESEL GENERATOR RELIABILITY

DG based critical power backup systems require the installation of a diesel generator with either an integrated sub-base tank or separately secured day tank to hold the fuel, as well as a larger fuel storage tank for extended run-time applications. With respect to the fuel system, there may be several pumps, valves, and filters that are critical to success at run-time. The diesel engine itself is a complex mechanical machine that may comprise a crankshaft, pistons, cylinders, fuel pump, fuel injectors, intake and exhaust valves, etc. The generator portion represents another set of complex electrical and electronic components. Each of these components contributes to the overall reliability of the system, and many of them benefit from, or require, regular and preventive maintenance.

A reliability model for a DG can be constructed by considering three main sources of failure to perform the intended function: (1) failure to start; (2) failure to run; and (3) failure due to maintenance or test. The potential for each of these failures can be expressed by probabilities related to expected lifetime of components, event-based expectation of failure, or simple analysis of preventive maintenance schedules or typical corrective maintenance turnaround times. These probabilities for failure are then converted to an equivalent availability using the formula [1]:

$$\boldsymbol{A = 1 - P(t)}, \text{ where P(t) is the probability of the failure} \qquad (1)$$

Each of these availabilities is assumed to be mutually exclusive and independent. Further, because any one of these potential sources for failure (or unavailability) will render the system unavailable, they can be represented as a series model, where success of the preceding stage (independent of the specific role) is required for the next stage to be successful. Therefore, to arrive at the final estimate of reliability for the system, the individual availabilities are multiplied together.

A failure to start is characterized by the DG’s inability to start from a standby condition, and can be caused by any number of failures in the starting system, e.g., the air start motor could fail, or the DG could fail to pick up the required load (as determined by achieving stable voltage and frequency while supporting the intended load). Failure due to maintenance or test is easily calculated from the expected frequency of preventive maintenance or testing activities, or in the case of corrective maintenance, from empirical data. A failure to run is more generally related to the mean time between failure (MTBF) for components that comprise the DG system; this probability is temporal and is generally assumed to have a normal distribution resulting in an exponential relationship [1], which can be expressed as

$$P_{fr}(t) = 1 - e^{\frac{-t}{MTBF}} \qquad (2)$$

The MTBF used in Equation 2 is calculated by considering the MTBF of all components in the system, normalizing to a common failure rate (typically failures per hour or failures per year), combining the failure rates, and then converting back to MTBF. Failure rates are combined according to whether components are potential single points of failure or if they are redundant within a system. For high reliability or critical systems, redundant components may be included to improve overall system reliability.

Overall availability of the DG system is the product of the individual availabilities, and is generally expressed as a percentage. This non-temporal value is then multiplied with the time-dependent value of Equation 2, producing the overall system availability at time *t*.

ENERGY STORAGE SYSTEM RELIABILITY

Overview

The reliability of an ESS can be framed in much the same way as the reliability of DG systems, but with greater granularity to actual availabilities that could impact the overall system. The largest difference occurs in the failure to test area: whereas the DG is periodically run as part of a preventive/corrective maintenance action, failure to test for a BESS bifurcates into two distinct paths: 1) as with the DG, this includes operation of the asset and associated switchgear, ensuring that the BESS is engaged and/or isolated with/from the grid, and may include its ability to support test loads in parallel or in an islanded state. The other path is 2) the time interval of periodically cycling the energy storage system, ensuring that the system has full capability to provide the required power at rated nameplate for the duration of time necessary to meet a specific use case. This latter component is vitally important, as some technologies degrade ("fade") in capacity over time and this degradation must be accounted for both in an operational sense as well as forecasting.

Like the DG reliability analysis, failure to run for the BESS is characterized by failures of the components that comprise an ESS. Similar to the DG, a failure to start would be characterized by a failure of the ESS to support the load during an outage condition, specifically during the transition from grid-connected to islanded mode as well as the return to grid-connected sequence, and includes the period of establishing stability of voltage and frequency after transition. Major components that would contribute to a failure to start are the electrical system switching components, e.g., output circuit breaker, automatic transfer switch, or disconnect switch, and also includes improper settings within the inverter subsystem that characterize full, four-quadrant utilization under actual load conditions and that are difficult to duplicate in a laboratory test or production environment.

An ESS may be procured to not only serve a critical power or reliability event, but also to participate in wholesale or local energy markets. Participation in either energy market could preclude the ESS from being able to serve its intended critical power or reliability function, depending on the overall size of the ESS and the required capacity to serve the critical function. Such systems can be designed to meet a critical function as a primary use case and participate in the energy markets to generate revenue as a secondary use case. The reliability of such a system can be calculated by considering the probability that the required capacity for the critical function is available given an assumed duration and frequency of market participation.

Probability of ESS Failure to Start

A calculation of the probability of a failure to start for a BESS centers on switching components as well as internal settings within the inverter that govern the transition from a grid-connected state to island state, and the reversal back to a grid-connected condition. The primary mechanisms that must function in order for a BESS to energize the electrical system experiencing an outage are the output breaker(s), automatic transfer switch, a disconnect switch, and possibly the interconnection transformer. These components are assumed to be single points of failure, that is, no redundancy is built in to any of the relay logic or power switching.

Although these components are typically rated for a lifetime number of switching cycles, the primary failure mechanisms are: (1) opening when it should not; and (2) failure in service (not while opening or closing) [2]. Consequently, although there is a fixed lifetime to these components, first-order approximations are evaluated at $t = 0$, e.g. availability is considered constant for the system, independent of the number of actual transitions that have actually occurred with the devices over their operational lifetime.

The MTBF and associated failure rate (λ) for these components are shown in Table 1, as well as the combined MTBF for all components contributing to a failure to start.

Table 1 – MTBF and Failure Rates of Switching & Interconnection Components

Component	MTBF [hr]	Lambda [hr^{-1}]	Availability
Output Breaker	864,889	1.156E-06	0.999 998 844
ATS	250,111	3.998E-06	0.999 996 002
Disconnect	7,369,646	1.357E-07	0.999 999 864
Transformer	1,670,904	5.985E-07	0.999 999 402
Combined (Calculated)	*169,820*	*5.889E-06*	*0.999 994 111*

Probability of ESS Failure due to Preventive Maintenance

The probability of a failure due to preventive maintenance *Ppm* is calculated by considering the preventive maintenance schedule of an ESS. For preventive maintenance, we assume that maintenance activities such as air/water filter replacement or coolant testing is performed once every month, and that the amount of time required for this preventive maintenance is 4 hours, and this maintenance activity is common for all ESS types. Considering the total number of hours in a year, the probability of failure due to preventive maintenance is given as

$$P_{pm} = \frac{4\frac{hours}{event} * 1\frac{event}{month} * 12\frac{months}{year}}{8760\frac{hours}{year}} = 0.55\% \qquad (3)$$

This number can be re-calculated accordingly if the maintenance needs differ from the example.

Probability of ESS Failure due to Corrective Maintenance

Next, the probability of corrective maintenance *Pcm*, which will take the ESS asset offline during diagnostics/root cause, parts procurement, and installation, is largely driven by the number of occurrences per year. As a conservative estimate, one event per year is expected, although MTBF for the system may be longer depending on complexity of the ESS and the components used within the overall system. 72 hours per occurrence per year is expected and is accounted for by the first 24 hours spent in root-cause/parts procurement, the next 24 hours in shipping/receiving, and the last 24 hours in installation/testing. Consequently, the probability of corrective maintenance can be described as:

$$P_{cm} = \frac{72\frac{hours}{event}*1\frac{event}{year}}{8760\frac{hours}{year}} = 0.82\% \quad (4)$$

As with preventive maintenance, this value can be recalculated if different durations and numbers of events per year are different than the provided assumptions.

Probability of ESS Failure due to Testing

Testing of an ESS is often the result of either preventive maintenance, e.g. dictated by a formal schedule or manufacturer's recommendation, or as the result of corrective maintenance. Probability of testing *Pt* is generally driven by manufacturer's specified recommendations on balance of system (BoS) components, and includes operation of systems external to the ESS but those that are required for proper operation of the ESS to perform the reliability use case function, that is, supporting a critical load for a duration of time.

The development of the probability of testing bifurcates depending upon the scope of use cases that are enacted for the energy storage system. This expands the scope of probability of testing because exercising the capacity of the ESS, e.g., enacting a full or partial charge and discharge cycle, or ensuring that maximum charging and discharging nameplate ratings are achieved, is critical to ensuring that all system components are capable of sustaining rated power levels and the associated heat rise that accompanies such performance behavior. Consequently, the probability of testing can be described as:

$$P_t = P_{ts} + P_{tc} \quad (5)$$

Where *Pts* is the probability of testing due to exercising the entire balance of plant system (switchgear and control system) and *Ptc* is the probability of testing associated with cycling of the battery to validate capacity.

The general development for ESS probability of testing proceeds as follows:

1. Test full system capability to switch in and out of the primary reliability mode;
2. Test the full system capacity in a discharge and charge cycle.

The first test includes conducting a simulated loss of grid scenario and enacting the ESS to provide islanded load support. Empirically, this testing generally can be accomplished in less than an hour, and based upon related industry experience, should be conducted at least once per month. The following shows the probability of testing, due to system switching and overall exercising of all components:

$$P_{ts} = \frac{1\frac{hours}{event}*1\frac{event}{month}*12\frac{months}{year}}{8760\frac{hours}{year}} = 0.14\% \quad (6)$$

Here, the probability of testing switching capability *Pts*, at a 1-hour and once-per-month cadence, is shown to yield an overall probability of 0.14%.

Lack of ESS secondary use cases (e.g. lack of market participatory use cases) drive the next development for probability of testing. A major cost driver for the ESS is the incremental additional energy capacity in the storage section. From a cost perspective, minimizing the size of ESS energy capacity produces the lowest capital costs for the system. For calculating the probability of testing, the smaller the rated capacity of the energy storage relative to the nameplate charging and discharging capacity, the shorter the duration required for testing.

Energy storage is typically sized in increments of duration, and that duration is driven by the intended use case. Typical durations span 0.5h, 1h, 2h, 4h, with other less common use cases requiring 10h or longer. This duration is a direct driver of energy storage capacity, and to ensure performance in the period (as well as to stay off the extremes of 100% charged or discharged), often requires that the energy storage system be increased in capacity by 10 or 20%. Note that this is in addition to what may also be referred to as "oversizing" the system in order to deliver rated end-of-life capacity, as opposed to beginning-of-life capacity.

Battery capacity drives one component in probability of testing. Power conversion efficiency, as well as energy conversion efficiency in the battery storage section, also drive this value. Due to differences in battery chemistry as well as power electronics, round-trip power conversion and energy storage efficiencies can vary from as low as 67% (e.g. vanadium redox flow) to nearly 90% (lithium ion). As a result, a four-hour discharge at rated power may take 5 hours to recharge, presuming 80% round-trip efficiency and an equivalent rate of discharge and recharge.

For the purposes of this development and presuming independent charging and discharging rates, probability of testing capacity *Ptc* of the ESS due to cycling of the battery can be modeled as:

$$P_{tc} = \frac{\frac{\left(\frac{Battery\ Capacity\ (MWh)}{ESS\ Discharge\ Nameplate\ (MW)}+\frac{Battery\ Capacity\ (MWh)}{ESS\ Charge\ Nameplate\ (MW)}\right)}{RT\ Efficiency} * 1\frac{event}{month} * 12\frac{months}{year}}{8760\frac{hours}{year}} \quad (7)$$

Here, it is presumed that at least one charge/discharge cycle, using the full capacity of the battery, is performed at least once per month.

The following is provided as an example. Presume 100% of the energy capacity is available (e.g. no oversizing). The inputs are:

- Battery Capacity: 8 MWh
- ESS Discharge Nameplate (Inverter): 2 MW
- ESS Charge Nameplate (Charger): 2 MW
- Round-trip Efficiency: 90%
- 1 cycle every 3 months or 4 cycles per year

The resulting probability of testing due to capacity testing is given as:

$$P_{tc} = \frac{\frac{\left(\frac{8\ MWh}{2\ MW}+\frac{8MWh}{2MW}\right)}{0.9} * 0.25\frac{event}{month} * 12\frac{months}{year}}{8760\frac{hours}{year}} = 0.30\% \quad (8)$$

As energy storage capacity increases, relative to charger/inverter nameplate capacity, the probability of testing increases due primarily to the increase in required time to perform the cycle.

Table 2 lists the probabilities of testing for exercising the switching components and ESS cycling. Recall from Equation 5 that the probabilities for testing due to switching and cycling are additive. Table 2 also lists the total availability associated with a probability of testing:

Table 2 – Total Probability of Failure Due to Testing

Component	Probability	Availability
Probability of Testing/Switching (*Pts*)	0.14%	99.86%
Probability of Testing/Cycling (*Ptc*)	0.30%	99.70%
Combined (Calculated)	*0.44%*	*99.56%*

Composite Probability of Failure / Availability of the ESS

So far, this development has focused on those components of availability that while variable, once a suitable system has been defined, the overall availability due to maintenance, testing, and failure to start can be determined. As a first-order approximation, this "composite" availability remains constant once the individual components are determined during the design and procurement phase.

To calculate the availability of the system, the individual availabilities are calculated. For the example system and conditions, we have:

Table 3 – Composite Probabilities of Failure and Availabilities for the ESS

Component	Probability	Availability
Probability of Preventive Maintenance (*Ppm*)	0.55%	99.45%
Probability of Corrective Maintenance (*Pcm*)	0.82%	99.18%
Probability of Testing (*Pt*)	0.44%	99.56%
Probability of Failure to Start (*Pfs*)	~	99.99941% *
Combined (Calculated)	*1.80%*	*98.20%*

** from Table 1*

As is shown in the table, the availability of the ESS with the presumed conditions is 98.20% although individual availabilities are greater than 99%. This is due to the no-redundancy/ product of availabilities of the system, and from this, reveals that at any time in a year (8,760 hours) that the system may not be available 1.80% of the time, or approximately 158 hours per year.

Single-System Reliability

The Table 3 results provide a "static" reliability that is not time variant. Equation (2) relates the MTBF of a system to the probability of failure to run (*Pfr(t)*), which is time-dependent.

Consequently, the single-system reliability is the product of the static, composite availability *Acomp* and the time-dependent availability *Afr(t)*, or

$$Rsys = 1 - [Acomp * Afr(t)] \quad (9)$$

To determine the time-dependent availability, the MTBF of various components are established, their failure rates (λ), and then individual availabilities are determined. The system MTBF is then calculated by first calculating the combined availability (product of the individual availabilities), then by determining λ (subtract from unity), and then by taking the reciprocal.

The MTBF of the energy storage sub-system is determined from the expected lifetime of the energy storage system. For example, typical manufacturer guaranteed lifetimes for various energy storage systems are given in **Error! Reference source not found.**.

Table 4 – Typical Lifetimes of ESS

ESS	Lifetime (yrs)	MTBF [hr]
Flow Battery	20	175,200
Li-ion – reliability	15	131,400
Li-ion – market participation	8	70,080

Li-BESS exhibits capacity fade over time, primarily due to cycling of the cells and storage at elevated state of charge (SOC). These systems will typically be sized to deliver rated capacity at end of life, therefore there is no time dependence incorporated into the model to account for capacity fade. The MTBF is calculated assuming that the vendor adequately accounts for end of life capacity when designing the system. However, if the system is procured with a particular use case in mind, but in practice the system is exercised more aggressively, cell aging models can be used to predict the change in remaining life, and the MTBF can be updated accordingly.

Table 5 shows the results performing the reliability calculations for an air-cooled power conversion system (PCS).

Table 5 – MTBF, Failure Rates, and Availability for an Air-Cooled ESS Power Conversion Subsystem

Component	MTBF [hr]	Lambda [hr^{-1}]	Availability
IGBT	12,696	7.8765E-05	0.999 921 235
Fan	52,069	1.92053E-05	0.999 980 795
Controls	1,051,711	9.50832E-07	0.999 999 049
Capacitors	171,927	5.81642E-06	0.999 994 184
Combined (Calculated)	***9,548***	***1.04728E-04***	***0.999 895 265***

The ESS thermal management system components must also be considered. Table 6 shows the resulting composite MTBF for the thermal management system (TMS) of an air-cooled ESS.

Table 6 – MTBF, Failure Rates, and Availability for an Air-Cooled ESS Thermal Management System

Component	MTBF [hr]	Lambda [hr^{-1}]	Availability
A/C	55,492	1.80206E-05	0.999 980 795
Fan	52,069	1.92053E-05	0.999 980 795
Controls	1,051,711	9.50832E-07	0.999 999 049
Heater	1,923,618	5.19854E-07	0.999 999 480
Combined (Calculated)	***25,842***	***3.86962E-05***	***0.999 961 304***

Finally, the combined MTBF, failure rate, and availability of the full ESS are shown in Table 7.

Table 7 – MTBF, Failure Rates, and Availability for an Air-Cooled ESS

Component	MTBF [hr]	Lambda [hr^{-1}]	Availability
TMS	25,482	3.86962-07	0.999 961 304
PCS	9,548	1.04735E-04	0.999 895 265
Combined (Calculated)	***6,972***	***1.43427E-04***	***0.999 856 573***

The implications of the findings of the composite system MTBF calculated in Table 7 are shown below in the following graphic:

General MTBF **6972 hours**

Failure to Run

Hours	Pfr(t)	1-Pfr(t)
1	0.000143421	99.9857%
2	0.000286821	99.9713%
3	0.0004302	99.9570%
4	0.000573559	99.9426%
10	0.001433281	99.8567%

Figure 2 – Probability of Failure to Run for an Air-Cooled ESS

This graphic provides the overall probability of failure to run (*Pfr(t)*) of an air-cooled ESS, as well as the availability of the system at the end of each listed duration. To determine the total single-system block availability / probability of failure, this information must be combined with the static, composite probabilities established in Table 3. This is accomplished by taking the static, composite availability and multiplying by the time-dependent probability. Doing so produces the following results:

Total Availability & Probability of Failure

Hours	Availability	Probability of Failure
1	98.19%	1.81%
2	98.17%	1.83%
3	98.16%	1.84%
4	98.14%	1.86%
10	98.06%	1.94%

Figure 3 – Total Availability and Probability of Failure for an Air-Cooled ESS

This figure shows that given the assumptions stated for the ESS that operating through 10 hours, for a generic ESS, should produce an availability of about 98.06%, or an unavailability of about 170 hours per year, for all conditions (maintenance, testing, failure to start, and failure to run). The green-colored background in availability is showing that the system is meeting a threshold of 95%, which is an arbitrary value set for this discussion/development and establishes the minimum overall system reliability requirements for the ESS.

Market Participation

In order to offset the cost of an ESS, the system can participate in wholesale or local energy markets when not being relied upon for the intended critical function. If allowing for market participation use cases, then the overall availability for performing the critical function should include a treatment of the probability of the system being unavailable due to such market participation.

The probability of unavailability due to market participation is dependent on the duration of the market participation function, the frequency of market participation, and the available capacity during market participation. For market participation use cases in which the available capacity of the ESS is always more than what is required to perform the critical function, the probability of a failure due to market participation defaults to 0. For example, consider an ESS participating in the energy markets in a capacity function. If the required energy storage capacity to perform the critical function is 60% of the system nameplate capacity, then any time at which the ESS capacity drops below 60% renders the system incapable of performing its intended critical function. If the use case restricts minimum SOC during participation in the capacity markets to 60% or more, then the probability of failure defaults to 0, and the availability given this use case is equal to 100%. Note that the ESS reliability/availability as established in the previous section (98.06% availability for the presented assumptions) is unchanged.

In the case that the ESS participates in the energy markets but does not have enough reserve capacity to perform the critical function, the probability of failure due to market participation defaults to being time-based. For example, allowing the ESS to participate in energy market applications up to 50 times a year, for 10 hours at a time, the probability of failure can be calculated as

$$P_{mk}(t) = \frac{(10\,\frac{hrs}{event})*50\frac{events}{year}}{8760\frac{hrs}{year}} = 5.71\% \tag{11}$$

If the ESS is allowed to participate in the energy markets in multiple applications, the total availability is a combination of the availability due to participation in each application. **The practical result of considering market participation as a contributing factor to reliability is that it becomes justifiable to size the ESS to be greater than the capacity required to serve the critical function.**

LI-BESS FULL RELIABILITY CALCULATION EXAMPLE

Example results showing how availability changes as a function of run-time are shown in Table 8. The design inputs for this system are:

- ESS sized to meet the critical function at 100% capacity
- 80% minimum SOC during capacity market participation
- 50 days/year capacity market participation, 6 hrs/day
- 10 hour run time capacity (*Ptc* scaled accordingly)

Table 8 – Li-BESS Availability

Hours	Availability
1	97.74%
2	97.73%
4	97.70%
8	97.65%
10	94.28%

The results show that for run-times up to 8 hours, the calculated availability of the system is greater than 97%, putting it above a typical required 95% availability threshold for DG-based critical power applications. However, as run-time extends to 10 hours, the availability drops below the 95% threshold. This is due to the reduced availability associated with capacity market participation, coupled with the fact that the ESS SOC is allowed to drop to 80% during market participation. The total system availability can be improved by limiting the number of days per year that the Li-BESS is allowed to participate in energy markets, by limiting the duration of market participation, or by sizing the battery to be larger than what is required to perform the critical function.

Four parametric analyses were performed to determine the sensitivity of the total system availability to changes in the capacity market participation, ESS capacity, and minimum SOC parameters. The design inputs for this system are:

- Variable additional capacity: 0%, 15%, 30%
- Variable minimum SOC during capacity market participation: 60%, 70%, 80%
- Variable capacity market participation: 50 days/year and 100 days/year
- Variable capacity market duration: 4 hrs/day, 10 hrs/day
- ESS sized for 10 hour run time capacity

The results are shown in Table 9Tables 9 through 12.

Table 9 – Li-BESS Parametric Reliability Analysis Results

50 days/year capacity market participation, 4hrs/day

% additional capacity	Minimum SOC during market participation					
		60%		70%		80%
	8 hrs	95.42%	8 hrs	95.42%	8 hrs	97.65%
0	10 hrs	95.39%	10 hrs	95.39%	10 hrs	95.39%
	8 hrs	95.31%	8 hrs	97.54%	8 hrs	97.54%
15	10 hrs	95.28%	10 hrs	95.28%	10 hrs	95.28%
	8 hrs	95.20%	8 hrs	97.42%	8 hrs	97.42%
30	10 hrs	95.17%	10 hrs	95.17%	10 hrs	97.40%

Table 10 – Li-BESS Parametric Reliability Analysis Results

100 days/year capacity market participation, 4 hrs/day

% additional capacity	Minimum SOC during market participation					
		60%		70%		80%
	8 hrs	93.19%	8 hrs	93.19%	8 hrs	97.65%
0	10 hrs	93.16%	10 hrs	93.16%	10 hrs	93.16%
	8 hrs	93.08%	8 hrs	97.54%	8 hrs	97.54%
15	10 hrs	93.06%	10 hrs	93.06%	10 hrs	93.06%
	8 hrs	92.98%	8 hrs	97.42%	8 hrs	97.42%
30	10 hrs	92.95%	10 hrs	92.95%	10 hrs	97.40%

Table 11 – Li-BESS Parametric Reliability Analysis Results
50 days/year capacity market participation, 10 hrs/day

% additional capacity	Minimum SOC during market participation					
		60%		70%		80%
0	8 hrs	92.07%	8 hrs	92.07%	8 hrs	97.65%
	10 hrs	92.05%	10 hrs	92.05%	10 hrs	92.05%
15	8 hrs	91.97%	8 hrs	97.54%	8 hrs	97.54%
	10 hrs	91.94%	10 hrs	91.94%	10 hrs	91.94%
30	8 hrs	91.86%	8 hrs	97.42%	8 hrs	97.42%
	10 hrs	91.84%	10 hrs	91.84%	10 hrs	97.40%

Table 12 – Li-BESS Parametric Reliability Analysis Results
100 days/year capacity market participation 10 hrs/day

% additional capacity	Minimum SOC during market participation					
		60%		70%		80%
0	8 hrs	86.50%	8 hrs	86.50%	8 hrs	97.65%
	10 hrs	86.47%	10 hrs	86.47%	10 hrs	86.47%
15	8 hrs	86.40%	8 hrs	97.53%	8 hrs	97.54%
	10 hrs	86.38%	10 hrs	86.38%	10 hrs	86.38%
30	8 hrs	86.30%	8 hrs	97.42%	8 hrs	97.42%
	10 hrs	86.28%	10 hrs	86.28%	10 hrs	97.40%

The results provide key findings:

- In the cases where the required SOC to meet the intended critical function exceeds the minimum SOC allowed during market participation, the total system availability actually ***decreases*** as the ESS is oversized. This is due to the increase in probability of test. Although the result is somewhat counterintuitive, it is inconsequential as the system parameters are not suitable for meeting the intended critical function.
- If market participation is limited on a yearly basis, then there exists a set of conditions that ***do not require the ESS to be oversized*** in order to both participate in energy markets and meet the availability criteria for the intended critical function.
- Outside of the two aforementioned corner cases, the general trend is that increasing ESS capacity and limiting minimum SOC during market participation drive the availability of the system higher.

CONCLUSION

The total reliability or availability of several example ESS was considered and calculated in this study. The parametric studies show how design variables such as capacity and use case definition can affect the total system availability. Quantifying these effects can allow for a more detailed cost-benefit analysis when comparing a set of alternatives for a critical power application. The ability to quantify system availability as a function of these design parameters allows the system owner to evaluate a variety of alternatives, and optimize the system design to achieve the best ratio of total system cost, which is driven primarily by capacity, to system benefits, allowing for various levels of market participation to offset the system cost by providing revenue while the system is idle and not serving a critical function.

Further model development can incorporate variable market participation duration and frequency. For instance, a use case could include energy arbitrage to discharge at a particular rate for a certain number of hours per day. The remaining capacity following this discharge, and the duration for which the ESS maintains this capacity, would dictate the availability of the system, depending on the capacity required to perform the critical function. For example, if the minimum capacity necessary for 10-hr critical operation is 1.2MWh, but the system remains at 0.9MWh for a duration of 6 hours due to an energy arbitrage excursion, then the system is essentially unavailable to perform the 10-hr critical function for those 6 hours. This opens up more variables to optimize when sizing ESS for critical functions and specifying ESS operational use cases, in order to reduce overall cost and provide a future revenue stream for an asset owner/operator.

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