FINAL REPORT

Energy Security for Military Installations through Optimized Integration of Large-Scale Energy Storage into Microgrids

ESTCP Project EW19-5046

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ABSTRACT

INTRODUCTION AND OBJECTIVES

This study addressed optimizing the integration of large-scale energy storage into microgrids for military installation's energy security. This Phase 1 Project Team includes the Electric Power Research Institute (EPRI), Southern Company, PowerSecure, and Lockheed Martin. The reliability performance targets and stacked grid services were investigated at five DoD installations, which were then incorporated into economically, viable energy storage enabled microgrids.

TECHNOLOGY DESCRIPTION

Evaluating two technologies, Li-ion, and Flow battery storage, is the distinguishing feature of this analysis for addressing energy security for military installations. Through the optimized integration of large-scale energy storage into microgrid designs, critical loads at five DoD installations: *Fort Bliss*, *Naval Air Station Corpus Christi, Naval Base Ventura County*, *Holloman Air Force base, and March Air Reserve Base* are considered that include each of the storage technologies with solar photovoltaics (PV), diesel generators, and an uninterruptible power supply (UPS) within the microgrid configurations assessed.

PERFORMANCE AND COST ASSESSMENT

As a baseline, analysis of a diesel generator-enabled microgrid provided reliability and economic operational fundamentals Then, a four-step design procedure was followed to design an economically viable storage-enabled microgrid. In **Step 1**, an initial storage-enabled microgrid was designed by replacing one or more generators from the baseline configuration with energy storage. The storage system was sized to meet the reliability target of the baseline microgrid. For **Step 2**, each design was analyzed separately to understand the potential to provide secondary services without compromising the reliability target by *reserving sufficient energy* for potential outages. For each design during **Step 3**, a sensitivity analysis was performed to evaluate the economics of *oversizing storage* (both power and energy capacities) to increase the value of secondary services with an understanding of the increased system costs. And finally, **in Step 4**, the most feasible design with the best financial performance was selected through a cost-benefit analysis.

STUDY CONCLUSIONS AND OUTCOMES

The project team executed its evaluation methodology and demonstrated the cost-effectiveness of storage-enabled microgrid solutions compared to diesel-based microgrids. The analysis methodology using a storage-enabled microgrid indicated the following benefits: 1) Microgrids enabled by storage are capable of meeting DoD performance objectives and reliability targets. Reliability performance of the storage-enabled microgrid demonstrated to have equal or higher reliability requirements for each DoD site; 2) Storage-enabled microgrids enhance reliability and energy security, lower cost of operations, allow power market participation, and provide a positive net present value (NPV) compared to diesel-based microgrids; 3) Microgrids enabled by storage reduce the risk of loss of critical load during grid outages and reduce the cost of serving critical load; and 4) Incremental value of storage-enabled microgrids results from a) Avoided peak demand charge (except Fort Bliss), b) Avoided energy charge through self-generation and arbitrage, c) Avoided cost due to generation reduction and fuel savings, d) Avoided cost due to generator O&M, e) Avoided cost due to UPS reduction, f) Avoided cost due to UPS O&M, g) Demand response program participation value (except Fort Bliss), and h) Emissions reduction through increased renewable generation.

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EXECUTIVE SUMMARY

INTRODUCTION

The U.S. Department of Defense (DoD) seeks to improve energy security through the deployment of microgrids at military installations. These microgrids plan to incorporate renewable generation to assist military installations meet their respective renewable energy goals as well as their "Three Pillars of Energy Security"; Reliability, Resiliency, and Efficiency. However, current microgrid designs fall short of the DoD's desired operational durations when islanded when balancing variable on-site generation against variable loads. Recent cost reductions and performance improvements of emerging energy storage (storage or ES) technologies may hold the key to improved operational duration, resilience, and cost-effectiveness of renewable microgrids.

OBJECTIVES

The study focused analysis on the integration of large-scale energy storage into microgrids for military installation's energy security using two leading energy storage technologies—Li-ion and Flow batteries—for the microgrid applications at DoD installations. The reliability performance targets and stacked grid services were investigated at five DoD installations, which were then incorporated into economically, viable energy storage enabled microgrids. The Phase 1 project team includes EPRI, Southern Company, PowerSecure, and Lockheed Martin. The analysis constrained energy storage operations to ensure primary services met or exceeded the baseline reliability target provided by ESTCP guidelines at each site. While meeting the reliability target, the modeling goals were set to maximize stacked benefits provided by energy storage at each site. Storage systems were sized to increase the cost-effectiveness of the microgrid, compared with the diesel based microgrids.

ENERGY STORAGE TECHNOLOGIES AND DOD INSTALLATIONS SELECTED

The project investigated the viability of long-duration energy storage in microgrid applications to improve energy security, reliability, and provide continuity of service for critical loads during grid outages at improved costs relative to an otherwise identical diesel generator-based microgrid. In addition, the project evaluated opportunities to use storage simultaneously for multiple applications ("stacking benefits") beyond resilience. Two storage technologies were considered for this study, summarized in Table ES-1.

Table ES-1. Storage Technologies and Design Variables considered for Phase 1 Analysis

	Availability	Roundtrip Efficiency	Feasible Duration
Li-ion ES[1]	98.63%	91%	30 minutes to 4 hours
Flow Battery ES[2]	98%	71%	5 hours to 12 hours

[1] Based on consultation with PowerSecure in 2019
[2] Based on consultation with Lockheed Martin by 2021

The analysis addressed five DoD sites: **One Army Site**: Fort Bliss, **Two Navy Sites**: Naval Air Station Corpus Christi and Naval Base Ventura County, **Two Air Force Sites**: Holloman Air Force base and March Air Reserve base

MODELING METHODOLOGY

Initially, a baseline analysis with a diesel generator-based microgrid was performed for each site. With the baseline case established, two storage-based microgrid investment cases were designed for each site—one for each storage technology: Li-ion and Flow batteries. The specific characteristics of the two technologies such as roundtrip efficiency and probabilistic availability are considered for the analysis. Figure ES-1 describes this storage-enabled microgrid analysis work plan. The steps include:

- ***Step 1: Sizing and Reliability Analysis***: Monte Carlo[3] reliability analysis & storage sizing for a Storage-enabled microgrid
- ***Step 2: Iterative State of Charge (SOC) Reservation Design:*** StorageVET®[4] SOC analysis to assess secondary services while also satisfying primary reliability targets
- ***Step 3: Oversizing Sensitivity Analysis***: Increase Power and Energy capacity of storage and study the corresponding Net Present Values (NPV)
- ***Step 4: Cost-Benefit Assessment:*** Compare Baseline Microgrid with Investment Cases

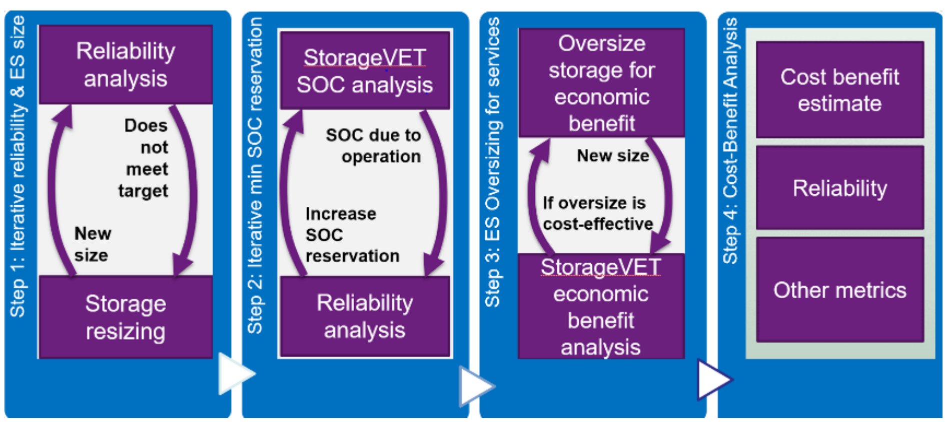

Figure ES-1. Illustration of the Technical Approach Developed for Phase 1 Analysis

DESIGNED MICROGRID CONFIGURATION

The microgrid configurations with the most feasible design and best financial performance for the five DoD installations and for each storage technology were determined using the four-step design methodology. The design configurations for Li-ion and Flow battery technologies are provided separately in Table ES-2. The table includes storage size in terms of power and energy and SOC reservation of the designed microgrid. The table also identifies the secondary grid services that energy storage can provide for best additional revenue.

[3] Metropolis, Nicholas, and Stanislaw Ulam. "The Monte Carlo Method." *Journal of the American Statistical Association* 44.247 (1949): 335-341

[4] StorageVET® is EPRI's energy storage project valuation toolthat is open source at no cost that informs decision-makers across the electric grid and is available at www.storagevet.com

Table ES-2. Energy Storage Size and Microgrid Design Configuration Results for DoD Sites Analyzed

		Ventura	March	Corpus Christi	Holloman	Fort Bliss
Number and Capacity of Baseline Gensets		7x750kW= 5.25MW	4x250kW=1 MW	7x750kW=5. 25MW	9x750kW=6.75 MW	8x2000kW=16 MW
Peak Critical Load		4MW	0.6MW	4.4MW	6MW	12.5MW
Li-ion ES Microgrid Config.	Power and Duration	4375kW 4hr	1000kW 4hr	4600kW 4hr	3600kW 4hr	1255kW 1hr
	SOC Reservation	5.16%	0.23%	0.00%	0.78%	100%
	# Gensets	5	3	6	7	6
	Secondary Services	Bill reduction	Bill reduction	Wholesale Market	Bill reduction	None
Flow ES Microgrid Config.	Power and Energy	975 kW 5hr	75kW 5hr	225kW 5hr	475kW 5hr	1075kW 5hr
	SOC Reservation	56.3%	6.25%	0%	6.25%	100%
	# Gensets	5	3	6	7	6
	Secondary Services	Bill reduction	Bill reduction	Wholesale Market	Bill reduction	None

The oversizing for maximizing value was carried out for all the sites except Fort Bliss. Due to the nature of tariff in Fort Bliss, any ES oversizing cannot translate into an increase in benefits. For the other four sites, the duration of the energy storage was assumed to be four hours and the power capacity was increased gradually in fixed steps as an iterative process with the critical load coverage cost calculated at each step in the form of a binary search. The results of the analysis are included in Figure ES-2.

For the sites at Ventura and Corpus Christi, the critical load coverage cost reduced monotonically with an increase in energy storage size. Hence, the energy storage size resulted in maximum benefit. However, for March ARB and Holloman AFB, the critical load coverage cost exhibited a non-monotonic behavior with respect to the energy storage size. The critical load coverage cost reduced initially and when upsized beyond a certain size it started to increase. Hence, after a few iterative steps, the optimal energy storage size was determined to be 1000 kW, 4 hr. and 3600 kW, 4 hr. for March ARB and Holloman AFB respectively.

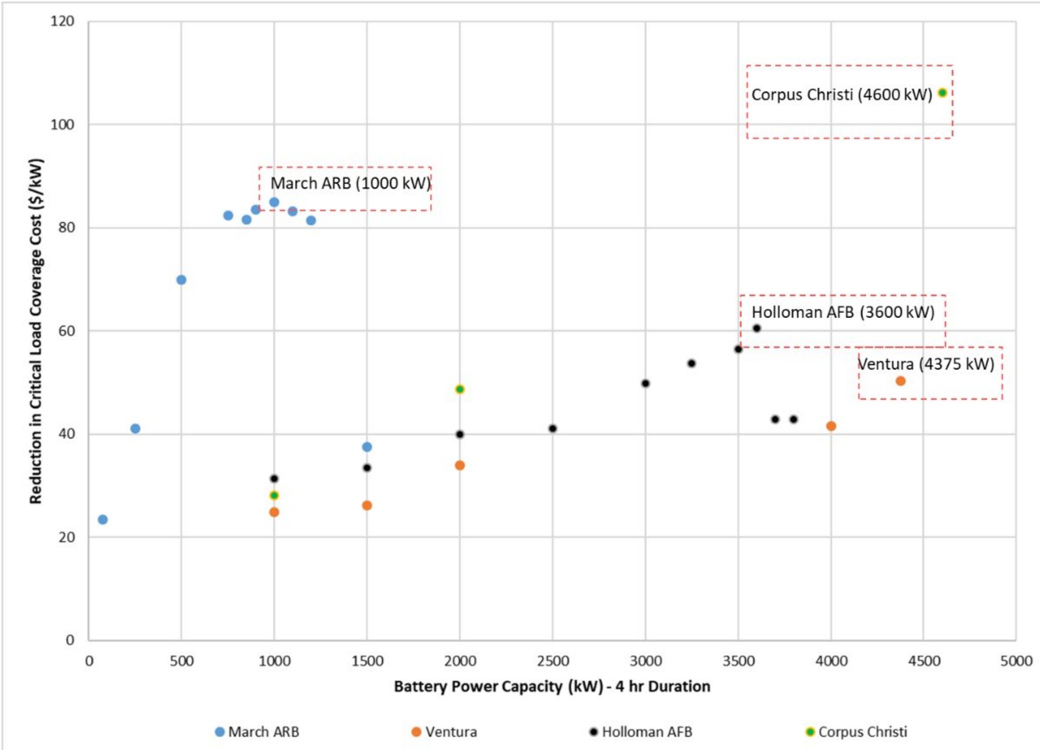

Figure ES-2. Improvement in Annual Net Cost of Serving each Kilowatt of Peak Critical Load ($/kW-yr) of the Investment case compared to Baseline Microgrid for all sites

PERFORMANCE ASSESSMENT

Reliability Performance Outcome

The technical reliability targets and performance objectives for Li-ion under different outage conditions are summarized in Table ES-3(a). The first metric, 100% critical load corresponds to the probability of the asset serving 100% of the critical load for each site. For 24- and 168-hour outages, the reliability performance is higher than the baseline. This result is also true for all outage durations between 1 and 168 hours according to the methodology.

A reliability analysis was also carried out under more stringent conditions. The results shown in Table ES-3 display the probability of serving an outage if the critical load grows to 130% of the original critical load. Finally, a reliability analysis was performed for the storage-enabled microgrid based on the critical load being 10% and 30% of the actual critical load where there is no fuel available for the diesel generators, which results in the probability of serving the critical load during a 24-hour period exceeding 90%, except at Fort Bliss. At Fort Bliss, the energy storage is sized only to meet the reliability requirements and is not oversized, as their tariff does not include provisions for energy storage to earn revenue from secondary services.

Similar results are shown in Table ES-3(b) for Flow battery-based designs, which provide better reliability performance than the baseline case for 100% critical load case. As the flow battery systems were not oversized, the probability of serving critical load is less than the results of Li-Ion storage designs.

Table ES-3. Probability of Serving Critical Load under Baseline and Investment Case

Performance Objective		Ventura		March		Corpus Christi		Holloman		Fort Bliss	
		Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment
100% Critical Load	24 hours	99.46%	99.85%	99.85%	99.98%	99.45%	99.98%	99.11%	99.95%	99.33%	99.38%
	168 hours	85.94%	96.60%	95.04%	99.98%	85.94%	99.39%	78.78%	99.46%	82.42%	89.09%
130% Critical Load	24 hours	-	98.80%	-	99.93%	-	99.49%	-	99.43%	-	73.19%
	168 hours	-	73.05%	-	97.82%	-	93.49%	-	94.48%	-	50.02%
No Gen + 10% Critical Load	24 hours	-	98.62%	-	98.60%	-	98.62%	-	98.62%	-	0.00%
No Gen + 30% Critical Load	24 hours	-	93.62%	-	98.60%	-	95.59%	-	91.64%	-	0.00%

(a) Li Ion

Performance Objective		Ventura		March		Corpus Christi		Holloman		Fort Bliss	
		Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment
100% Critical Load	24 hours	99.46%	99.68%	99.85%	99.91%	99.45%	99.55%	99.11%	99.33%	99.33%	99.50%
	168 hours	85.94%	92.99%	95.04%	97.29%	85.94%	88.19%	78.78%	88.86%	82.41%	90.79%
130% Critical Load	24 hours	-	76.32%	-	98.42%	-	70.27%	-	73.00%	-	74.65%
	168 hours	-	29.72%	-	84.26%	-	32.57%	-	43.00%	-	53.47%
No Gen + 10% Critical Load	24 hours	-	95.38%	-	40.10%	-	13.89%	-	1.12%	-	10.31%
No Gen + 30% Critical Load	24 hours	-	0.00%	-	0.00%	-	0.00%	-	0.00%	-	0.00%

(b) Flow Battery

COST ASSESSMENT

A baseline economic analysis of operating a diesel genset-based microgrid for each site was established. Inputs included capital expenditures (CapEx) and operational expenditures (OpEx).

Then, the economics of operating a Li-ion storage-enabled microgrid investment case was analyzed for each site. The cases compared 20-year Net Present Value (NPV) and of covering Annual Net Cost of Serving of Peak Critical Load ($/kW-yr) improvement. The inputs and results are presented in Table ES-4. Also, Table ES-4 shows that there is a positive improvement in NPV at all sites. The maximum improvement is 13.57% at Holloman AFB.

In regards to the annual net cost of Critical Load Coverage ($/kW-yr), it is calculated by annualizing the total NPV of installing and operating the microgrid over a 20-year period and then normalizing it based on the total critical load served. The annual cost of serving each kW of peak critical load for the Li-ion based microgrid and the baseline microgrid are compared in Figure ES-3. For the sites (entura, March ARB, and Holloman, the reduction in the number of generators and UPS systems in the investment case significantly reduces costs. In addition, the investment case designs resulted in lowering DoD site bills through lowering energy demand by.

For Corpus Christi, the Li-ion system generated more value by participating in wholesale market services. There are no regulatory restrictions related to battery upsizing limits, the battery was upsized to 4.6 MW, which also increased the capacity offering into wholesale markets. This resulted in a net negative cost. Due to the nature of tariff structure in Fort Bliss, there was no possibility of capturing other secondary value streams (wholesale market participation or bill reduction). Hence, the battery was sized primarily for reliability alone and this yielded a very marginal reduction to annual net cost of Critical Load Coverage.

Further, the revenue from secondary services, from energy storage's participation in either bill reduction or wholesale market services is also accounted for in the NPV calculation. The secondary services revenue for each site is also included in Table ES-4. The revenue was calculated using EPRI's optimization tool StorageVET®. Including the avoided assets costs and additional secondary revenue, an improvement in 20-year NPV is recorded for all sites.

Table ES-4. Cost Benefit Analysis of Li-ion based Microgrid Configuration

	Naval Base Ventura County	March ARB	Corpus Christi	Holloman AFB	Fort Bliss
Battery Size (Li Ion)	4375 kW, 4 hr	1000 kW, 4 hr	4600 kW, 4 hr	3800 kW, 4 hr	1225 kW, 1 hr
Li Ion Cost (CAPEX) ($/kWh)	$445/kWh	$540/kWh	$445/kWh	$477/kWh	$1084/kWh
Li Ion Cost (OPEX) ($/kW-yr)	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year
Baseline NPV (20 Yr) (Cost)	$108.95	$62.45	$113.05	$96.14	$302.40
Investment Case NPV (20 Yr) (Cost)	$105.27	$61.50	$101.16	$83.09	$301.32
% NPV Improvement	**3.38%**	**1.52%**	**10.52%**	**13.57%**	**0.36%**
Baseline Critical Load Coverage ($/kW-yr)	**135.5**	**416.09**	**88.52**	**98.35**	**$82.70**
Storage-Enabled Critical Load Coverage ($/kW-yr)	**85.2**	**337.42**	**-17.3**	**65.53**	**$76.20**
% Critical Coverage Improvement	**37.12%**	**18.91%**	**119.54%**	**33.37%**	**7.86%**
# Generators Retired	2	1	1	2	2
Secondary Services	Retail Bill Reduction	Retail Bill Reduction	Wholesale Services	Retail Bill Reduction	N/A
Total Sec. Service Revenue ($)	$8,785,963	$2,340,716	$18,175,974	$8,275,987	N/A
Avoided Costs due to Demand Charge Reduction	$4,850,519	$1,249,439	N/A	$7,031,375	N/A
Avoided Costs due to Energy Cost Reduction	$3,935,444	$1,091,277	N/A	$1,244,612	N/A
Demand Response	2,490,684	$43,611	N/A	$1,558,580	N/A

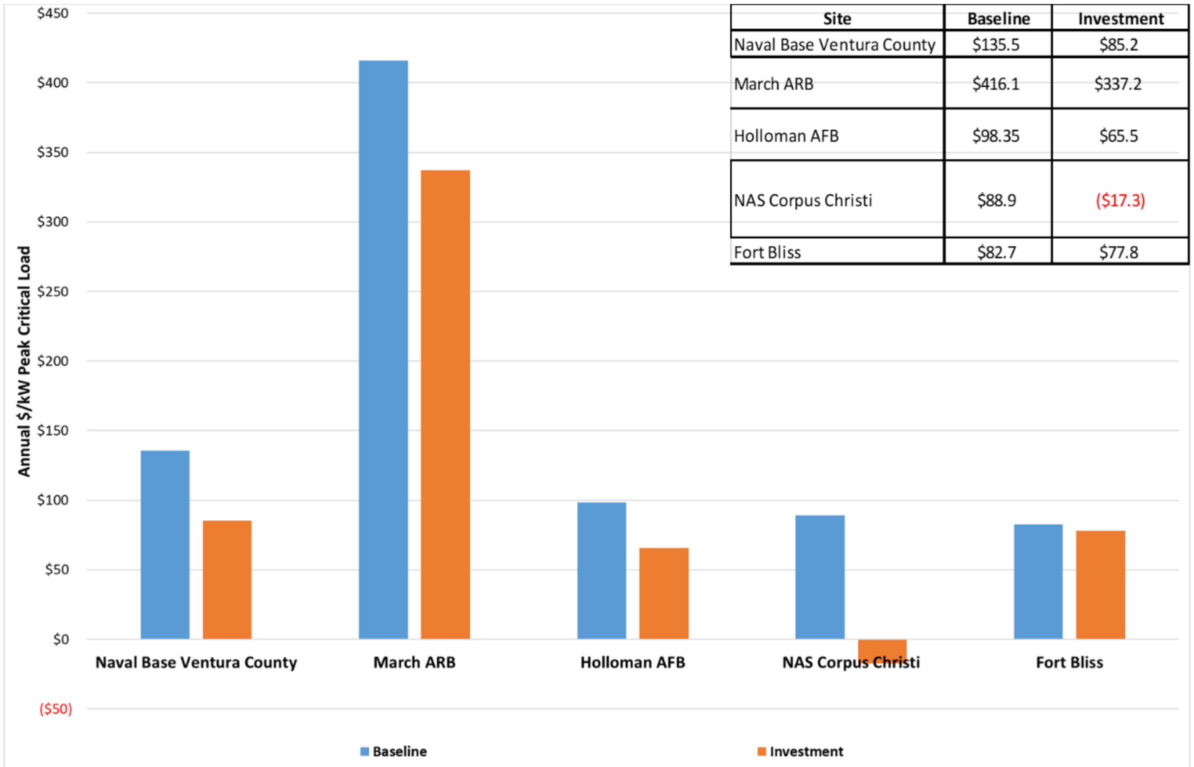

Figure ES-3. Annual $/kW Peak Critical Load Coverage Variations Across Five Installations

Next, economic analysis for the Flow battery-based microgrid was carried out. Unlike the Li-ion technology, the CapEx[5] and OpEx data for the Flow battery system was not available, and so a different approach for these investment cases was required. It was determined that the "need to cost"[6] methodology could be used that would result in comparable values to the Li-ion NPV improvement analysis.

Table ES-5. Flow Battery Cost Development Based on 'Need to Cost'

	Naval Base Ventura County	March ARB	Corpus Christi	Holloman AFB	Fort Bliss
Flow Battery Size	975 kW, 5 hr	75 kW, 5 hr	225 kW, 5 hr	475 kW, 5 hr	1075 kW, 5 hr
Li-ion Battery Size used for deriving Flow Battery "Need to Cost"	875 kW, 5 hr	75 kW, 5 hr	225 kW, 5 hr	450 kW, 5 hr	1225 kW, 5 hr
Flow Battery "Need to Cost" (CapEx + OpEx) ($/kWh)	$502/kWh	$926/kWh	$724/kWh	$735/kWh	$822/kWh

[5] CapEx cost determined based on EPRI cost study 3002013957 *Energy Storage Technology and Cost Assessmentv3002013958 Energy Storage Technology and Cost Assessment: Executive Summary,* which is publicly available

[6] CapEx and OpEx costs were not provided by Lockheed Martin (LM) for the flow battery system. LM indicated that the information is proprietary, therefore EPRI and LM jointly came up with the "need to cost" methodology

The "need to cost" numbers for the minimum Flow battery size requirement case was then compared with the $/kW and $/kWh numbers that were captured from several Flow battery manufacturers. The "need to cost" numbers at each site was outside the cost ranges that were obtained from the vendors, therefore the project team found no feasible oversized Flow battery systems and chose to forego sensitivity analysis on them.

Table ES-6. Flow Battery Cost Range from Various Vendors

	Vendor 1	Vendor 2	Vendor 3	Vendor 4
$/kW	4134	4120	5860	3489
$/kWh	1060	1373	1173	1162

STUDY CONCLUSIONS AND OUTCOMES

The microgrid analysis methodology using storage-enabled microgrids, as illustrated in the results shown in Table ES-3 through Table ES-5, indicated the following overall benefits:

1) Optimized microgrid designs at five DoD installations, consisting of diesel generators, UPS, storage, and solar PV are capable of meeting DoD performance objectives and reliability targets as a function of outage durations between 1 and 168 hours. Reliability performance of the storage-enabled microgrid is equal to or greater than the reliability targets specified for each DoD site for all outage durations ranging up to 168 hours.
2) Storage-enabled microgrids, using either Li-ion or Flow batteries, enhance reliability and energy security by avoiding the cost of lost loads during outages, lower cost of operations, enable power market participation, and result in a positive NPV compared to diesel-based microgrids
3) Storage-enabled microgrids, either Li-ion or Flow batteries, reduce the 'loss of critical load' risk during grid outages and reduce the cost of serving critical load
4) Incremental values of using storage-enabled microgrids were found to include:
    - Avoided energy costs through self-generation and arbitrage
    - Avoided cost due to diesel generation reduction and fuel savings
    - Avoided peak demand costs (except at Fort Bliss)
    - Avoided cost due to diesel generator OpEx
    - Avoided cost due to UPS reduction
    - Avoided cost due to UPS OpEx
    - Demand response program participation value (except at Fort Bliss)
    - Emissions reduction through increased renewable generation
5) The annual cost of serving peak critical load ($/kW-yr) is lower for the proposed storage-enabled microgrid compared to the baseline microgrid. The maximum decrease in the cost is at Corpus Christi and the minimum is at Fort Bliss. At Fort Bliss, the energy storage is not allowed to gain additional revenue from secondary services, and hence the annual cost of serving the critical load is higher.

6) The proposed microgrid design for Corpus Christi site provided negative annual cost of serving peak critical load ($/kW-yr). It implies that there is a possibility of making profit by installing storage-enabled microgrid.

7) Energy storage systems are sized initially to meet the reliability target for each of the five sites. The oversizing analysis proved that a large storage-enabled microgrid could provide more benefits and thereby reduce the annual cost of serving peak critical load ($/kW-yr). The oversizing iterations and the corresponding cost change ($/kW-yr) are included in Figure ES-2. At Corpus Christi and Ventura, large energy storage size meant more benefits. And the oversizing had to be capped to the site's min load. Whereas, at March and Holloman site, the annual cost of serving peak critical load saturated and increasing the power capacity further did not lower the cost further.

8) The SOC reservation for the final microgrid design were less than 5% for all sites. And at Corpus Christi it is 0%. A minimal energy storage reservation is required to meet the primary objective of meeting the reliability target.

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1.0 INTRODUCTION

The U.S. Department of Defense (DoD) seeks to improve energy security through the deployment of microgrids at military installations. These microgrids are evaluating the viability and benefits of incorporating energy storage technologies. Recent cost reductions and performance improvements of emerging energy storage (ES) technologies may hold the key to improved operational duration, resilience, and cost-effectiveness of renewable and hybrid microgrids. The maturation of these technologies with the advance of their control will assist military installations meet their renewable energy goals as well as their "Three Pillars of Energy Security"; Reliability, Resiliency, and Efficiency.

1.1 OBJECTIVES

The overall objective of the Phase 1 project was to improve energy security on military bases while reducing the cost of providing electric service by optimally designing and implementing microgrids with large-scale energy storage[7]. An innovative and repeatable microgrid design methodology was developed to generate least-cost, robust microgrid designs that are competitive with similar diesel generator-based microgrids in net cost and critical load coverage probability. By subjecting the designs to rigorous stochastic simulation, the method explored many reliability and economic scenarios to characterize the reliability, resiliency, and economic performance of the designs.

As part of the Phase 1 project, the Project Team, which includes EPRI, Southern Company, PowerSecure, and Lockheed Martin applied a microgrid analysis methodology and successfully modeled the use of ES technologies. Reliability performance targets, valuation of stacked services, and economically optimal sizing at five DoD installations were investigated. The Baseline analysis modeled diesel based microgrids with Uninterruptible Power Source (UPS) for each of five identified DoD sites. The investment cases modeled renewable/storage-enabled microgrids comprised of solar photovoltaics (PV), diesel generators, UPS, and either Li-ion ES or a Flow battery ES, in order to indicate improved reliability for each DoD site as a function of cost. The results then compared the Baseline diesel microgrid to two investment microgrid cases; a Li-ion ES and a Flow battery ES. The evaluation methodology executed by the project team demonstrated the cost-effectiveness of storage-enabled renewable microgrid solutions compared to diesel based microgrids.

The outcomes of Phase I analysis for each of the five selected sites resulted in:

- Detailed technical and financial outcomes for the proposed storage enabled microgrid design;
- The expected critical load coverage probability for grid outages lasting between 0 and 168 hours relative to the provided baseline microgrid;
- The expected economic benefits from the microgrid due to wholesale electricity market participation to offset diesel generator and UPS costs, and energy bill reduction.

[7] Storage-enabled microgrids are also termed "Investment Cases"

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The project investigated the viability of using long-duration energy storage in a microgrid to improve energy security, reliability and provide continuity of service for critical loads during grid outages at improved costs relative to an otherwise identical *diesel generator-based microgrid*. In addition, the project evaluated opportunities to use storage simultaneously for multiple applications ("stacking benefits").

The two energy storage technologies considered for this study are summarized in Table 1. Design variables considered are also summarized in Table 1. The storage system design consisted of modeling energy and power capacity, roundtrip efficiency, and availability for two different storage technologies: Li-ion and Flow batteries.

The storage design variables namely availability and round-trip efficiencies were obtained from PowerSecure and Lockheed Martin. Even though for battery storage one could build a failure model like the one used for diesel gensets, finding data on probability of failure is a difficult task. Instead, the probability of a storage system to be operational is usually characterized by the availability. Availability is the percentage of time that a storage system is operating (excluding planned outages). This implies that 1-availability is the time that a storage system is inoperative due to failures. In this work, the failure model consists on having a probability of 1- Availability of the battery system to be operational at the beginning of an outage. If the system is operational at the beginning of an outage, it will remain operational until the end of said outage.

Factors that lead to unavailability: Currently, there are ongoing efforts within EPRI (part of a Reliability Initiative with utility members) to obtain more formal data on the root-cause of issues that take battery storage systems offline, however, practical experience has shown that failure in network communications, as well as HVAC issues are among the top causes of storage outages. Given that this is a valuation-based planning model, we have followed the assumption that the battery system provides the nameplate capacity during its full lifetime. This is done to prevent over complicating the optimization problem. This is a standard assumption to carry-out techno-economic analysis.

Table 1. Storage Technology Design Variables

	Availability	Roundtrip Efficiency	Feasible Duration
Li-ion ES[8]	98.63%	91%	30 minutes to 4 hours
Flow Battery ES[9]	98%	71%	5 hours to 12 hours

Based on consultation with PowerSecure in 2019

9 According to Lockheed Martin by 2021. The vendor-provided data from 2021 to come up with the cost estimate to represent the 2020 scenario

2.1.1 LI-ION Technology[10]

Commercial lithium ion batteries have been around since the 1990s. Lithium ion batteries have higher energy densities and longer cycle life than other forms of electrochemical storage, and are capable of performing in either high power and energy applications. These characteristics have enabled lithium ion batteries to be prevalent in portable electronics, hybrid electric vehicles (HEVs), and plug-in hybrids (PHEVs), and more recently, grid-connected stationary energy storage. Lithium ion batteries are unique among other storage technology options in that they share the economies of scale of battery production for electric vehicle, a separate and growing market. This is an important factor driving the dramatic cost declines for lithium ion batteries in recent years. Key stakeholders in grid-scale deployments – utility companies, regulators, battery vendors, and system integrators – are now gaining significant working experience with lithium ion battery grid-scale energy storage systems.

Several well-defined oxide cathode chemistries for lithium ion batteries have been developed over the last several decades. Thus, the term "lithium ion battery" describes a general type of device, rather than a single specific device with a well-defined materials composition. However, all types of lithium ion batteries with oxide cathodes have the same principle and mechanism of operation.

Lithium ion batteries are well suited to a wide range of stationary storage applications due to their combination of energy density and power density. Several other technical characteristics contribute to the successful application of lithium ion batteries:

- Good round-trip efficiency. Lithium ion batteries have 80-90% AC-AC round-trip efficiency, higher than most other energy storage technologies.
- Fast response. Lithium ion batteries can begin charging or discharging very rapidly, and so are capable of fast-response services such as frequency regulation.
- Flexible configuration. Lithium ion batteries are commercially deployed in systems ranging from 15 minutes to four hours' duration (i.e. duration of dispatch at maximum rated power).
- Low self-discharge. Lithium ion batteries have modest self-discharge (loss of stored energy over time).

This combination of desirable characteristics is reflected in the successful (commercially demonstrated) application of lithium ion batteries for a range of front-of-meter applications (frequency regulation, resource adequacy, transmission/distribution investment deferral) and behind-the-meter applications (demand response, backup power, demand charge reduction).

Lithium ion batteries also have some characteristic disadvantages that include potential for thermal runaway, capacity degradation due to both cycling and time, and high raw materials costs for some chemistries.

[10] https://energystorage.epri.com

2.1.2 Flow Battery Technology

The flow battery system that was evaluated was Lockheed Martin's GridStar Flow battery, it is comprised of two tanks of electrolytes which are pumped through a separate reaction stack, where the energy-releasing electrochemical reaction takes place. In principle, flow batteries allow much longer duration than conventional batteries, as additional duration can be achieved simply by adding additional tanks of electrolyte. Thus, for long-duration, Flow batteries have the potential to be much lower cost than Li-ion batteries. This decoupling of energy and power is key to cost-effective long-duration storage. As duration increases, the power equipment is amortized over more energy, so the cost per watt-hour is reduced. From an applications standpoint, this ability to independently specify power and energy improves asset utilization. Another advantage of the flow battery cell architecture is the ability to perform full charge-discharge cycles without degrading capacity. Sealed batteries (e.g., Li-ion) in contrast, suffer structural or morphological changes which limit cycle life when deep discharged. In practice, this means that sealed battery deployments must be oversized and/or augmented with new cells during their project life to compensate for capacity loss.

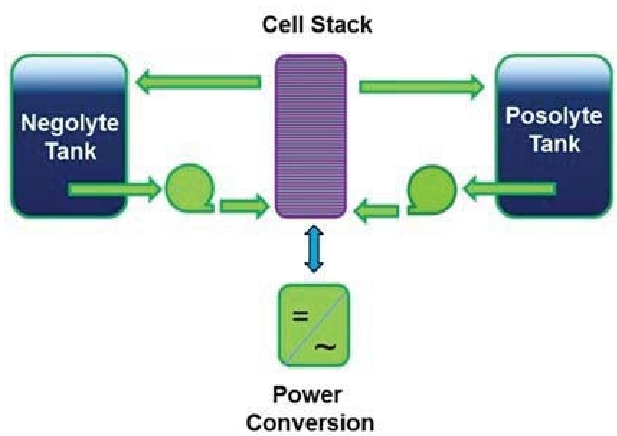

Figure 1. Schematic Depiction of a Redox Flo Battery Architecture

<u>*CCFB Electrolyte*</u>: The heart of the GridStar™ Flow CCFB technology is a novel redox chemistry that enables low cost, high efficiency energy storage and the potential for long service life. The patented coordination chemistry framework provides the basis for tailoring the physical and electrochemical properties of the solutions to achieve many desirable product attributes simultaneously. The positive and negative active material solutions (posolyte and negolyte, respectively), are complexes of earth-abundant first-row transition metals and organic ligands. In keeping with a desire to utilize off-the-shelf balance of plant equipment and piping, the electrolytes are formulated and maintained in aqueous solutions at pH 11. The high solubility and molecular stability of this mildly alkaline liquid is a consequence of proper electrolyte molecule design.

<u>*CCFB System Configuration and Balance of Plant*</u>: GridStar™ Flow energy storage systems are comprised of one or more 250kW blocks called Energy Storage Units (ESU), each having four electrochemical stacks, a pair of electrolyte tanks, independent power conversion electronics, and the requisite balance-of-plant equipment to manage electrolyte delivery, thermal management, and control. Figure below depicts a pilot-scale system with five modules and tanks capable of accommodating ten hours of storage, yielding a 1.25MW, 12.5MWh system as shown. Larger tanks will provide longer storage durations of storage.

System Controls: Each 250kW ESU includes a battery management system (BMS) which monitors state-of-charge and state-of-health of the DC battery and controls the flow of electrolytes. This ruggedized industrial controller employs advanced algorithms to optimize hydraulic efficiency in real-time, compensating for plant variability and aging. State-of-charge balance between the two electrolytes is also managed by the BMS. At the site level, a GridStar™ Site Controller provides supervisory control and coordination of the DC modules and associated AC-DC-AC power conversion systems (PCS). It is a flexible platform, written in Java, with several customer interface options. In stand-alone operation, a web dashboard accepts real and reactive power commands for immediate or scheduled execution. Common energy storage applications, such as load following, can also be launched through Graphical User Interface (GUI). MODBUS TCP/IP and DNP3 interfaces are available as well. The site controls include a hardened network router and Lockheed Martin developed cyber security measures. The GridStar™ Site Controller provides role-based access and user input validation.

2.1.3 Key Performance Attributes

System power ratings are defined as net power provided on the AC side of the PCS at end of life. Electrolyte volumes are selected to minimize the total system installed cost for a given power and energy rating. Since conversion and pumping inefficiencies are high at extreme electrolyte states of charge, the system is designed to operate over a restricted depth of discharge. The resulting "excess" active material is excluded from the nameplate energy capacity. From an operator's perspective, the battery can be cycled through 100% discharge cycles with no derating required.

Round trip losses in GridStar™ Flow are a non-linear function of the state of charge of the battery and the rate at which the battery is charged and discharged. In general, it is expected that the average AC-AC round trip efficiency over a full charge and discharge cycle will be greater than about 70%.

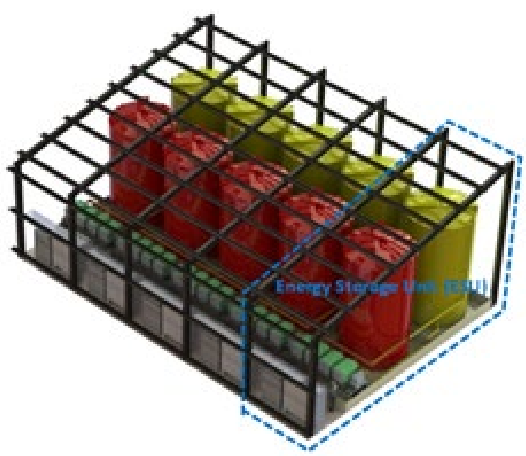

Figure 2. 1.25MW | 12.5MWh GridStar Flow™ ESS Consisting of (5) 250kW Energy Storage Units (ESU).

Dimensions: 15m x 20m x 9m (W x L x H)

Since flow battery electrolytes are stored away from the stacks, flow batteries can experience relatively little self- discharge, and, unlike sealed cells, can store energy at high states-of-charge without accelerated degradation.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The proposed Li-ion technology is at the *diffusion* stage (commercial products now being adopted with wide deployments). However, little data exist to validate battery ES system performance when targeting simultaneous stacked values. Flow battery technology is primarily in the prototype development and verification stage. For the purpose of this analysis, Lockheed Martin Energy (LM) GridStar™ Flow was targeted. The GridStar™ is their latest product to be commercialized by LM Energy. Full-scale testing is underway at LM Energy's development center in Massachusetts. Pre-production Beta testing was accomplished in 2018, leading to first production units being deployed in 2019.

2.3 RISKS ASSOCIATED WITH THE TECHNOLOGY

The principal risks for the project are associated with integration of various technologies into a single microgrid at a given location accounting for military cyber security requirements using the DoD Risk Management Framework (RMF) approach. The microgrid analysis and design approaches, as well as energy storage design, are well-established. Applying these approaches in a military installation will require a comprehensive multi-dimensional approach. The individual distributed generation technologies as well as microgrid control and integration technologies are in varying stages of maturity but have been deployed successfully in past projects. The LM GridStar™ Flow battery technology is relatively new and has not been deployed in the field; the risks associated with this technology are being addressed through Lockheed Martin's well-established record of qualification and acceptance testing through which advanced technologies are tested extensively at the component and subsystem level to ensure high performance and reliability in the completed commercial product.

2.4 FEDERAL ENERGY REGULATORY COMMISSION

The Federal Energy Regulatory Commission (FERC) regulates interstate commerce for the energy industries in the United States. As part of its purview, it establishes regulations for the operation of the organized independent system operator/regional transmission organization (ISO/RTO) markets. Through a series of FERC orders in recent years (Order 745 on demand response and Order 841 on energy storage), ISO markets have made various provisions to enable new resources such as demand response to actively participate in energy, ancillary service, and capacity markets, where they exist. DER is subject to a separate proposal-making process at present.

FERC has recently had three main initiatives focused on the broad umbrella of DER integration—order-on-demand response, energy storage, and an ongoing proceeding on DER. FERC Order 841, introduced in 2018, directs the ISO/RTO markets to develop and implement a participation model for electric storage that accounts for its physical and operational limitations and provides the option to the asset owner to manage its own state of charge (SoC) [1]. This is designed to remove the existing barriers that prevent the DER from participating in multiple market products, such as ancillary services, capacity, and energy. Furthermore, the minimum size threshold for participation models is lowered to 100 kW for both multi-node and single-node aggregations to reduce the participation barrier and encourage participation from DER aggregations that are required to be located at a single pricing node. In its original Notice for Proposed Rulemaking in 2017, FERC required the ISO/RTO markets to allow for DER resources to aggregate and participate in the wholesale electricity markets. FERC is currently in the process of creating an order to determine and set the related rules; it held a technical conference on the topic in May 2018. The envisaged participation models should be such that the DER can participate in the wholesale electricity markets—that is, the DER are dispatchable, able to set the wholesale market-clearing price or the locational marginal price (LMP), and are settled at the LMP for energy, analogous to the conventional resources. Contemporary market practices limit the participation of electric storage in markets as either a demand participant or a generation participant. Furthermore, electric storage is not allowed to participate in multiple markets simultaneously, such as the co-optimized energy and operating reserve markets found in the United States. Presently, all the ISO/RTO markets are in the process of modifying and updating their procedures and software to comply with FERC Order 841, the deadline for which is December 2019. FERC Order 841 modifications related to storage include:

- ISOs must include a **participation model** for electric storage resources (ESRs) that allows them to participate in energy, ancillary service, and capacity markets when technically capable of doing so
- ESRs must be eligible to **set the wholesale price** as both a buyer and seller when the marginal resource
- ISOs must **account for physical parameters** of ESRs through bidding or otherwise
- ISOs must allow a minimum size requirement that is at most **100 kW**
- Sale of energy that is stored from purchases in the wholesale market must be **sold at wholesale nodal prices**
- ISOs must allow **self-management** of state of charge (SOC)

841 Aspect	NYISO	PJM	SPP	ISO-NE	MISO	CAISO
Participation Model	1. Most entities are proposing two separate participation models: Continuous (e.g., batteries) and discontinuous (e.g., PSH) models 2. Can participate in energy, AS, and capacity markets (wherever applicable)					
	ESRs and **ELRs**; PSH cannot submit a charge and discharge offer in the same hour	**ESRs**; PSH plants can still use **pumped hydro optimizer**	**MSRs**; PSH plants cannot submit a charge and discharge offer in the same hour	**CSFs** and **BSFs**	**ESRs**	**NGRs** and **PSH model**
Offer Parameters	1. Almost all entities are proposing a continuous model for ESRs (continuous offer curve, excludes commitment related parameters, e.g., min and max charge and discharge/run times, fixed costs)					
	ESRs must submit SOC (RT telemetry) and roundtrip efficiency; excludes max and min charge and run times	ESRs must submit RT SOC telemetry for **situational awareness**; excludes max and min charge and run times	MSRs must submit SOC (DA offer/RT telemetry), loss factor and SOC limits; introduced max and min charge and run times	ESFs must submit two new telemetry points in RT; min charge and run times required in DAM & RTM	Must submit SOC (DA offer/RT telemetry), efficiency factor and SOC limits; max and min charge and run times managed by ESR owner	ISO manages SOC if SOC limits submitted; min charge and run times for NGRs to be managed by SOC parameters or offers
Pricing and Settlement	1. All entities are allowing ESRs to: set wholesale prices in all markets when marginal, purchase/sell at wholesale prices, and receive make-whole payments if dispatched out-of-market 2. Almost all entities are proposing that withdrawals from ESRs will not be subject to transmission charges when charging to provide a specific service to the ISO/RTO (including withdrawals for later injection of energy)					
	Self-committed fixed or flexible ESRs ineligible to receive DA BPCG, self-committed flexible eligible for RT BPCG; ISO-SOCM ESRs ineligible for RT BPCG; withdrawals exempt from transmission charges	PSH using hydro optimizer cannot set wholesale prices and offer negative dispatchable range		Limited duration CSFs will not be paid an opportunity cost payment when dispatched below 15 minute available energy to provide reserve	Transmission charges to ESRs applicable when charging to resell energy at a later time (only regulation exempted)	NGRs not charged transmission charges when charging to resell energy later

841 Aspect	NYISO	PJM	SPP	ISO-NE	MISO	CAISO
Ancillary Services	1. All ISOs are allowing ESRs to provide AS (without requiring energy schedules) provided ESRs respect AS duration requirements while allowing for capacity de-rates to meet the duration					
	1-hour duration; AS schedules will respect RT telemetered SOC regardless of SOCM mode	ESRs providing synchronized reserve must update SOC in RT; ESRs can offer synchronized reserve without energy offers	1-hour duration; MSRs can provide AS without energy schedule but require energy offers	BSFs cannot provide regulation as DARD until 2024; automatic de-rating for CSFs to meet duration requirements (1-hour AS duration, 0.25-hour duration for DARD AS); limited duration CSFs can use the reserve down flag to opt out of reserve provision and only provide energy	1-hour duration; regulation deployment by ESRs should meet energy storage limitations	1-hour duration in DAM, 0.5-hour in RTM; NGRs providing AS must telemeter SOC; restricted market participation for NGRs if opting for reg. energy management in DA
Capacity Market	1. All ISOs have modified their tariffs to allow ESRs to de-rate their capacity to meet their capacity market's minimum duration requirements					
	4 sustained hours (proposed to be modified to 6 hours); ESRs should elect ISO-SOCM in DAM if participating in capacity market, but can opt for Self-SOCM in RTM	**10 sustained hours**	**4 sustained hours** to meet RA requirements	**2 sustained hours**	**4 sustained hours**	**4 sustained hours** for RA participation; aggregation allowed across multiple PNodes for capacity provision

841 Aspect	NYISO	PJM	SPP	ISO-NE	MISO	CAISO
State of Charge Management	1. Only a few ISOs are proposing to allow for both ISO-SOCM and Self-SOCM 2. Entities that are offering only the Self-SOCM option, i.e., SPP, ISO-NE and MISO, are ensuring SOC feasibility					
	ISO-SOCM (ensures SOC feasibility, but not optimality) and **Self-SOCM** (does not ensure SOC feasibility, but ISO will align schedules with telemetered SOC in RTM); ESRs can switch between SOCM modes within RTM, between DAM and RTM; **PSH plants – Self-SOCM**	**ESRs** (continuous model) – **Self-SOCM** (does not ensure SOC feasibility, current SOC telemetry will not be used to optimize ESRs across intervals); **PSH plants – ISO-SOCM**	**Self-SOCM**; ensures SOC feasibility; can submit max daily MWh limit	**Self-SOCM**; two new telemetered points in RT (15-mins and 1-hr available energy and storage) to ensure SOC feasibility; ESFs can submit max daily MWh charge and discharge limits in the DAM	**Self-SOCM**; ensures SOC feasibility; max daily MWh limit included only for PSH plants	**ISO-SOCM** (ensures SOC feasibility, but not optimality) and **Self-SOCM** (does not ensure SOC feasibility); can submit daily min and max MWh limits for DAM
Minimum Size	1. All entities have reduced their minimum size limit to 100 kW for all markets					
	Allows aggregation behind the same T node	Allows aggregation behind the same electrical location		Allows aggregation behind a single POI (unlike DR assets)	Phased approach with limited number (50) of ESRs at this size in Y1	500 kW for AS; allows aggregation across multiple PNodes
Metering	1. All entities have required ESRs to be directly metered					
			Meter agents required to submit settlement meter values			

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3.0 PERFORMANCE OBJECTIVES

The performance objectives that were taking into consideration for the analysis are shown in Table 2. These performance objectives were used as the primary criteria to evaluate the modeling of the two selected energy storage technologies. As will be described in the subsequent sections, they provided the basis for evaluating the energy security performance and the net costs of the technologies.

Table 2. Performance Objectives Considered

<table>
<tr><th>Performance Objective</th><th>Metric</th><th>Requirements</th><th>Success Criteria</th></tr>
<tr><td>1. Reliability to Meet 100% of Installation Critical and Ride-through Load</td><td rowspan="4">Critical and ride-through load served during outage (that can begin at any time)</td><td rowspan="2">Performance measured for outages of any duration between 1 hour and 168 hours</td><td>Meets or exceeds reliability probability curve from baseline microgrid specifically for 24- and 168-hour outages. Compares favorably with baseline microgrid at other outage durations under 168 hours.</td></tr>
<tr><td>2. Reliability to Meet 130% of Installation Critical and Ride-through Load</td><td>Proportion of critical and ride-through load served (probabilistically) for 24- and 168-hour outages. No minimum standard.</td></tr>
<tr><td>3. Reliability to Meet 10% and 30% of Installation Critical and Ride-through Load when no Diesel Fuel is Available</td><td>Performance measured for outages of any duration between 1 hour and 24 hours</td><td>Proportion of critical and ride-through load served (probabilistically). No minimum standard.</td></tr>
<tr><td>4. Net Life-cycle Costs of Deployment and Operation (corresponding to technical objective 1 above)</td><td>Calculate per methodology distributed with baseline microgrid data and results</td><td>Net cost (per kW of critical load) is at or below level of baseline microgrid in current and future volatile scenarios</td></tr>
</table>

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4.0 FACILITY/SITE DESCRIPTION

The five sites analyzed and evaluated in this project are: Fort Bliss, Naval Air Station Corpus Christi, Naval Base Ventura County, Holloman Air Force base, and March Air Reserve base. For each site the load was analyzed for its load statistics, available generation and seasonality in data. June through September is considered as summer months and October through May is considered as winter for all the sites. The results are shown in Table 3.

Table 3. Site Characteristics

Analysis metrics		Naval Base Ventura County	March Air Reserve base	Naval Air Station (NAS) Corpus Christi	Holloman Air Force base	Fort Bliss
Peak load (kW)	**Annual**	14992	7998	23965	15990	67605
	Summer	14992	7996	23965	15990	67605
	Winter	14787	7998	23720	13855	57399
Critical Load (kW)		4003	600	4410	5996	12507
Max PV gen. (kW)		811	386	1159	4828	5986
# of Diesel Gensets		7	4	7	9	8
Genset Size (kW)		750	250	750	750	2000
Ratio of peak load to total generation		0.76	0.6	0.838	0.88	0.78

All sites are seen to have a summer peak load. Critical load is calculated as a given percentage of peak load that needs to be powered at all times. At each site, there is a designated number of diesel gensets, as shown in Table 3. For reliability calculation, 20% of the given PV output is considered as firm capacity able to serve the load to take into account the uncertainty of PV output. For storage charging, 100% of the hourly PV output is available. All sites are analyzed to participate in the wholesale market and perform demand/bill reduction. Wholesale market services taken into consideration are: day ahead (DA) energy time shift, and frequency regulation. Bill reduction components taken into consideration include: energy cost reduction, demand charge reduction, and participation in the demand response program. For the wholesale market services case, only the battery's capacity was used for revenue. For the bill reduction case, both the battery and the PV capacities were considered for optimizing the battery's operation for bill reduction. However, while calculating the NPV of the project only the incremental value offered by the ESS was considered since the PV was already a part of the baseline microgrid. For the California sites, no demand response was modeled for the baseline microgrid case.

4.1 FACILITY/SITE ASSUMPTIONS AND INITIAL CONDITIONS

For each site, storage was modelled on basis of critical[11] load, and available generation using the two storage technologies. Li-ion storage sizes varied between 0.5-4hrs in steps of 0.5 hrs. Flow battery sizes were varies from 5 to 12 hours in steps of 1 hr. The yearly site load for all sites are included in Appendix A1.

11 Site load is the total load on the site. Critical load is only the load that must be supported by the microgrid

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5.0 METHODOLOGY

The end goal is to design the most cost-effective microgrid with storage, diesel generators, UPS and PV that meets the ESTCP reliability targets, which is associated with a baseline microgrid consisting of diesel generators and UPS. The reliability target is given as a probability curve for serving the site's critical load during for outage duration lasting between 1 and 168 hours. The design must take into consideration the effect of failures of energy resources on the performance of the microgrid.

With an understanding of the site characteristics and loading specifics, the storage-enabled microgrid is designed. In order to analyze two battery storage technologies, Li-ion and Flow, microgrids with each technology are separately analyzed and compared. Differences between the two technologies include roundtrip efficiency, feasible duration, and reliability. Table 4 describes the analysis steps for the Phase 1 storage enabled microgrid design. The full microgrid design process applied to each site includes the following steps:

Step 1: Sizing and Reliability Analysis: Monte-Carlo[12] based reliability analysis & storage sizing for a PV/Diesel/Storage-enabled microgrid

Step 2: Iterative SOC Reservation Design: StorageVET® State of Charge (SOC) analysis for to identify minimum SOC reservation requirement to satisfy the reliability requirement while providing economic services

Step 3: Oversizing Sensitivity Analysis: Sensitivity analysis over storage size identify potential value of storage oversizing

Step 4: Cost-Benefit Assessment: Analyze the reliability performance and economic performance of the designed microgrid

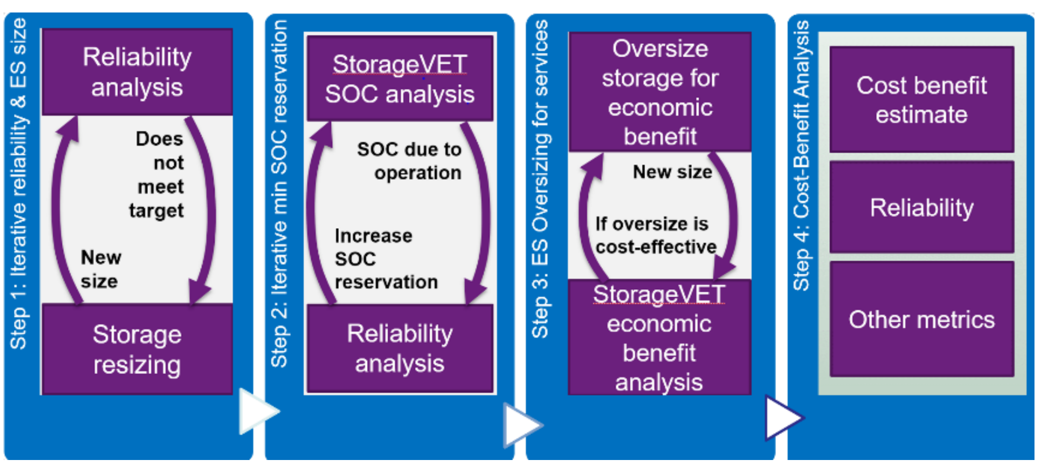

Figure 3. Technical Approach – Workflow

12 Markov Chain Monte-Carlo Simulations and Their Statistical Analysis (With Web-Based Fortran Code). Hackensack, NJ: World Scientific. Kroese, D. P.; Taimre, T.; Botev, Z.I. (2011). Handbook of Monte Carlo Methods. New York: John Wiley & Sons. p. 772

Figure 3 shows the logical flow for the design and analysis of the microgrid. Table 4 shows the inputs and outputs of each step followed in the analysis logic.

Table 4. Inputs and Outputs for Each Step of the Technical Approach to Microgrid Design and Analysis

<table>
<tr><th></th><th>Inputs</th><th>Outcomes</th></tr>
<tr><td>Step 1: Iterative design for reliability and ES sizing</td><td>Failure model for storage and gensets, critical load data, PV generation data, storage model, Storage CapEx</td><td>Energy storage size (power and energy capacity) and number of diesel generators for the least cost microgrid capable of supplying critical load with the required performance, given by a probability vs outage duration curve. Outage duration curve.</td></tr>
<tr><td>Step 2: Iterative SOC reservation design</td><td>Energy storage size, market prices, tariff rates, failure model for storage and gensets, critical load data PV generation data</td><td>Minimum State of Charge reservation (energy) requirement to satisfy reliability objective while performing economic services.
List of economic services to be performed by the microgrid.</td></tr>
<tr><td>Step 3: ES oversizing sensitivity analysis</td><td rowspan="2">Minimum energy reservation requirement, CapEx of equipment, equipment lifespan, OpEx, economic grid services to be provided, tariff rates, market prices, failure parameters</td><td>Energy storage size and number of diesel generators for the best NPV microgrid of the sensitivity analysis</td></tr>
<tr><td>Step 4: Cost-Benefit assessment</td><td>Probability vs outage duration outage curve for the best NPV microgrid, NPV, critical load coverage economics</td></tr>
</table>

A more detailed explanation of the process that is carried out in each step is presented next.

Step 1: Sizing and Reliability Analysis: The battery storage system is designed to meet the reliability objective at the least possible cost. The present step involves finding the smallest battery storage system that meets the reliability requirement. To that end, a Monte Carlo reliability simulation is combined with a binary search algorithm that updates the battery size at each iteration.

Step 2: Iterative SOC reservation design: Once the minimum battery size for reliability has been found, the focus of the analysis is to find any potential use of the battery for economic objectives without affecting the ability to meet the reliability objective.

In the previous step we found a storage system size that would satisfy the reliability objective, if it was only used to provide back-up for critical loads. This implies a system where 100 % SOC is always reserved for back-up. This second step of the modeling process finds the minimum % SOC reservation of the battery, while still satisfying the reliability objective.

To this end, this step combines the use of the Monte Carlo reliability simulation with the EPRI-developed energy storage valuation tool StorageVET. StorageVET models the revenue of a storage system providing various grid services, subject to specific operational constraints. These constraints can be due to interconnection requirements, or prior operational commitments. As an outcome, StorageVET will provide the hourly dispatch profile, the hourly SOC evolution, and the annual operational costs/benefits associated to the grid services provided by the battery. Extended information on the modelling assumptions followed in StorageVET can be found in Subsection 5.2.2.

Cycling due to economic objectives could make the battery SOC to be low during some hours of the year. If an outage happened at any of those hours, the battery would not be able to supply the critical load. This raises the question on how much can the SOC decrease without deteriorating the system reliability. In this step, the constraint that we use for analysis is the minimum SOC reservation. This reservation guarantees that the battery will always have at least a given amount of energy stored for reliability.

Step 3: Oversizing analysis: Once the battery system has been designed, it would be important to understand whether it makes sense to increase the system size to get higher revenues. To this end, we run a sensitivity analysis over the energy size of the battery system using StorageVET. The results will show if the economics of a smaller sized battery used for only reliability purpose is better than the value obtained from the larger battery that is providing reliability benefits first followed by benefits from secondary services.

Step 4: Final results: The final design selected as the one that provides the best cost/benefit metric while meeting the reliability target will be selected as the result to be recommended for subsequent steps of the microgrid procurement process.

5.1 DATA INPUTS AND ASSUMPTIONS

5.1.1 Storage Technologies Considered

Li-ion and Flow battery. The storage duration considered include:

- Li-ion: Sizes considered 0.5 to 4 hours in steps of 0.5
- Flow Battery: Sizes considered 5 to 12 hours in steps of 1

5.1.2 Parameters for Failure Modeling Considered

- One Li-ion storage – 98.6% availability. Round trip efficiency (RTE) 91%
- One Flow battery storage - 98% availability. RTE 71%

5.1.3 PV Assumptions Considered

PV Variability assumption: 20% for reliability calculation (Yearly variation not considered). According to the EPRI report[13,14], PV generators of sizes larger than 500 kW exhibit intra-hourly variability that with probability 99.9% remains under 40% of the AC-rated capacity. This gives us the basis to assume that with very high probability solar PV system should not go below 60% of its hour-average power. To ensure that the firm capacity that PV can provide is not overestimated, we choose it to be 20%.

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[13] EPRI Report, Monitoring and Assessment of Solar PV Plants Large (10–30 MW Class) PV System Performance and Variability, Product ID#3002003272

[14] EPRI Report, Monitoring of Photovoltaic Plant Output and Variability, Product ID#1025408

5.1.4 UPS Assumption

The portion of critical load that requires reliable power source at all times is supported with UPS. UPS is designed to provide ride-through for critical loads during the transition period which is between the time when the outage starts and the time when the microgrid comes on-line. In this study, it is assumed that the UPS can be replaced by a battery storage system within the microgrid. Following are the design criteria to consider for replacing the UPS system with a battery storage system:

- The battery storage system siting and connection to the critical load needs to be well planned. They can be co-located or have an appropriate switching arrangement with an automatic transfer switch that ensures that the storage system supports the critical load immediately when an outage happens. When the diesels come on-line, the power sharing between battery storage system and the diesel gen-set can be coordinated through controls.
- Battery storage system control algorithm ensures that there is sufficient SOC to support the critical load during the transition period. In this study, the portion of the critical load that requires ride-through from a UPS is considered to have the same load coverage probability as the rest of the critical load. If higher reliability is required for the critical load that requires ride-through, then an appropriate amount of SOC needs to be reserved to provide backup service.
- Power surge characteristics of the battery storage system that replaces UPS has to meet the critical load characteristics and requirements.
- Faster response – the battery is expected to discharge very rapidly to support the critical load from the moment the outage starts

Based on this analysis, some of the sites could retire one or more UPS, which is determined on the ratings of the UPS and the storage system on a site-specific basis. If the power capacity of the battery storage system is larger than the UPS, a UPS systems may be retired. For example, the reliability analysis for Naval Base Ventura County yielded a minimal Li-ion storage size of 875 kW, 1312.5 kWh. The rating of each UPS at the site was 250 kVA, hence, up to three UPS systems could be replaced with the 875-kW battery.

5.1.5 SERVICES CONSIDERED

- Primary service: Reliability
- Secondary[15]: Energy arbitrage, frequency regulation, operating reserves, demand response, TOU, demand charge reduction (refer to Table 9 and 10 in Section 5.2.2 w.r.t. the types of secondary services that can be realized by diesel gensets and energy storage at each location based on current regulations)

Table 5. Secondary Services Considered

Wholesale Market Services	Bill Reduction
DA Energy Arbitrage	Energy Time Shift (TOU)
Frequency Regulation	Demand Charge Reduction
Demand Response	Demand Response

[15] The total incremental value captured by modeling spinning reserves is significantly small compared to the overall benefit. Therefore, it hasn't been included in the analysis.

Only DA energy price is used for the analysis since the *variability* associated with real time energy price is very high and might be difficult to predict DER operations. This is illustrated in Figure 4.

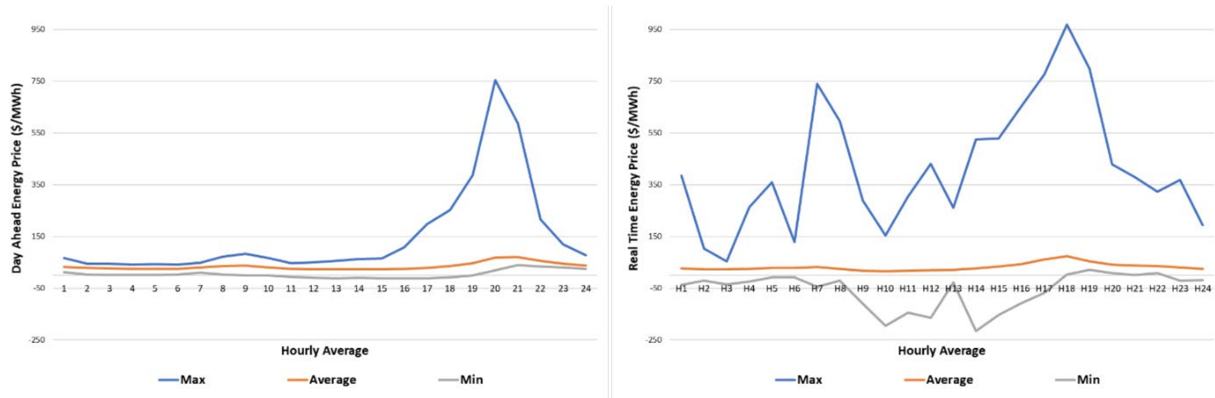

Figure 4. Day Ahead Energy Price (left) vs Real Time Energy Price (right) Variations for Naval Base Ventura County

5.1.6 Assumptions for the Cost Benefit Analysis (CBA)

Table 6. Assumptions Made for the CBA[16]

Item	Li-ion	Flow Battery
Upfront CapEx Cost	From EPRI's cost study • EPRI cost study 3002013957 *Energy Storage Technology and Cost Assessmentv3002013958 Energy Storage Technology and Cost Assessment: Executive Summary* (publicly available)	To be run as a sensitivity to identify cost of capital at which the Flow battery would break even with a Li-ion system of similar size for each scenario
Annual CapEx Cost Reduction	6%/yr (EPRI Cost study)	6%/yr
Replacement Time[17]	7 years (replace energy storage due to battery degradation. Replacement cost is 50% of the initial CapEx. 50% accounts for full replacement of the battery capacity)	None. After discussion with LM engineers it was agreed that unlike the Li-ion system that needs to be replaced after 7 years, no replacement of the Flow battery system is necessary across the 20-year time horizon
O0pex	$10/kw-year (from EPRI cost study)	Assumed to be included in the breakeven CapEx calculation

[16] The information in Table 6 only applies to the two energy storage systems considered for analysis. It does not include other infrastructure and microgrid controller costs

[17] Replacement time is used in this context as the asset's expected lifespan

5.2 DETAILED DESCRIPTION OF THE MODELLING APPROACH

The steps described throughout this analysis build upon two fundamental models, referred to as Reliability analysis and StorageVET analysis. In the following, a detailed explanation of these models is presented.

5.2.1 Reliability Analysis

The reliability characterization of the microgrid system allows to probabilistically model the available capacity that the microgrid can contribute to the critical load. In this analysis, this characterization can be used to determine the probability that the microgrid be able to support an outage of a given duration. The probabilistic behavior that characterizes reliability of the microgrid is given by the failure models associated with the individual energy resources present in the microgrid.

5.2.1.1 Failure model for standby Generator

According to exponential failure models, if the mean time between failure (**MTBF**) is provided for an equipment, then the probability that such equipment is operational after t hours given that it was operational at time 0 is $e^{-t/MTBF}$. Therefore, the probability that the equipment fails before time t given that it was operational at time 0 is $1 - e^{-t/MTBF}$.

- At the start of an outage, the probability that a generator is out of service is **0.3%.**
  - If the generator is determined out of service, then it remains out-of-service throughout the period of outage.
  - Else if it is operational, then at the beginning of every hour during the outage, the status of generator is redetermined. The meantime between failure (**MTBF**) of a standby is given to be 1700 hours. Then the probability that the generator remains operational at time t is **99.94%**.
    - If during the start of an hour it is determined that the generator is not operational, then the generator remains non-operational during the whole outage duration
    - If the generator is operational, the process is repeated to check if they are operational the next hour. This is repeated for the entire outage duration

5.2.1.2 Failure Model for Li-ion and Flow Battery

Even though for battery storage one could build a failure model like the one used for diesel gensets, finding data on probability of failing is a difficult task. Instead, the probability of a storage system to be operational is usually characterized by the availability. **Availability** is the percentage of time that a storage system is operating (excluding planned outages). This implies that 1-availability is the time that a storage system is inoperative due to unplanned outages.

In the present work, we model failures on battery storage according to the following logic:

- At the start of an outage, the probability that li-ion energy storage is operational is **98.63%** and the probability that Flow battery is operational is **98%**.
  - If the battery is determined to be out of service, then it remains out-of-service throughout the period of outage.
  - Else if it is operational, then it is operational for the rest of the outage period

Note: For the reliability calculations, random number-based reliability assessments are carried out. Random numbers are generated to simulate different generator states. If probability that an equipment is operational at time t is **98%**, and if the random number generated is greater than **0.98**, then the generator is considered non-operational for the test case. Whereas If the random number is lesser than **0.98**, then the generator is considered operational.

5.2.1.3 Monte Carlo Simulation

Standby Diesel Generators:

$\boldsymbol{P_{max}^{GENj}}$	**Max Generator capacity**
$ISon_t^{GENj}$	Generator status – Binary variable: 1 – Generator is operational 0 – Generator is non-operational
PR_0^{GEN1}	Probability that generator is operational at the start of an outage
PR_{GB}^{GENi}	Probability of transition from the current good state to bad (non-functional) state
β	The mean time between failures of Generators

Energy storage:

$\boldsymbol{P_t^{BESS}}$	**Power output of Energy storage at time $\boldsymbol{t}$**
E_{cap}	Energy rating of Energy storage
Ch^{max}	Maximum power that can be charged from energy storage
Dch^{max}	Maximum power that can be discharge from energy storage
η_{RT}	Roundtrip of Energy storage
SOC_{t-1}	State of charge of battery at time t-1
PR_0^{BESS}	Probability that battery is operational at the start of an outage

Load and PV:

$\boldsymbol{L_t}$	**Critical load at time t**
$\bar{P}_t^{PV}$	Mean PV power over a time period 't' be
Δt	Time interval

A Monte Carlo based approach allows estimation of the outcome of a system whose inputs are random processes. It starts by generating multiple samples from a probability distribution. Then, these samples are individually simulated through the system to obtain multiple samples of the system's output. Samples from the output are used to reconstruct its probability distribution. For the microgrid design in this study, the scope of the Monte Carlo analysis is to estimate the probability of a microgrid to serve the critical load during an outage of different durations. The sources of uncertainty of this Monte Carlo model are:

- Outage starting hour
- Critical load profile during outage
- Solar generation profile during outage
- Failure profile for each energy resource (whether each energy resource is available or not at each hour of the outage)

5.2.1.3.1. Outage Starting Hour

Given the information available from the military bases, an outage could start at any time with same probability. For this study, 10,000 outage scenarios of each duration between 1 and 168 hours are created and individually analyzed. The starting hour of each scenario is randomly generated from a uniform distribution between hours 1 and 8592 (8760-168). They are created randomly using python's random numbers generator.

5.2.1.3.2. Critical Load Profile

The hourly critical load at each military site is modeled as a percentage of the hourly total load profile, which is available as an 8760-length time-series[18]. The percentage of load that is critical is also known for each site. For each outage scenario, the critical load profile is simply the critical load data that starts at the starting hour of the scenario and covers the duration of the outage.

5.2.1.3.3. Solar Generation Profile

The Military sites are also provided with yearly PV profiles on hourly resolution. Similar to the critical loads, PV profiles are also chosen corresponding to the outage duration. A PV plant's power production varies according to the solar irradiance at the location, which depends on various external factors. To characterize the expected capacity contribution from a PV system, it is necessary to identify the lowest instantaneous power generation that is possible during a specific time interval.

From past works carried out by EPRI report[19,20], it has been identified that for a PV solar generator, 99.9% of the ramps measured every minute have a magnitude less than 40% of the AC rated capacity. Since typically, the power drop is limited by the average generated capacity during a specific hour, one would expect that power should not drop below 60% of the average generation. However, to avoid overestimation of the PV power capacity that can be relied on, this work considers that 20% of the average hourly generation can be counted as firm capacity for the microgrid.

Let mean PV power over a one-hour time period 't' be $\bar{P}_t^{PV}$. From the explanation above, we assume that the firm capacity provided by a PV generator during hour t is $0.2\bar{P}_t^{PV}$. If the power during time t is a symmetric random variable with mean $\bar{P}_t^{PV}$, one could assume that with 99.9% chance, the power will stay below 1.6_t^{PV}. Then, the sub-hourly PV power is assumed to be between 0.2 to 1.6 of the mean $\bar{P}_t^{PV}$. If the PV generation is less the mean $\bar{P}_t^{PV}$ during any time of the hour, we need to make sure that the battery has enough power and energy available to support the net critical load.

[18] Time-series dispatch is a time-series with the hourly dispatch of the battery system
[19] EPRI Report, Monitoring and Assessment of Solar PV Plants Large (10–30 MW Class) PV System Performance and Variability, Product ID#3002003272
[20] EPRI Report, Monitoring of Photovoltaic Plant Output and Variability, Product ID#1025408

Then, the net load at time t can be bounded as,

$$NetL_t \geq L_t - 0.2 * \bar{P}_t^{PV}$$

Let $P_{max,t}^{GENj}$ be the maximum power that the j^{th} controllable energy resource, i.e., a diesel generator or a battery storage system can deliver during time t. The controllable resource may or may not be functional at time t. Let $ISon_t^{GENj}$ be a binary variable that equals 0 if the resource is not available and 1 if it is available. Similarly, $ISon_t^{BESS}$ is the binary variable to represent the functional state of energy storage. Then, the resource adequacy constraint for the microgrid is given by:

$$L_t - \sum_{j=1}^{N} P_{max}^{GENj} ISon_t^{GENj} - 0.2 * \bar{P}_t^{PV} + ISon_t^{BESS}(P_{t\,Ch}^{BESS} - P_{t\,Dch}^{BESS}) \geq 0$$

If the inequality holds, then the energy resources in the microgrid have enough power capacity to support the load.

To guarantee that the battery storage has enough capacity to support the critical load, let us assume a worst-case scenario where the PV production is at the minimum of 0.2*$\bar{P}_t^{PV}$ capacity during the first x% of the hour t, and 1.6*$\bar{P}_t^{PV}$ for the rest of the hour. If the PV is at its minimum continuously at the beginning of the hour, it does not give the storage system enough time to replenish energy. Therefore, it corresponds to the scenario in which most energy needs to be available as the battery's stored energy to support the load during t in case of an outage. The PV profile that maximizes the time with low PV generation at the beginning of hour t is one in which during the rest of the time the PV generation is equal to $1.6\bar{P}_t^{PV}$. Although unrealistic, it represents the very worst-case scenario of energy requirement for the battery. For the described PV profile, $\bar{P}_t^{PV}$ can be written as:

$$\bar{P}_t^{PV} = \frac{0.2 * \bar{P}_t^{PV} * x + 1.6 * \bar{P}_t^{PV} * (1 - x)}{1}$$

Where x is the percentage of the hour during which the PV generation is $0.2\bar{P}_t^{PV}$. Solving for x from the above expression, we get $x = 0.43$. Therefore, in order for the energy storage to be able to supply the critical load during time t, the following must hold:

$$E_{tmin}^{BESS} \geq NetL_t * 0.43hr$$

If the SOC of the energy storage at the starting of hour h is greater than or equal to support the above energy requirement E_{tmin}^{BESS}, then the microgrid has satisfied the resource adequacy requirement it can support the critical load during the hour.

Note that the above conservative assumptions on 20% PV production are for reliability considerations only, to make sure that the energy storage can satisfy the load requirements. For the SOC evolution calculations during the outage, 100% PV production is taken into account.

5.2.1.3.4. Failure Conditions of Each Microgrid Component

Reliability Model for STANDBY Generator:

At the start of an outage, the steady state probability of a standby generator being functional is PR_0^{GEN1}= **99.7%.**

$$ISon_0^{GENi} = rnd(0,1) < PR_0^{GEN1}$$

Let $ISon_0^{GENi}$ be a binary variable that represents generator i's operational state at the start of an outage. Once the outage starts, the functional state of the generators is redetermined as follows:

- If the generator is determined out of service at the start, then it remains out-of-service throughout the period of outage.
- Else if it is operational, then at the beginning of every hour during the outage, the status of generator is calculated according to the following condition:

$$ISon_t^{GENi} = \begin{cases} 0 & if \quad ISon_{t-1}^{GENi} = 0 \\ rnd(0,1) > PR_{GBt}^{GENi} & if \quad ISon_{t-1}^{GENi} = 1 \end{cases}$$

Where, $ISon_t^{GENi}$ is the binary variable representing generator i's operational state at time period t, and PR_{GB}^{GENi} is the probability of the generator to transition from functional to non-functional state in one simulation period. If one assumes that the time between failures follows an exponential distribution, these parameters are calculated as:

$$PR_{GB}^{GENi} = 1 - e^{-\frac{\Delta t}{\beta_{GENi}}}$$

- If during the start of an hour it is determined that the generator is not operational, then the generator remains non-operational during the whole outage duration
- If the generator is operational, the process is repeated to check if they are operational the next hour. This is repeated for the entire outage duration

Reliability Model for LI-ION and Flow Battery:

Similar to the diesel generators, at the start of an outage, the operational status of the battery energy storage system is determined. The probability that energy storage is functional at the start of an outage is PR_0^{BESS}. The probability differs based on battery technology. The probability for li-ion and Flow battery ES are **98.63%** and **98%** respectively.

$$ISon_0^{BESS} = rnd(0,1) < PR_0^{BESS}$$

$ISon_0^{BESS}$ -Binary variable to represent ES operational state at the start of an outage.

- If the battery ES is determined to be out of service, then it remains out-of-service throughout the period of outage.
- Else if it is operational, then it is operational for the rest of the outage period

5.2.1.3.5. Battery's SOC at the Beginning of the Outage

Another variable that depends on the probabilistic construct of the scenario is the battery's SOC at the beginning of an outage. Since the battery participates in market services or behind the meter services, the battery's state of charge goes up and down, which may affect the ability of the battery to support the critical load during an outage. The SOC at the beginning of an outage is represented using results from the StorageVET tool.

StorageVET is a tool that models the behavior of a battery system that performs economic objectives subject to constraints. More discussion on the reservation and how it works is available in section below. StorageVET outputs the battery's optimal dispatch and corresponding SOC evolution throughout the year. The SOC at the beginning of an outage scenario, denoted by SOC_{ts} is given by the SOC provided by StorageVET at the starting time ts of said scenario.

5.2.1.3.6. Control Strategy During Outage

With the generated data for each scenario, the microgrid dispatch is calculated according to a well-defined control strategy described in the following. At every time $t \in \{1, \dots, T\}$, diesel gensets are dispatched first to meet the net load. If there are not enough functional diesel gensets to meet the load ($\sum_{j=1}^{N} P_{max}^{GENj} ISon_t^{GENj} < L_t$), then the storage system is discharged to meet the fraction of the load that cannot be met by diesel gensets. The battery discharge power is given by:

$$P_{t\,Dch}^{BESS} = \min\left\{L_t - \sum_{j=1}^{N} P_{max}^{GENj} ISon_t^{GENj}, Dch^{max}, SOC_{t-1} E_{cap}/(\Delta t)\right\}$$

The storage system must have enough SOC to maintain the required power during the time interval t, which in this study is 1 hour. If the fraction of the load that cannot be met by diesel gensets is greater than the battery's power capacity or the maximum constant power that can be provided during time t given the available SOC, then the scenario is considered 'failed'.

If the diesel gensets operational at time t are enough to power the critical load ($\sum_{j=1}^{N} P_{max}^{GENj} ISon_t^{GENj} > L_t$), the battery system charges. The charging power is the maximum between the extra genset capacity that is available after powering the critical load, and the charging power capacity of the battery. The corresponding battery charging power is given by,

$$P_{t\,Ch}^{BESS} = -\min\left\{\sum_{j=1}^{N} P_{max}^{GENj} ISon_t^{GENj} - L_t, Ch^{max}, (1 - SOC_{t-1}) E_{cap}/(\Delta t \eta_{RT})\right\}$$

If at all time t, there is enough power to serve the critical load, the scenario is considered 'successful.'

At the end of the scenario simulation for all the randomly generated scenarios, the probability of serving the load for an outage of duration T is calculated as the percentage of scenarios that were found to be successful.

The battery SOC at the start of an outage is obtained from StorageVET as explained before. But, during the outage, the battery SOC evolves depending on the charging and discharging cycles as explained in the above equations. The evolution of SOC_t is given by:

$$SOC_t = SOC_{t-1} + (\eta_{RT}[P_{t\,Ch}^{BESS}]_+ - [P_{t\,Dch}^{BESS}]_-)\Delta t / E_{cap}$$

The SOC is updated after time period t.

Let us consider an outage scenario at Ventura military site that last for 168 hours. The designed microgrid at the site has 5 diesel generators of capacity 750kW each - the total DG capacity is 3750kW at the site. Installed PV power is 830kW and the peak critical load is 4MW. The chosen Li-ion energy storage for this analysis has a power and energy rating of 1050 kW and 1575 kWh respectively with an energy to power ratio of 1.5.

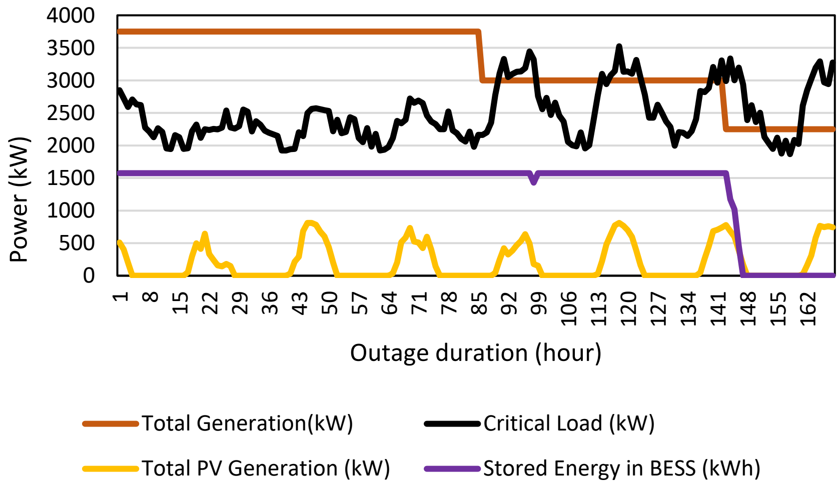

Figure 5. Total Generation and Critical Load of an Outage Scenario at Ventura Site

At the start of the outage, all the generators are operational and it can be observed from Figure 5, that there is excess generation capacity available compared to critical load during the hour, so the generators are dispatched during the initial periods of the outage. .

Two diesel generators fail during this outage scenario at hour 87 and 144 respectively. With one diesel generator failing at hour 87, the microgrid can meet the critical load with the support of solar generation and battery energy storage. At hour 99, the existing diesel generation could not meet the critical load, and so 10% of the energy storage capacity is dispatched. At the 100th hour, since there was excess diesel generation, the energy storage is charged again to full capacity. But, when 2 diesel generators fail at hour 144, there is not enough capacity to serve the critical load. The stored energy in the energy stroage depletes in 3 hours and the microgrid cannot support the critical load after hour 147.

Figure 6 show the difference between the total generation (diesel, energy storage, and PV) and total critical load in the microgrid, which is referred to as the net generation. It can be observed the net generation is over 1MW, when all the generators are operating. When a diesel generator fails, the net generation is still positive but when the second diesel generator fails, the net generation goes negative. The scenario is considered a failure when the net generation goes negative, which implies that there is not sufficient generation to meet the critical load. At hour 147 net generation is negative and the corresponding binary reliability metric is at the hour. The reliability metric is zero for the rest of the outage period.

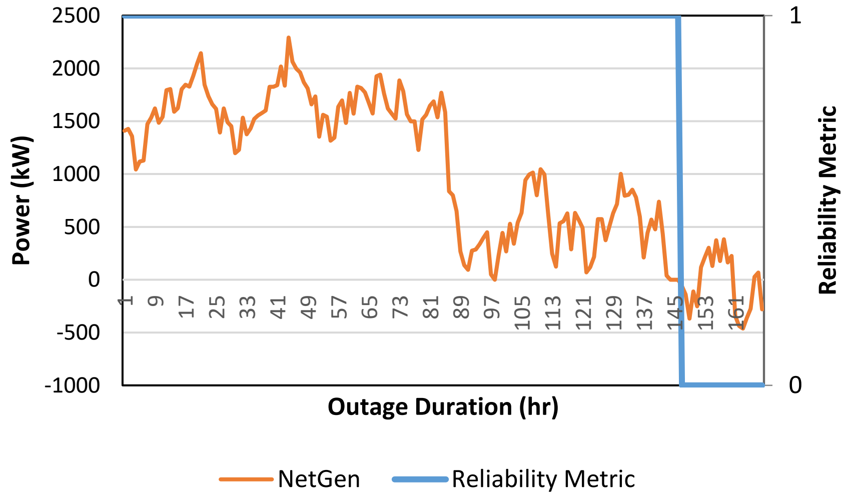

Figure 6. Net Generation at an Outage Scenario at Ventura Site

5.2.1.4 Reliability Curve Calculation

In order to calculate the probability of supplying the critical load during an outage of duration T, the Monte-Carlo simulation is employed. We model 10,000 random scenarios of outage in our analysis. Every outage scenario is created considering the variables specified in the previous section such as the start time, load and PV profiles, failure models of the assets and battery SOC at the start of an outage.

With the generated data for each scenario, the microgrid dispatch is calculated according to a well-defined control strategy described in the previous section. At every time $t \in \{1, \ldots, T\}$, diesel gensets are dispatched first to meet the net load. If there are not enough functional diesel gensets to meet the load, then the storage system is discharged to meet the fraction of the load that cannot be met by diesel gensets. The storage system must have enough SOC to maintain the required power during the time interval t, which in this study is 1 hour. If the fraction of the load that cannot be met by diesel gensets is greater than the battery's power capacity or than the maximum constant power that can be provided during time t given the available SOC, then the scenario is considered 'failed'. If the diesel gensets operational at time t are enough to power the critical load, the battery system charges. The charging power is the maximum between the extra genset capacity that is available after powering the critical load, and the charging power capacity of the battery. If at all time t, there is enough power to serve the critical load, the scenario is considered 'successful.'

Since in our study, 10,000 outage scenarios are created, a binary matrix of size 10,000 x 168 is created. A value of 1- means success and 0 – failure to meet the critical load demand at the corresponding hour and scenario. A probabilistic performance curve is then generated by determining the average of all the 10,000 scenarios during every hour. Thus, at the end of the scenario simulation for all the randomly generated scenarios, the probability of serving the load for an outage of duration T is calculated as the percentage of scenarios that were found to be successful. This performance curve is compared with baseline performance curve. At all hours of outage, for 168 hours, it is made sure that the probability of serving the critical load is equal or greater than the base-line performance curve.

5.2.2 STORAGEVET ANALYSIS: Calculation of Economic Benefits of the Microgrid

The designed microgrids can provide secondary services based on the regulations of the military base site, with the requirement that they do not affect the reliability objective of the microgrid.

Theoretically, it is possible to analyze scenarios where economic objectives are a mix of wholesale market participation and bill reduction services. However, EPRI has consistently found that in practice, utilities do not accept devices subject to tariff rates to participate in market services, where there could be potential conflict with the metering scheme. Wholesale market services that require power to be exported through the interconnection point, could lead to double-counting of benefits for customers by being paid for market energy sale and utility feed-in.

In this analysis, two possible secondary service settings are studied:

1. Bill reduction: Energy charge reduction, demand charge reduction, and demand response
2. Wholesale market participation: Energy arbitrage, frequency regulation, spinning reserves, non-spinning reserves

Even though demand response is a bulk system service, since it provides system capacity, here it is described as a bill reduction service, considering that it is available for customer's systems under demand response programs.

In both service settings, the microgrid operation as well as the storage dispatch and SOC evolution over time are calculated using the storage valuation tool StorageVET.

StorageVET is an optimization model that represents a battery system in terms of constraints of an optimization problem, where power dispatch, capacity reservations, and State of Charge are optimization variables. The system's roundtrip efficiency is represented as a percentage of loss in the energy that is charged into the system. No loss is modeled to affect the discharged energy.

Grid services associated to economic objectives are modeled as terms in the objective function of the optimization problem. External constraints on the storage dispatch and the State of Charge can be imposed in StorageVET to model different operational circumstances. For example, if a battery system is assumed to provide backup capacity the optimization problem can be formulated with a constraint on the minimum State of Charge. All the operation to maximize economic benefits will be subject to guaranteeing that the State of Charge always stays above the minimum. This is particularly useful to calculate the microgrid performance to support the critical load.

5.2.2.1 Bill Reduction Services

The microgrid is located behind-the-meter, being able to reduce customer's energy and demand charges, and participate in demand response programs available on the site. In order to comply with regulatory requirements of the two sites in California and Fort Bliss, an assumption that diesel generators wouldn't be used for bill reduction was made. For the remaining two sites, some amount of bill reduction was performed using diesel generators. At certain locations, diesel generators can be used as demand response capacity. Since demand response call are assumed to occur very infrequently, it is assumed that it does not affect the system's ability to reduce demand and energy charges. Therefore, the analysis is carried out modelling the site as a battery system, a load, and a PV system, where the battery is used for energy and demand charge reduction.

The system's dispatch is calculated by solving the optimization problem with objective given by the total demand charges and energy charges associated to the tariff at the location. Savings are calculated as the difference between energy and demand charges without storage and those with storage. Given that energy and demand charges are co-optimized, there might be months in which energy charges with storage could be higher than without storage. Nonetheless, the total bill is always lower in the case with storage than in the base case.

5.2.2.2 Wholesale Market Services

The microgrid is located in front of the meter, although capable of serving the military base's load in case of an outage. No ownership assumptions are made at this point.

For all sites it is assumed that diesel generators cannot participate in the energy market, nor participate in frequency regulation, spinning or non-spinning reserves. This is consistent with emissions regulations that limit diesel operations.

Table 7. Economic Grid Services Studied in the Microgrid Analysis

Service Type	Grid Service	Definition	Modeling Assumptions
Wholesale Market	DA Energy Arbitrage	Wholesale market participation to buy and sell energy.	The battery dispatch is optimized to maximize the revenue from energy trade, according to the market price data available. Energy arbitrage is co-optimized with ancillary services in StorageVET
	Frequency Regulation	Frequency Regulation helps address the real-time imbalance of electricity supply and demand. The ISO issues a Frequency Regulation signal every few seconds.	In StorageVET regulation is modeled as a capacity reservation and energy throughput that depends on how much capacity up and down are provided. Co-optimized with energy arbitrage and other ancillary services
	Spinning and non-spinning reserves	Spinning and non-spinning reserves require an energy resource to stay online to deliver power if there is a contingency. The asset must be able to operate in short notice. Assets providing these reserves need to provide power very infrequently	In StorageVET, these services only reserve power capacity from the storage system. But no energy is consumed. However, providing the service imposes a constraint of having sufficient SOC at the beginning of the performance period
Bill Reduction	Energy Time Shift	Time-of-use (TOU) utility rates offer a variable rate for energy consumption at different times of day. Energy-time shift focuses on moving load from high-price times to lower price times, reducing a customer's electricity bill	StorageVET optimizes the operation of the energy storage by minimizing the electricity bill subject to the storage mode, customer's load, and PV generation
	Demand Charge Reduction	Demand charges are applied to the maximum load attained during a billing period. Demand charge reduction consists on reducing the peak load of the month, by discharging during peak hours, reducing the capacity required to supply the customer	In StorageVET demand charges are co-optimized with energy charges for total bill reduction
	Demand Response	It includes reducing the total customer's load to modify the load shape by changing end-use consumption patterns, thereby reducing the need for additional and costly generation or transmission infrastructure	Since the number of annual DR events is very small, DR isn't explicitly modeled. However, the financial incentives of DR participation are included in the total benefits calculation

Table 8. Economic Grid Services Provided with Battery Storage.

Site	Energy arbitrage	Freq. Regulation	Operating reserves	Demand response	TOU	Demand charge
Ventura	✓	✓	X	✓	✓	✓
March	✓	✓	X	✓	✓	✓
Holloman	X	X	X	✓	✓	✓
Fort Bliss	X	X	X	X	X	X
Corpus Christi	✓	✓	X	✓	✓	✓

Table 9. Economic Grid Services Provided by Diesel Gensets.

Site	Energy arbitrage	Freq. Regulation	Operating reserves	Demand response	TOU	Demand charge
Ventura	X	X	X	X	X	X
March	X	X	X	X	X	X
Holloman	X	X	X	✓	✓	✓
Fort Bliss	X	X	X	X	X	X
Corpus Christi	X	X	X	✓	✓	✓

5.3 REVIEW OF BASELINE MICROGRID MODELING

5.3.1 Outcome of Baseline Diesel Gensets Based Microgrid Reliability Performance

The reliability of baseline diesel genset based microgrid is calculated according to the guidance provided by ESTCP. Following are the assumptions for the calculation:

- Standby diesel generator's is as the failure model provided in Section 5.2.1.
- The baseline microgrid is serving a fixed load equal to peak critical load of the site
- Although available fuel capacity is provided for each site, it is assumed that the fuel can be replenished over time.
- PV power output is disregarded for the reliability calculation

Reliability performance for the five military sites are calculated using Monte-Carlo approach and their corresponding performance curves are included in Figure 7. The baseline diesel gensets based microgrid's reliability performance for the sites vary widely, except for Ventura and Corpus Christi, which have the same performance.

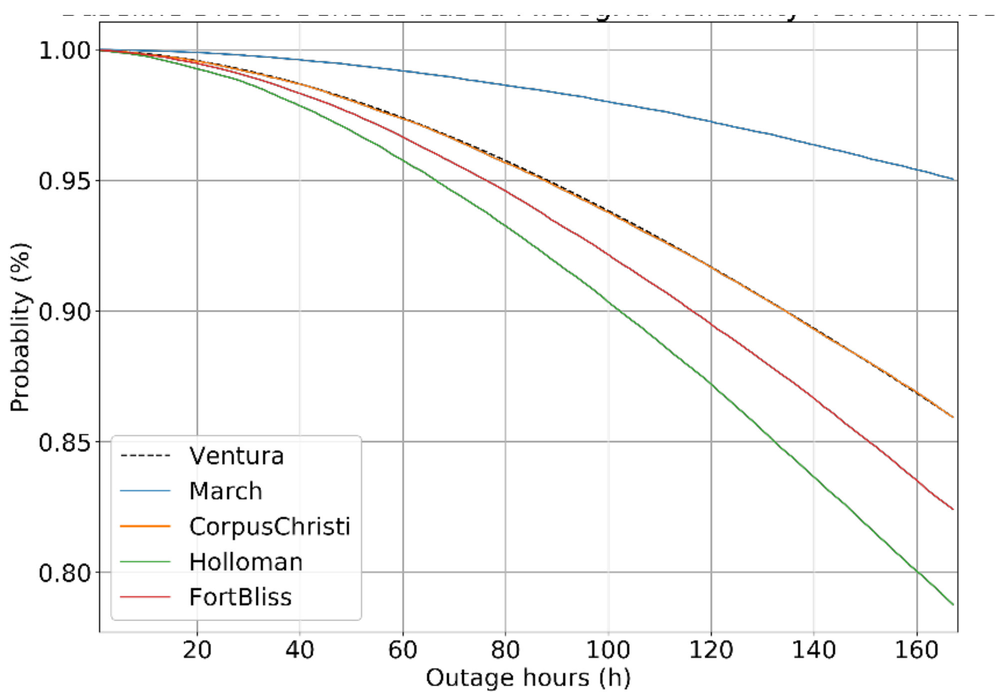

Figure 7. Baseline Diesel Genset based Microgrid Probabilistic Reliability Performance Curves for All Five Military Sties

Following is the discussion on reliability performance of the baseline microgrid. The factors that affect the performance are number of generators, generator rating and peak critical load at each site. The factors are summarized in Table 3. Additionally, the ratio of peak load to the total generation capacity is also included in Table 3. If there is ratio is less than one, it implies that there is enough generation to serve the peak load of the site. Since there is excess generation capacity in all the sites, all the sites have peak load to total generation ratios less than one. Further among the five sites, March ARB has the lowest ratio and Holloman has the highest ratio. Correspondingly the reliability performance of March is higher, and Holloman is lower compared to the other sites. Interestingly, Ventura and Corpus Christi sites have the same reliability performance, although they have different peak load to generation ratios. Also, Fort Bliss has lower reliability performance compared to Corpus Christi. This difference could be attributed to the number of generators which is not captured in the peak load to generation ratio. Given that all generators have same failure rate, more generators in a microgrid could mean more redundancy and higher reliability i.e., a microgrid with 10 small generators is more reliable than a microgrid with one large generator of same capacity.

5.3.2 Outcome of Baseline Diesel Gensets Based Microgrid CBA

The 20-year Net Present Value (NPV) breakdown for the various baseline microgrid sites is provided in Table 10 below.

Table 10. 20-Year NPV for Baseline Diesel Generator Enabled Microgrids

	Naval Base Ventura County	March ARB	Holloman AFB	NAS Corpus Christi	Fort Bliss
Microgrid CapEx	$3,000,000	$2,000,000	$3,000,000	$3,000,000	$3,000,000
Microgrid Fixed OpEx	$1,363,585	$913,602	$1,363,585	$1,363,585	$1,363,585
UPS CapEx	$1,455,750	$485,250	$2,102,750	$1,455,750	$3,888,000
UPS Fixed OpEx	$419,098	$10,245	$650,364	$419,098	$652,339
Generator CapEx	$3,937,500	$1,100,000	$5,062,500	$3,937,500	$9,600,000
Generator Fixed OpEx	$668,157	$354,532	$859,059	$668,157	$2,181,737
Utility Bill	$98,101,276	$57,453,945	$83,150,664	$102,692,152	$162,578,904
Demand Response	$0	$0	($1,199,200)	($2,998,800)	$0
Total Cost	**$108,945,366**	**$62,447,029**	**$94,944,721**	**$110,537,442**	**$183,264,564**
Annual Net Cost of Protecting each kW of Peak Critical Load ($/kW)	**$135.50**	**$416.10**	**$98.35**	**$88.90**	**$82.70**

The calculation of the critical load coverage cost provides an estimate of how expensive it is to serve the critical load. This is represented in Figure 8 as well. The "Annual Net Cost of *Serving* each Kilowatt of Peak Critical Load" was calculated by annualizing the total NPV of installing and operating the microgrid over a 20-year period and then by normalizing it based on the total critical load served. The comparison of this calculation performed by EPRI yielded very similar numbers to the baseline numbers provided by ESTCP guidelines.

March ARB has the highest critical load coverage among all the sites due to the large upfront CapEx and small critical load it serves.

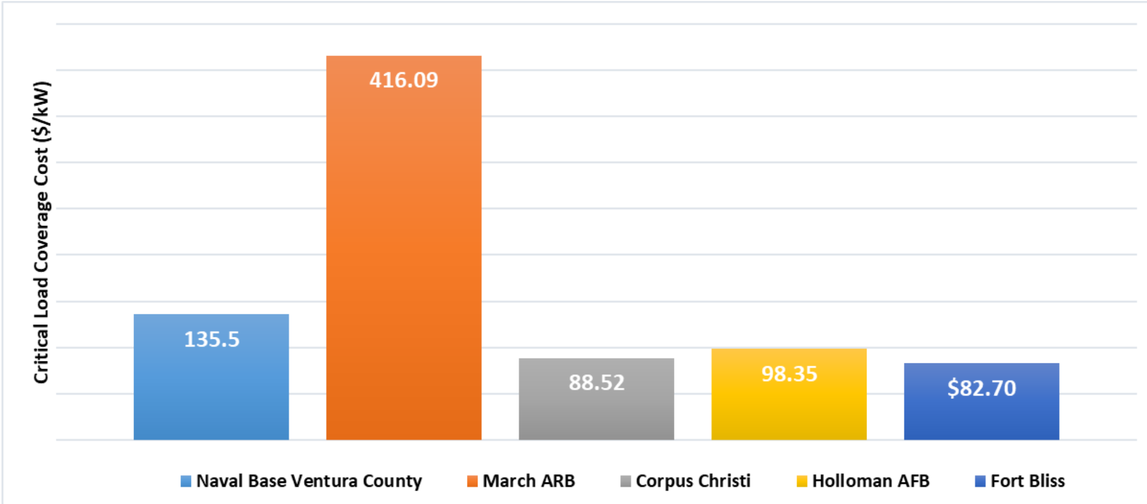

Figure 8. Baseline Microgrid Critical Load Coverage Cost

The baseline microgrid costs include diesel generators and UPS equipment as well as the OpEx. The NPV for each site ranges from $62M to $110M. The only exception is Fort Bliss which is $312M, which includes fuel costs. The cost of critical load coverage for the sites is between $80/kW-year to $140/kW-year. The only exception to this is March ARB, which is $416/kW-year due to a small critical load of 600 kW. For the 2 CA sites and Fort Bliss, there is no possibility of providing secondary service using the diesel genset due to the utility tariff and market rules. For Corpus Christi and Holloman sites, some amount of demand response value can be captured in the baseline case due to the diesel's participation in secondary services.

5.4 STORAGE-ENABLED MICROGRID INVESTMENT CASE MODELING

Storage enabled microgrid modeling has three steps as explained in the prior sections. First, based on reliability analysis, minimum feasible energy storage sizes are determined for each site. Secondly, with the same feasible storage size, the minimum SOC reservation is calculated to maximize the secondary benefits by participating in wholesale market or performing bill reduction. Finally, a sensitivity analysis on oversizing the energy storage is carried out, to find the best storage size based on cost and benefit analysis of storage enabled investment model. The results and inference for all five sites are discussed step-by-step in this section.

5.4.1 STEP 1: Sizing and Reliability Analysis

For a given site, the first step finds the minimum feasible ES storage size that can provide same or higher reliability performance than the reliability target provided for all outage durations ranging up to 168. First the energy storage is sized for a microgrid with one less diesel generator than the baseline microgrid. Then the energy storage sizes are determined for cases when more than one diesel generators are replaced. In this study, these microgrid configurations are referred as N-x (or N-1 or N-2), where N is the number of diesel generators in the baseline microgrid and x is the number of diesel generators in baseline microgrid that are replaced. Since the energy storage characteristics of Li-ion and Flow battery technology vary widely, the minimum feasible energy storage size is determined separately for each storage technology. The sizing results from step 1 analysis for Li-ion technology is presented first and then the results for Flow battery technology are presented

5.4.1.1 Energy Storage Sizing for Li-Ion Technology

Li-ion energy storage is assumed to have an Availability of 98.63% and round-trip efficiency of 91%. The duration of the storage technology is considered to vary between 0.5 hour to 5 hours in steps of 0.5 hours (totally 10 possible battery technology durations). Based on the assumed metrics for Li-ion technology, the minimum feasible Li-ion storage technology size for each microgrid configuration is calculated using binary search algorithm-based storage sizing and Monte-Carlo approach-based reliability analysis. The analysis finds minimum feasible power rating for all 10 ES durations, while ensuring that the corresponding size is reliable. The results of the analysis for each microgrid configuration are summarized in this section.

For most of the sites, the minimum feasible ES power rating reported is constant for all the 10 Li-ion durations (0.5h to 5h). This implies that there is a minimum power constraint in these microgrid and increasing the duration of the ES does not affect the power requirement. However, for the two sites- Ventura and Fort Bliss sites in N-2 microgrid configurations, the power rating of the ES varies with the ES duration. Figure 9 shows the feasible energy storage power rating as a function of Energy rating for the two sites. It can be observed that for lower ES energy rating, higher ES power is required to meet the reliability target at those two sites. Further similar to other sites, the ES power rating becomes constant for higher ES energy ratings.

As discussed above, every site has 10 feasible Li-ion sizes for each N-x microgrid configuration. The best Li-ion size for each microgrid configuration is chosen based on lowest CapEx of battery technology. The CapEx of the technology for various duration and power ratings were obtained from EPRI cost study 3002013957 *Energy Storage Technology and Cost Assessment (3002013958 Energy Storage Technology and Cost Assessment: Executive Summary* is publicly available). The feasible ES sizes that have lowest CapEx are summarized in Table 11 for N-1 and N-2 microgrid configurations. As expected, the feasible energy storage size for N-1 microgrid configuration is lower than the N-2 microgrids. It is interesting to note that Holloman and Fort Bliss does not require energy storage for N-1 microgrid configuration, since they have enough genset capacity to serve the critical load demand. Further, no feasible energy storage size for determined for March and Corpus Christi sites for N-2 microgrid configuration. Also, no feasible energy storage sizes were found for N-3 microgrid configurations for all sites. This is because the feasible energy storage size for these microgrid configurations are large and without redundancy in number of storage devices it is not able to meet the reliability target of the microgrid. This is because of the relatively low reliability of storage plants. Without redundancy in the number of storage devices, the microgrid is not able to meet the reliability target

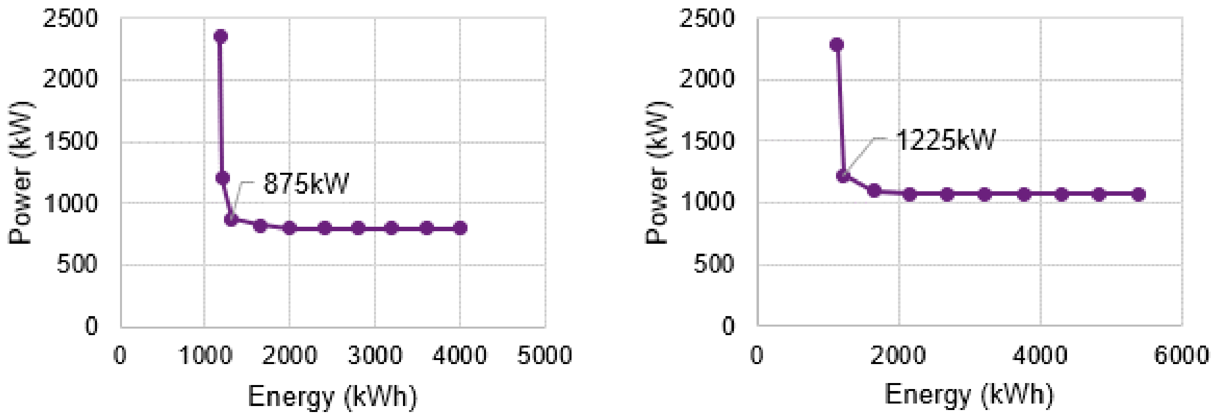

Figure 9. Energy Storage Sizes for Ventura and Fort Bliss Sites in N-2 Microgrid Configurations

Table 11. Minimum Li-ion Energy Storage Size for Various Microgrid Configuration Based on Reliability Calculation

		Ventura	**March**	**Corpus Christi**	**Holloman**	**Fort Bliss**
Number of Baseline microgrid Generators and capacity		7x750kW=5.25MW	4x250kW=1MW	7x750kW=5.25MW	9x750kW=6.75MW	8x2000kW=16MW
Min Li-ion ES Configuration N-1	Power and Energy	25 kW 12.5 kWh	75kW 37.5kWh	225kW 112.5kWh	0	0
Min Li-ion ES Configuration N-2	Power and Energy	875 kW 1312.5kWh	-	-	450kW 225kWh	1255kW 1255kWh

5.4.1.2 Energy Storage Sizing for Flow Battery Technology

Minimum feasible storage size for Flow battery based microgrid is summarized in this section. Sizing calculations are similar to Li-ion technology as explained in previous section, except for a few technology specific characteristics as follow. Flow battery technology is assumed to have Availability of 98% and round-trip efficiency of 71%. The duration of the storage technology is considered to vary between 5 hours and 12 hours in steps of 1 hours (totally 8 possible battery technology durations). The results of the analysis for each microgrid configuration are summarized in this section.

Table 12. Minimum Flow Battery Energy Storage Size for Various Microgrid Configuration Based on Reliability Calculation

		Ventura	March	Corpus Christi	Holloman	Fort Bliss
Number of Baseline microgrid Generators and capacity		7x750kW=5.25MW	4x250kW=1MW	7x750kW=5.25MW	9x750kW=6.75MW	8x2000kW=16MW
Min Li-ion ES Configuration N-1	Power and Energy	25 kW 125 kWh	75kW 375kWh	225kW 1125kWh	0	0
Min Li-ion ES Configuration N-2	Power and Energy	975 kW 4875 kWh	-	-	475kW 2375kWh	1075kW 5375kWh

Comparing the energy storage sizes for battery technologies in Table 11 and Table 12, it can be observed that the power ratings of the two energy storage technologies are quite comparable. Lower efficiency of Flow battery technology does not affect the energy storage power requirement a lot. For Ventura and Holloman sites, the Flow battery storage's power rating is greater by 100kW and 25kW respectively, which could be attributed to the technology's round trip efficiency. Interestingly, the power rating of Fort Bliss for Flow battery technology is lower compared to the Li-ion technology. This difference can be explained from Fig. 3. For Fort Bliss site, the feasible power rating for Li-ion technology chosen based on minimum capital turned out to be 1225 kW but it can be observed that the power rating requirement decreases and becomes constant at 1075 kW for higher energy storage durations. The calculated feasible size for Flow battery is also 1075 kW at 5-hour duration, and therefore it is lesser than the power rating of chosen Li-ion technology.

5.4.2 STEP 2: SOC Reservation Analysis

The feasible energy storage size determined in the previous section is based on an assumption that 100% of the battery capacity is reserved for reliability services. This step uses binary search algorithm to find the minimum SOC reservation for battery technology that satisfies the reliability target of the microgrid, in order to maximize the secondary benefits from storage technology, while still meeting the reliability target of the microgrid. The analysis is carried out for wholesale market and bill reduction cases separately, since they affect battery technology's state of charge differently. EPRI's StorageVET tool is used in this analysis to calculate the net present value of installing the energy storage in the microgrid. The SOC reservation is provided as a constraint to the StorageVET optimization tool. The results of the analysis are summarized in this section.

The results for Ventura site for Li-ion technology are summarized in Table 13. The energy storage size for N-1 and N-2 microgrid configurations calculated from Step 1 is provided as an input for this step. Output of this step of the analysis is minimum SOC reservation that meets the reliability target and provide better economic benefits from secondary services. The storage economics are calculated from StorageVET optimization. Results of the analysis are summarized in Table 13.

It can be observed that for N-1 microgrid configuration, the minimum SOC reservation is determined to be 0% for both wholesale market and bill reduction cases, which implies that there is no energy reservation required to meet the reliability target. This result is backed by the fact that batteries can charge from PV or diesel during an outage, whenever there is enough capacity available. The corresponding NPV values are also included in Table 13. It can be inferred that the bill reduction services provide higher NPV benefit for this California site compared to the wholesale market services. Similarly, results for N-2 microgrid configuration are also included in Table 13. Interestingly, the minimum SOC reservation for reliability is higher for bill reduction services and yet it provides higher NPV improvement for N-2 microgrid configuration. Of all Ventura microgrid configurations, N-2 microgrid provide highest NPV improvement over baseline for customer-sided bill reduction.

Table 13. Ventura Site: Energy Storage Size and SOC Reservation for Li-ion and Flow Battery Based Microgrid

Microgrid configuration	ES Power Rating (kW)	ES Energy Rating (kWh)	Minimum SOC Reservation for Reliability		Baseline NPV Improvement ($)	
			Wholesale	Bill Reduction	Wholesale	Bill Reduction
Li-ion Technology						
N-1 Microgrid	25	12.5	0%	0%	$652,441	$661,731
N-2 Microgrid	875	1312.5	50%	68.75%	$900,871	$977,047
Flow battery Technology					**Total NPV of Benefits* ($)**	
N-1 Microgrid	25	125	0%	0%	$685,789	$748,158
N-2 Microgrid	975	4875	56.25%	56.25%	$2,815,150	$4,099,883

Similarly, SOC reservation analysis for Flow battery technology is included in Table 13. It is to be noted that the CapEx of Flow battery is not known, therefore for Flow battery technology, the last column of Table 13 is the total NPV of benefits ($), not including the CapEx of battery. It can be observed that the Flow battery also has higher benefits for bill reduction as compared to wholesale services.

Similar to Table 13, step 2 results summary for other sites are also calculated and are included in Appendix A2.1. The step 1 and 2 results summary for all sites are included in Table 14. These are the minimum storage requirements that meet the reliability targets.

Table 14. Minimum Energy Storage Size and Microgrid Design Based on Reliability Requirements

		Ventura	March	Corpus Christi	Holloman	Fort Bliss
Number and capacity of baseline Gensets		7x750kW= 5.25MW	4x250kW=1 MW	7x750kW=5 .25MW	9x750kW=6. 75MW	8x2000kW=16 MW
Peak critical load		4MW	0.6MW	4.4MW	6MW	12.5MW
Li-ion ES Microgrid Config.	Power and Battery duration	875kW 1.5hr	75kW 0.5hr	225kW 0.5hr	450kW 0.5hr	1255kW 1hr
	SOC Reservation for Reliability	68.75%	25%	0%	50%	100%
	# Gensets	5	3	6	7	6
	Secondary services	Bill reduction	Bill reduction	Wholesale Market	Bill reduction	None
Flow ES Microgrid Config.	Power and Battery duration	975 kW 5hr	75kW 5.0hr	225kW 5.0hr	475kW 5.0hr	1075kW 5.0hr
	SOC Reservation for Reliability	56.25%	6.25%	0%	6.25%	100%
	# Gensets	5	3	6	7	6
	Secondary services	Bill reduction	Bill reduction	Wholesale Market	Bill reduction	None

5.4.3 STEP 3 & 4: Sensitivity Analysis – Oversizing & Cost Benefit Analysis

The previous two steps of the analysis find the minimum feasible energy storage and SOC reservation for all DoD installations. The design was primarily based on the reliability requirements. The energy storage sizes in the previous steps are sized to just enough to meet the reliability target. This section is focused on understanding the economics of oversizing the battery size. Since larger energy storage size implies higher CapEx, this analysis is carried out if see the more revenue from secondary services could negate the increase in CapEx.

The economics of the baseline microgrid is established in Section 5.3. In this analysis, details on the economics calculation for the storage-enabled microgrid investment case using StorageVET are provided. StorageVET optimizes the operation of the energy storage system by charging during hours with lower energy prices and discharging during hours with higher energy prices. The benefits due to bill reduction are calculated for a site using an optimization model included in the valuation tool StorageVET, developed by EPRI. The model uses the site's tariff rate applied to the net power flowing through the site meter as the problem's objective function. The optimization problem aims at minimizing the cost of the electricity bill for each month of the year, subject to the problem's constraints. They include:

- Battery storage constraints: Battery storage constraints model power and energy limitations of the battery, as well as state of charge (SOC) evolution over time, including the effect of roundtrip efficiency.
- Power balance constraints: The power flowing through the site meter for bill reduction services is the sum of the power associated with the load, the PV generation, and the storage system, with the corresponding sign. The power is positive if it is going outwards (net export), and negative if it is going inwards (net import)

When the optimization problem is solved, the hourly battery power, hourly SOC, and hourly power flowing through the site meter are found. The benefits due to bill reduction are calculated as the difference between the electricity bill's Net Present Cost (NPC) without the storage microgrid and the electricity bill's NPC with storage. From the results, 20-year Net Present Value (NPV) and the cost of covering critical load coverage ($/kW-yr) are recorded. These two metrics are used to compare the performance of various microgrid configurations.

The NPV calculations are for a 20-year analysis period, with a 2.2% annual cost escalation and 6% discount rate. Note that the CapEx cost for Li-ion energy storage systems were determined based on EPRI cost study 3002013957 *Energy Storage Technology and Cost Assessment,* as well as *3002013958 Energy Storage Technology and Cost Assessment: Executive Summary* (publicly available). OpEx cost for Li Ion is $10/kW-year. The NPV improvement introduced here corresponds to the NPV of the storage-enabled microgrid investment case where the avoided cost of the baseline microgrid is considered as a benefit of the investment. It should be noted that in both the baseline and the investment cases, the overall installation and operation of the microgrid results in a net cost. This is represented throughout the analysis as a negative Net Present Value (NPV). However, in the investment cases, this overall microgrid installation and operation cost reduces marginally because of the removal of one or more generators and UPS. This cost reduction is referred to as NPV improvement throughout the analysis.

For the investment cases, the microgrid configurations for two different types of storage technologies are evaluated separately. First, the analysis results for the Li-ion technology is presented.

5.4.3.1 Li-Ion Storage-Enabled Microgrid Investment Case Cost Details

Since the capital and OpEx of the Li Ion system are readily available, the cost benefit analysis for the investment cases involving a Li Ion system were performed in a straightforward manner. Table 15 below shows that the results for the minimum feasible energy storage size calculated just enough to satisfy the reliability target. It also includes the secondary services that provides maximum benefit for all sites. For 3 of the 5 sites (Ventura, March ARB, and Holloman) more value can be accrued from reducing the customer's bill than in wholesale market participation. This is primarily resulting from favorable load profiles at the site, relative to the time-of-use (TOU) utility tariff structure. In addition, demand response presents an added opportunity. For Corpus Christi, the utility tariff is a flat energy price, therefore offering little value from energy arbitrage. This results in a more favorable opportunity for wholesale market participation to improve NPV. In the case of Fort Bliss, the tariff offers little opportunity for bill reduction and contains no provision for wholesale market participation. As a result, at Fort Bliss, the battery offers only the primary service (reliability). Further, the two metrics of comparison are also included in the Table 20. It can be observed that the investment is definitely better than the baseline diesel genset microgrid.

The maximum NPV improvement is 1.5%. The major contributing factor behind the NPV improvement was the avoided cost of owning and operating extra generators. For some of the sites, the ES deployment solutions also support retirement of at least one UPS system. In addition to the retirement of generators, the installation of energy storage systems also allowed the removal of a few UPS systems. However, this was possible only for a few sites where the power capacity of the energy storage was sufficiently high to allow ride through of critical load. It should be noted that when generators and UPS are retired in the investment case, it not just reduced the capital expense of these assets but also reduced the overall operational and maintenance expense associated with them.

Table 15. Minimum Energy Storage Size Requirements at Each Site that Satisfy the Reliability Targets

	Naval Base Ventura County	March ARB	Corpus Christi	Holloman AFB	Fort Bliss
Battery Size (Li Ion)	875 kW, 1.5 hr	75 kW, 0.5 hr	225 kW, 0.5 hr	450 kW, 0.5 hr	1225 kW, 1 hr
Li Ion Cost (CAPEX) ($/kWh)	$881/kWh	$1013/kWh	$1187/kWh	$1184/kWh	$1084/kWh
Li Ion Cost (OPEX) ($/kW-yr)	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year
Baseline NPV (20 Yr) (Cost)	$108.95	$62.45	$110.53	$96.14	$302.40
Investment Case NPV (20 Yr) (Cost)	$108.03	$62.08	$109.49	$94.71	$301.32
% NPV Improvement	**0.84%**	**0.59%**	**0.94%**	**1.49%**	**0.36%**
Baseline Critical Load Coverage ($/kW-yr)	**135.5**	**416.09**	**88.95**	**98.35**	**$82.70**
Storage-Enabled Critical Load Coverage ($/kW-yr)	**123.24**	**385.39**	**77.08**	**86.63**	**$76.20**
% Critical Coverage Improvement	**9.05%**	**7.38%**	**13.34%**	**11.92%**	**7.86%**
# Generators Retired	2	1	1	2	2
Secondary Services	Retail Bill Reduction	Retail Bill Reduction	Wholesale Services	Retail Bill Reduction	N/A
Total Sec. Service Revenue ($)	$607,500	$59,418	$705,383	$279,473	N/A
Avoided Costs due to Demand Charge Reduction	$478,250	$48,404	N/A	$267,932	N/A
Avoided Costs due to Energy Cost Reduction	$129,250	$11,014	N/A	$11,541	N/A
Demand Response	$61,539	$4,220	N/A	$12,271	N/A

However, it should also be noted that in the investment cases, the addition of an energy storage system added a few additional cost components which included the CapEx of the energy storage system, the operational and maintenance expenses associated with it and a possible replacement expense. The CapEx of a li-ion system was assumed to fall at 6% annually. The lifetime of one li ion system was about 7 years and each replacement would involve only replacing the energy portion of it while the electronic circuitry was assumed to be functional for the entire 20-year analysis period. The replacement of the energy portion would account for half of the overall energy storage system CapEx. However, the Flow battery system was assumed to last for the entire 20-year analysis period without any replacement.

The NPV calculation of the investment cases also included the potential value of offering secondary services during the grid connected days. This was either in the form of utility bill reduction of the site or in the form of revenue generated by offering wholesale market services like energy time shift and frequency regulation. For the Naval Base Ventura County, March Air Reserve Base and Holloman Air Force Base, there was more value in reducing the sites' utility bill than offering wholesale market services due to the nature of the sites' load profiles and the structure of the retail tariff. For NAS Corpus Christi, there was more value in offering wholesale market services like energy time shift and frequency regulation since it had a flat retail energy price. For Fort Bliss, there was no possibility any secondary services due to the nature of the utility rate structure. In addition to the secondary benefits described above, the value of participating in the demand response program was also included in the analysis. However, this was done only for the sites where there was more value in performing bill reduction than wholesale market services, i.e., Naval Base Ventura County, March ARB and Holloman AFB.

5.4.3.2 Maximizing Benefits from a Larger Sized Storage System

The improvement in NPV and Annual Net Cost of *Serving* each Kilowatt of Peak Critical Load was marginal in the previous analysis, since the energy storage was sized for reliability purpose. Further analysis is carried to understand the effect of oversizing the energy storage size. Larger battery provides additional benefits from the secondary services, generating a greater NPV improvement including bill savings and avoided OpEx.

Once the minimum size of energy storage for meeting the reliability target was determined, the next step was to check if oversizing the energy storage would improve benefits. This oversizing exercise was carried out for all the sites except Fort Bliss. Due to the nature of tariff in Fort Bliss, any ES oversizing wouldn't necessarily translate into an increase in benefits. For the remaining four sites, the duration of the energy storage was assumed to be four hours and the power capacity was increased gradually in fixed steps as an iterative process and the critical load coverage cost was calculated at each step in the form of a binary search. Moreover, an arbitrary cap was enforced to the extent to which the battery power capacity could potentially be upsized to. This arbitrary cap was determined based on the annual minimum load of each site. For the sites at Ventura and Corpus Christi, the critical load coverage cost reduced monotonically with an increase in energy storage size. Hence, the energy storage size was maxed out for maximum benefit. However, for March ARB and Holloman AFB, the critical load coverage cost exhibited a non-monotonic behavior with respect to the energy storage size. The critical load coverage cost reduced initially and when upsized beyond a certain size it started to increase. Hence, after a few iterative steps, the optimal energy storage size was determined to be 1000 kW, 4 hr and 3600 kW, 4 hr for March ARB and Holloman AFB respectively. The results of the analysis are included in Figure 10.

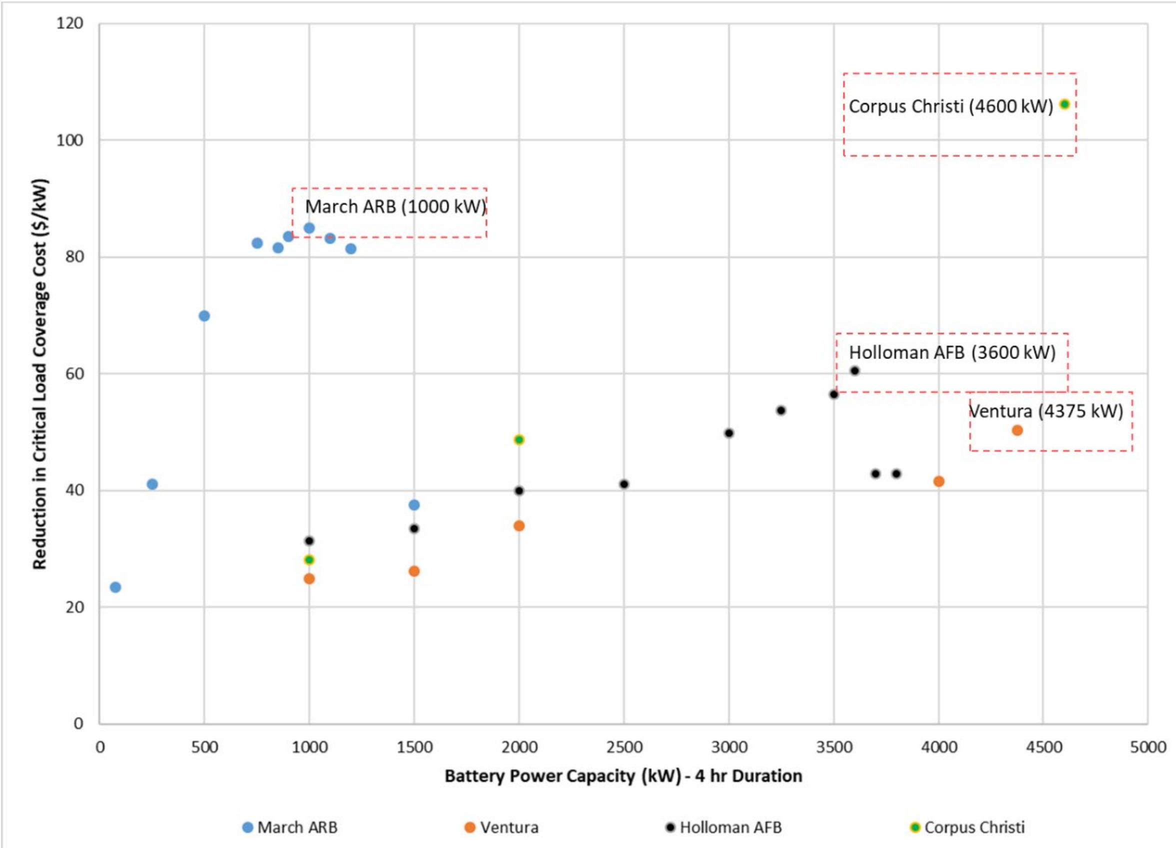

Figure 10. Improvement in Annual Net Cost of Serving each Kilowatt of Peak Critical Load ($/kW-yr) of the Investment Case Compared to Baseline Microgrid for All Sites

Table 16. Final Energy Storage Size and Microgrid Design Based on Cost-Benefit Analysis

		Ventura	**March**	**Corpus Christi**	**Holloman**	**Fort Bliss**
Number and Capacity of Baseline Gensets		7x750kW= 5.25MW	4x250kW=1 MW	7x750kW=5. 25MW	9x750kW=6.75 MW	8x2000kW=16 MW
Peak Critical Load		4MW	0.6MW	4.4MW	6MW	12.5MW
Li-ion ES Microgrid Config.	Power and Duration	4375kW 4hr	1000kW 4hr	4600kW 4hr	3600kW 4hr	1255kW 1hr
	SOC Reservation	5.16%	0.23%	0.00%	0.78%	100%
	# Gensets	5	3	6	7	6
	Secondary Services	Bill reduction	Bill reduction	Wholesale Market	Bill reduction	None
Flow ES Microgrid Config.	Power and Energy	975 kW 5hr	75kW 5hr	225kW 5hr	475kW 5hr	1075kW 5hr
	SOC Reservation	56.3%	6.25%	0%	6.25%	100%
	# Gensets	5	3	6	7	6
	Secondary Services	Bill reduction	Bill reduction	Wholesale	Bill reduction	None

The results of oversizing are presented in Table 17. It can be observed from Table 17 that there is positive % NPV improvement at all sites. The maximum NPV improvement is 10.52% at Hollowman AFB. The baseline 20-year microgrid NPV at the site is $96.14 million. The NPV of the investment case with energy storage is $83.09 million. The decrease in NPV is due to the replacement of a diesel generator and the UPS in the baseline microgrid with a Li-ion energy storage system. Further, the revenue from the energy storage secondary services participation in bill reduction program and/or wholesale services is also accounted for in the NPV calculation. The secondary services revenue for each site is also included in Table ES-5. The revenue numbers are obtained from EPRI's optimization tool StorageVET®.

Table 17. Oversizing Energy Storage Size (P&E) Beyond the Minimum Requirements at Each Site that Satisfy Reliability Targets as well as Provide Additional Revenue Improvements

	Naval Base Ventura County	March ARB	Corpus Christi	Holloman AFB	Fort Bliss
Battery Size (Li Ion)	4375 kW, 4 hr	1000 kW, 4 hr	4600 kW, 4 hr	3800 kW, 4 hr	1225 kW, 1 hr
Li Ion Cost (CAPEX) ($/kWh)	$445/kWh	$540/kWh	$445/kWh	$477/kWh	$1084/kWh
Li Ion Cost (OPEX) ($/kW-yr)	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year	$10/kW-year
Baseline NPV (20 Yr) (Cost)	$108.95	$62.45	$113.05	$96.14	$302.40
Investment Case NPV (20 Yr) (Cost)	$105.27	$61.50	$101.16	$83.09	$301.32
% NPV Improvement	**3.38%**	**1.52%**	**10.52%**	**13.57%**	**0.36%**
Baseline Critical Load Coverage ($/kW-yr)	**135.5**	**416.09**	**88.52**	**98.35**	**$82.70**
Storage-Enabled Critical Load Coverage ($/kW-yr)	**85.2**	**337.42**	**-17.3**	**65.53**	**$76.20**
% Critical Coverage Improvement	**37.12%**	**18.91%**	**119.54%**	**33.37%**	**7.86%**
# Generators Retired	2	1	1	2	2
Secondary Services	Retail Bill Reduction	Retail Bill Reduction	Wholesale Services	Retail Bill Reduction	N/A
Total Sec. Service Revenue ($)	$8,785,963	$2,340,716	$18,175,974	$8,275,987	N/A
Avoided Costs due to Demand Charge Reduction	$4,850,519	$1,249,439	N/A	$7,031,375	N/A
Avoided Costs due to Energy Cost Reduction	$3,935,444	$1,091,277	N/A	$1,244,612	N/A
Demand Response	2,490,684	$43,611	N/A	$1,558,580	N/A

Figure 11 represents the reduction in annual cost of serving each kW of peak critical load for the Li-ion storage-enabled microgrid case as compared to the baseline case on a site-specific basis. For the first three sites, Ventura, March ARB, and Holloman, there was a significant reduction in cost due to the reduction in the number of generators and UPS systems used in battery case. On top of that, there was also the added benefit reducing the customer's bill which contributed to these cost reductions. For Corpus Christi, the battery generated more value by offering wholesale market services as compared to bill reduction. There are no known regulatory restrictions to battery upsizing limits, and was upsized to 4.6 MW, which increased the capacity offering into the wholesale market.

This resulted in a negative cost. Due to the nature of tariff structure in Fort Bliss, there was no possibility of exploring other secondary value streams, neither wholesale market norbill reduction. Hence, the battery was sized primarily for reliability alone and this yielded a very marginal reduction to critical load coverage cost.

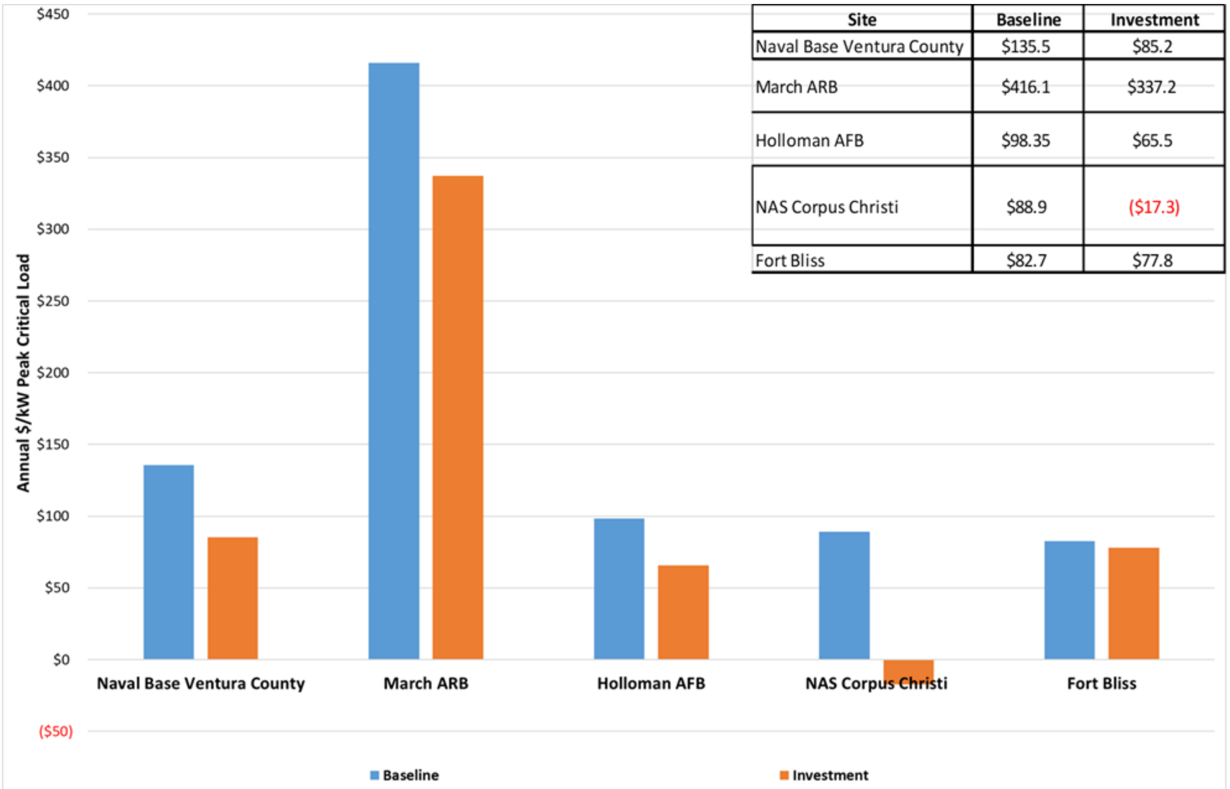

Figure 11. Annual $/Kw Peak Critical Load Variations Across Five Installations

5.4.3.3 Future Volatile Price Discussion

Only DA energy price is used for the analysis since the variability associated with real time energy price is very high and uncertain. Table 18 summarizes the comparison between cost benefit results of the Li-ion microgrid cases using present and future DA energy prices. It is not surprising that the higher variability of the future prices creates more opportunity to perform high-value arbitrage, however, potential increase in revenue must be interpreted carefully, since higher variability may also carry lower predictability, which may affect the ability of the asset operator to realize market gains.

Table 18. CBA for Current and Future DA Energy Price

Site	Battery Size	Total NPV Improvement (20 Yr)		Change (%)
		Current DA Energy Price	Future DA Energy Price	
Naval Base Ventura County	875 kW, 1.5 hr	$900,871.00	$973,513.00	8.06%
March ARB	75 kW, 0.5 hr	$347,722.82	$352,232.06	1.30%
NAS Corpus Christi	225 kW, 0.5 hr	$1,157,871.53	$1,208,021.68	4.33%

5.4.3.4 Flow Battery Storage-Enabled Microgrid Investment Case Cost Details

Next, economic analysis for the Flow battery-based microgrid was carried out. Unlike the Li-ion technology, the CapEx[21] and OpEx data for the Flow battery system was not available, and so a different approach for these investment cases was required. It was determined that the "need to cost"[22] methodology could be used that would result in comparable values to the Li-ion NPV improvement analysis.

Table 19. Flow Battery Cost Development Based on 'Need to Cost'

	Naval Base Ventura County	March ARB	Corpus Christi	Holloman AFB	Fort Bliss
Flow Battery Size	975 kW, 5 hr	75 kW, 5 hr	225 kW, 5 hr	475 kW, 5 hr	1075 kW, 5 hr
Li-ion Battery Size used for deriving Flow Battery "Need to Cost"	875 kW, 5 hr	75 kW, 5 hr	225 kW, 5 hr	450 kW, 5 hr	1225 kW, 5 hr
Flow Battery "Need to Cost" (CapEx + OpExX) ($/kWh)	$502/kWh	$926/kWh	$724/kWh	$735/kWh	$822/kWh

The "Need to cost" numbers for the minimum Flow battery size requirement case was then compared with the $/kW and $/kWhr numbers that were captured from several flow battery manufacturers.

Table 20. Flow Battery Cost Range from Various Vendors

	UET	Sumitomo	Primus	Avalon
$/kW	4134	4120	5860	3489
$/kWh	1060	1373	1173	1162

The "Need to cost" numbers at each site was outside the cost ranges that were obtained from the vendors, therefore further sensitivity analysis based on oversizing is not carried out.

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[21] CapEx cost determined based on EPRI cost study 3002013957 *Energy Storage Technology and Cost Assessmentv3002013958 Energy Storage Technology and Cost Assessment: Executive Summary,* which is publicly available

[22] CapEx and OpEx costs were not provided by Lockheed Martin (LM) for the flow battery system. LM indicated that the information is proprietary, therefore EPRI and LM jointly came up with the "need to cost" methodology

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6.0 PERFORMANCE ASSESSMENT

Table 21 summarizes the technical reliability targets and performance objectives for Li-ion under different outage conditions. The first metric, 100% critical load, which corresponds to the design requirement shows the probability of serving 100% of the critical load for each site. For 24 and 168-hour outages, the reliability performance is higher than the baseline. This result is true for all outage durations between 1 and 168. Reliability performance for hours between 1 and 168 is included in Appendix A3.1 for Li-ion energy storage based microgrids and Appendix A3.2 for Flow battery energy storage microgrids.

Reliability analysis was carried out under more stringent conditions. The next set of results display the probability of serving an outage if the critical load was 130% of the critical load used for design. The performance curves for Li-ion battery based microgrid is included in Appendix A3.3. It can be observed that except Fort Bliss, the other sites having probability of 98% for serving critical load during a 24-hour outage. At Fort Bliss, the energy storage is sized only to meet the reliability requirements and it is not oversized beyond the minimum requirement. This is because the current tariff structure at the Fort Bliss site does provide the opportunity for the energy storage to make additional revenue from secondary services.

Similarly, the reliability analysis is carried out for the designed microgrid with the following conditions: no diesel fuel is available, and the critical load is 10% and 30% of the actual load. Again, all sites, except Fort Bliss, have a high the probability (over 90%) of serving the critical load during a 24-hour outage. The probability curves for all sites are included in Appendix A3.5 and A3.7 for 10% and 30% critical load coverage respectively.

Table 21 shows the probability percentage for different scenarios at all five sites. The probability percentage of Li-Ion based microgrid for covering 10% critical load when no diesel fuel is available, is calculated to be 98.62% for all sites except Fort Bliss. The reason for this observation is explained using Fig. A3.9 which is included in Appendix. Fig A3.9 shows the histogram on net load for the first 24 hours for all the 100,000 Monte Carlo scenarios. The 100,000 scenarios exhibit differences in outage start times and battery operational status, which is defined by their Availability percentages. Li-Ion is assumed to have an availability of 98.63% and Flow battery has an availability of 98%. Two histograms are included in the figure, one for 10% (blue color) and other for 30% (orange color) of critical load. The net load assumes 20% of solar PV generation, to account for solar variability. The plot also includes the designed battery storage energy capacity (Li-Ion – violet and Flow battery rating- Green). It can be observed that the designed energy rating of Li-Ion storage system for all sites except Fort Bliss is much greater than the maximum 24hour 10% net load. This implies that the designed storage is capable of meeting the critical load for 24 hours unless the battery fails. Therefore, the probability of serving 10% critical load for 24 hours is 98.6%, which is Li-Ion storage availability percentage.

Similarly, histogram for 30% critical load is included in Fig. A3.9. It can be observed that the designed Li-Ion storage size is greater than the maximum 24hr net load only for March AFB. So, the 24 hr probability is 98.6% for March ARB. For other sites, it is less than 98.6%, varying between the sites depending on factors such as actual PV generation and battery SOC when outage starts.

Similar results are shown in Table 21(b) for Flow battery-based designs. Corresponding probabilistic curves are also included in Appendix. It can be observed that the designed microgrid provides better reliability performance than the baseline case for 100% critical load case. For other stringent analysis scenarios, the probability of serving critical load is relatively lesser than Li-ion storage cases, because of the same reason that oversizing of the battery storage is not carried out. The reason for not oversizing the Flow battery system is explained in the next section on cost assessment.

Table 21. Probability of Serving critical load under Baseline and Investment Case

Performance Objective		Ventura		March		Corpus Christi		Holloman		Fort Bliss	
		Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment
100% Critical Load	24 hours	99.46%	99.85%	99.85%	99.98%	99.45%	99.98%	99.11%	99.95%	99.33%	99.38%
	168 hours	85.94%	96.60%	95.04%	99.98%	85.94%	99.39%	78.78%	99.46%	82.42%	89.09%
130% Critical Load	24 hours	-	98.80%	-	99.93%	-	99.49%	-	99.43%	-	73.19%
	168 hours	-	73.05%	-	97.82%	-	93.49%	-	94.48%	-	50.02%
No Gen + 10% Critical Load	24 hours	-	98.62%	-	98.60%	-	98.62%	-	98.62%	-	0.00%
No Gen + 30% Critical Load	24 hours	-	93.62%	-	98.60%	-	95.59%	-	91.64%	-	0.00%

(a) Li Ion

Performance Objective		Ventura		March		Corpus Christi		Holloman		Fort Bliss	
		Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment	Base-line	Invest-ment
100% Critical Load	24 hours	99.46%	99.68%	99.85%	99.91%	99.45%	99.55%	99.11%	99.33%	99.33%	99.50%
	168 hours	85.94%	92.99%	95.04%	97.29%	85.94%	88.19%	78.78%	88.86%	82.41%	90.79%
130% Critical Load	24 hours	-	76.32%	-	98.42%	-	70.27%	-	73.00%	-	74.65%
	168 hours	-	29.72%	-	84.26%	-	32.57%	-	43.00%	-	53.47%
No Gen + 10% Critical Load	24 hours	-	95.38%	-	40.10%	-	13.89%	-	1.12%	-	10.31%
No Gen + 30% Critical Load	24 hours	-	0.00%	-	0.00%	-	0.00%	-	0.00%	-	0.00%

(b) Flow Battery

7.0 STUDY CONCLUSIONS AND OUTCOMES

As illustrated from the results, the proposed analysis methodology using an ES-enabled microgrid provide the following benefits:

1) Optimized microgrid designs at five DoD installations, consisting of diesel generators, UPS, storage, and solar PV are capable of meeting DoD performance objectives and reliability targets as a function of outage durations between 1 and 168 hours. Reliability performance of the storage-enabled microgrid is equal to or greater than the reliability targets specified for each DoD site for all outage durations ranging up to 168 hours.

2) Storage-enabled microgrids, either Li-ion or Flow batteries, enhance reliability and energy security by avoiding the cost of lost loads during outages, lower cost of operations, enable power market participation, and result in a positive NPV compared to diesel-based microgrids

3) Storage-enabled microgrids, either Li-ion or Flow batteries, reduce the 'loss of critical load' risk during grid outages and reduce the cost of serving critical load

4) Incremental values of using storage-enabled microgrids were found to include:

   - Avoided energy costs through self-generation and arbitrage
   - Avoided cost due to diesel generation reduction and fuel savings
   - Avoided peak demand costs (except at Fort Bliss)
   - Avoided cost due to diesel generator O&M
   - Avoided cost due to UPS reduction
   - Avoided cost due to UPS O&M
   - Demand response program participation value (except at Fort Bliss)
   - Emissions reduction through increased renewable generation

5) The annual cost of serving peak critical load ($/kW-yr) is lower for the proposed storage enabled microgrid compared to the baseline microgrid. The maximum decrease in the cost is at Corpus Christi and the minimum is at Fort Bliss. At Fort Bliss, the energy storage is not allowed to gain additional revenue from secondary services, and hence the annual cost of serving the critical load is higher.

6) The proposed microgrid design for Corpus Christi site provided yielded negative annual cost of serving peak critical load ($/kW-yr), meaning that the microgrid will be profitable during its lifetime.

7) Energy storage systems are sized initially to meet the reliability target for each of the five sites. The oversizing analysis proved that a large storage-enabled microgrid could provide more benefits and thereby reduce the annual cost of serving peak critical load ($/kW-yr). The oversizing iterations and the corresponding cost change ($/kW-yr) are included in Figure 10. At Corpus Christi and Ventura, large energy storage size meant more benefits. And the oversizing had to be capped to the site's min load. Whereas, at March and Holloman site, the annual cost of serving peak critical load saturated and increasing the power capacity further did not lower the cost further.

8) The SOC reservation for the final microgrid design were less than 5% for all sites. This increases the potential revenues to be accrued by the microgrid and is enabled by the ability of the storage system to charge from distributed generation when there is enough capacity.

APPENDICES

A1 SITE LOAD APPENDIX

FACILITY/SITE LOCATION AND RELEVANT CHARACTERISTICS

One Army Site: Fort Bliss – As seen in Table 3 this site has 8 diesel gensets capped at 2000kW.

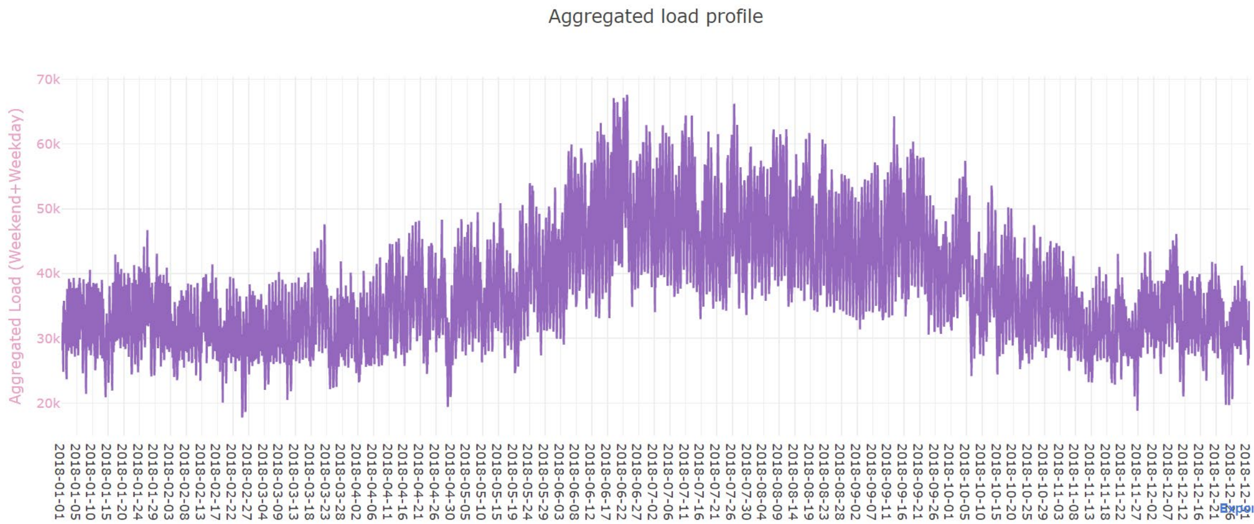


Figure 12. Aggregated Load Profile – Fort Bliss

Two Navy Site: Naval Air Station Corpus Christi and, Naval Base Ventura County –

Naval Air Station Corpus Christi – As seen in Table 3 this site has 7 diesel gensets capped at 750kW.

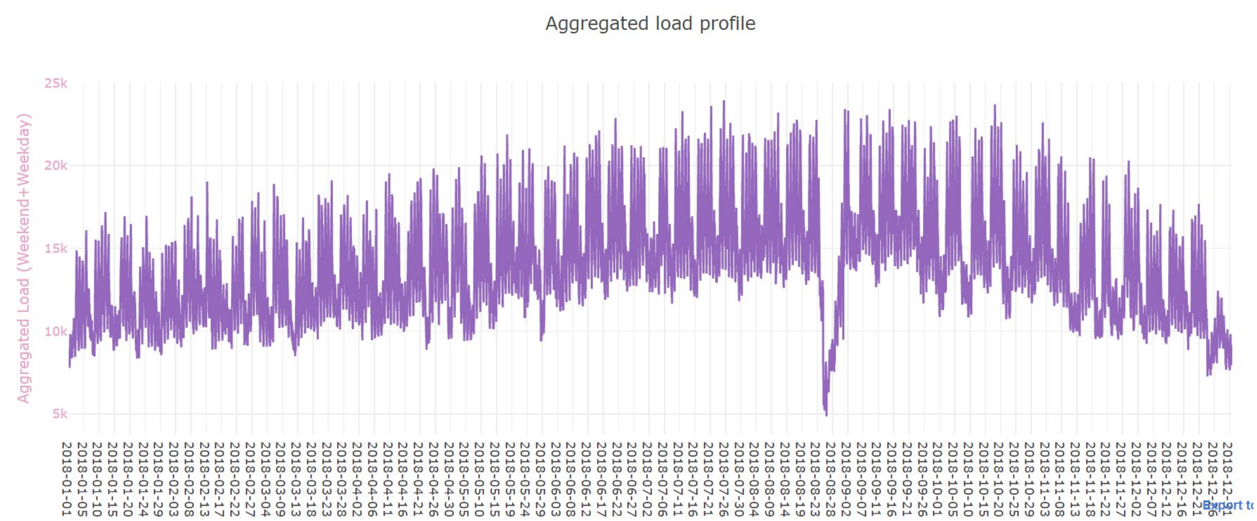


Figure 13. Aggregated Load Profile – Naval Air Station Corpus Christi

Naval Base Ventura county – As seen in Table 3 this site has 7 diesel gensets capped at 750kW.

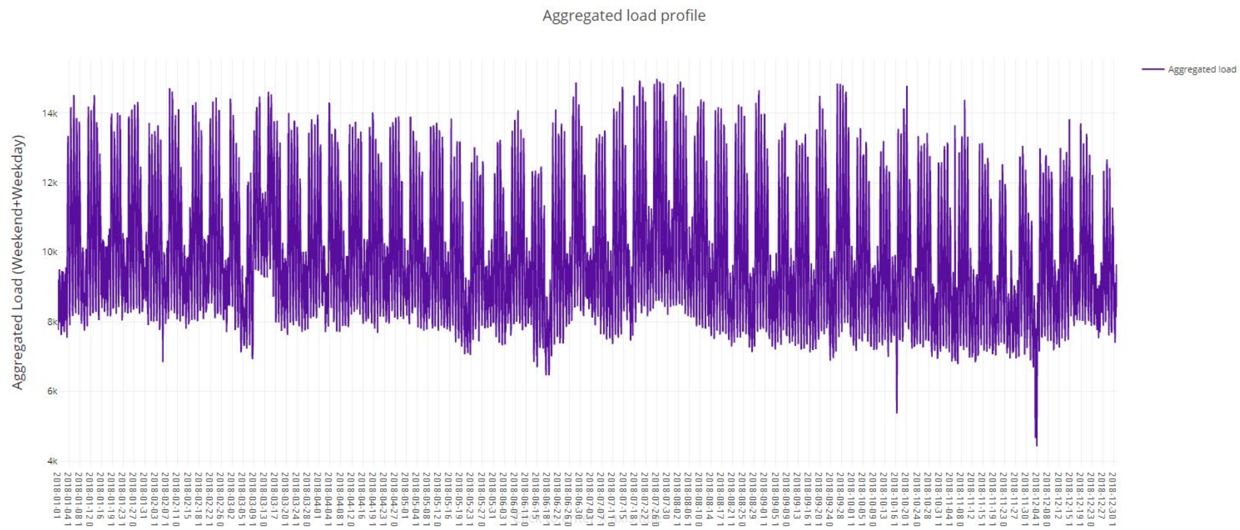


Figure 14. Aggregated Load Profile – Naval Base Ventura County

Two Air Force Sites: Holloman Air Force base, and March Air Reserve base

Holloman Air Force base–This site has 9 diesel gensets capped at 750kW.

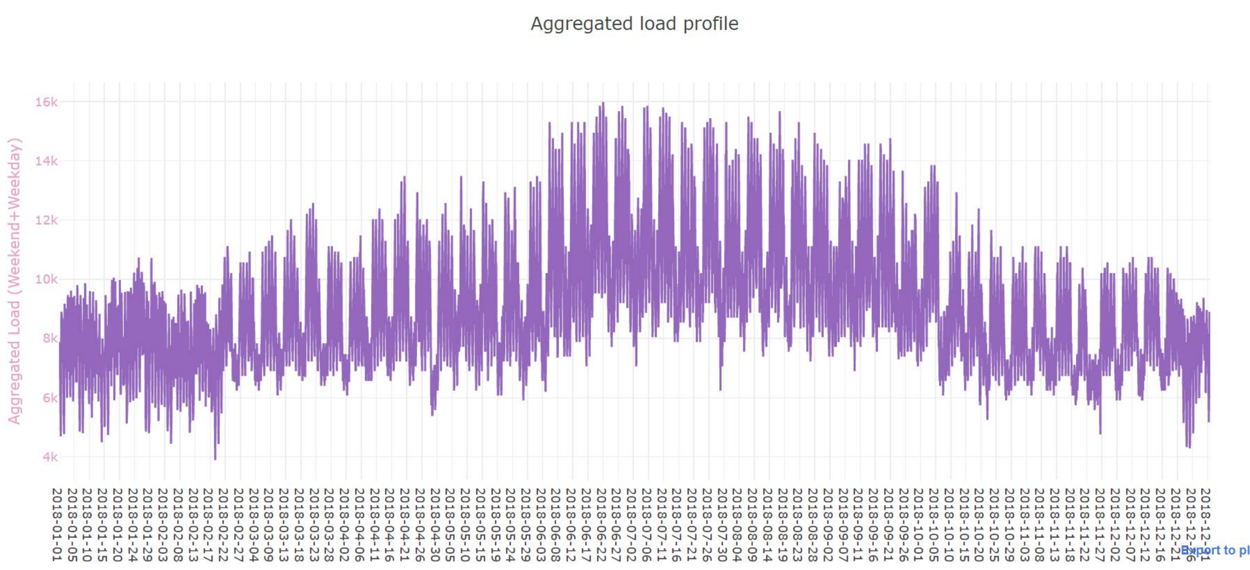


Figure 15. Aggregated Load Profile – Holloman Air Force Base

March Air Reserve base–This site has 4 diesel gensets capped at 250kW.

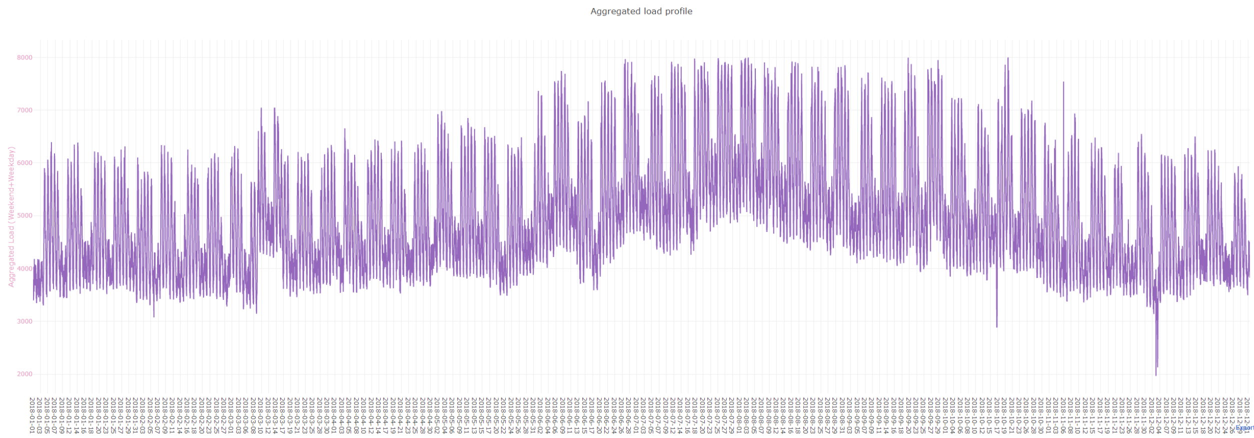


Figure 16. Aggregated Load Profile – March Air Reserve Base

A2 METHODOLOGY APPENDIX

Step 1: Reliability and Sizing Analysis:

For a given microgrid configuration, Figure 17 shows the approach to find the minimum feasible energy size required to meet the reliability target of the microgrid. Since the size of energy storage has two variables – power (kW) and duration (hr), the duration of the battery technology is fixed for the analysis and the minimum feasible power rating of the energy storage for the ES duration is determined using the approach detailed in Figure 17. The process is repeated for different durations. For Li-ion energy storage, the energy storage durations from 0.5 hour to 5 hours in increments of 0.5 hour are considered and for Flow battery storage durations from 5 to 12 hours in increments of 1 hour are considered. As a result, 10 feasible sizes for Li-ion and 8 feasible sizes for Flow battery are determined from the analysis.

The binary search algorithm is explained in detail as follows. A large energy storage size is chosen as the initial feasible size for the binary search algorithm as shown in Figure 17. and a small size is considered as the initial infeasible ES size for the approach. Before proceeding with the analysis, it is made sure that the initial sizes are feasible and infeasible respectively. If the initial chosen feasible size is not feasible, then the size is increased exponentially to find a feasible size that can satisfy the reliability target of the microgrid. In case, no feasible size is found, then it is concluded that the more than one energy storage technology is required for the meeting the reliability target. This is observed in most of the sites when one energy storage is replacing more than one generator in the baseline microgrid. This is analysis is limited to sizing one energy storage technology at each site and so incase the initial feasible is not, the analysis is stopped. Similarly, if the initial infeasible size is found to feasible, it implies that there is no need for additional energy storage and the diesel generators are sufficient to provide required reliability performance of the microgrid. The analysis is stopped, and the next Energy storage duration is analyzed further.

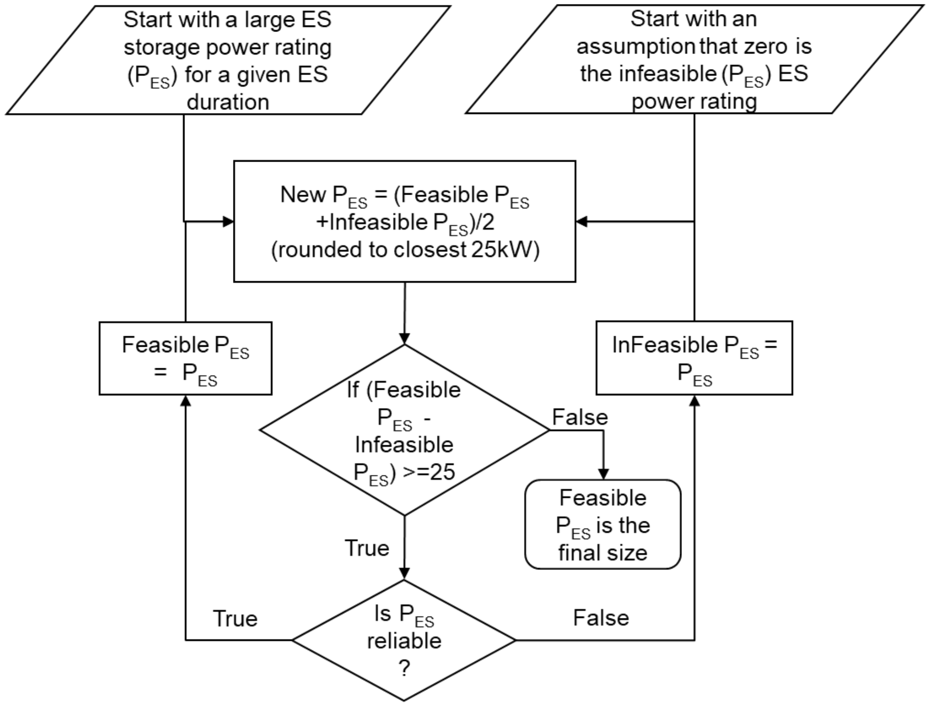


Figure 17. Binary Search Algorithm to Find Minimum Feasible ES Power Rating for a Given ES Duration

After the initial feasible and infeasible sizes are chosen as show in Figure 17 the new ES size is calculated as a mean of the both the initial sizes. For this analysis it is rounded to the closest 25kW. The new size is checked for reliability, and if it is reliable the initial Feasible size is replaced with the new size. Otherwise, the new size replaces the initial Infeasible size. The process is continued until the difference between the feasible and infeasible size is within 25kW.

A2.1 Storage-enabled Microgrid Investment Case Modeling Appendix

Table 22. March Site: Energy Storage Size and SOC Reservation for Li-ion and Flow Battery Based Microgrid

Microgrid configuration	ES Power Rating (kW)	ES Energy Rating (kWh)	Minimum SOC Reservation for Reliability		Baseline NPV Improvement ($)	
			Wholesale Market	Bill Reduction	Wholesale Market	Bill Reduction
Li-ion Technology						
N-1 Microgrid	75	37.5	0%	25%	$347,723	$358,135
Flow Battery Technology					**Total NPV of Benefits* ($)**	
N-1 Microgrid	75	375	0%	6.25%	$447,186	$644,884

Table 23. Corpus Christi Site: Energy Storage Size and SOC Reservation for Li-Ion and Flow Battery Based Microgrid

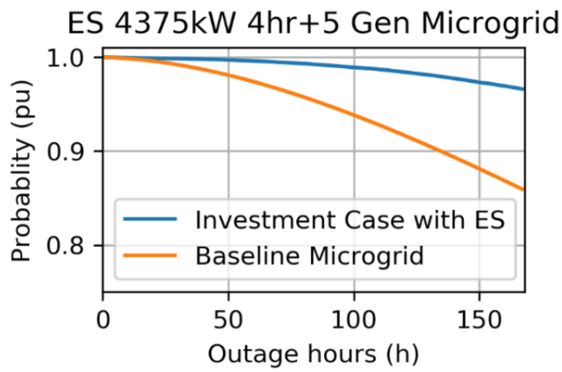
Microgrid configuration	ES Power Rating (kW)	ES Energy Rating (kWh)	Minimum SOC Reservation for Reliability		Baseline NPV Improvement ($)	
			Wholesale Market	Bill Reduction	Wholesale	Bill Reduction
Li-ion Technology						
N-1 Microgrid	225	112.5	0%	0%	$1,157,870	$694,497
Flow Battery Technology					**Total NPV of Benefits* ($)**	
N-1 Microgrid	225	1125	0%	0%	$1,622,050	$1,383,790

Table 24. Holloman Site: Energy Storage Size and SOC Reservation for Li-ion and Flow Battery Based Microgrid

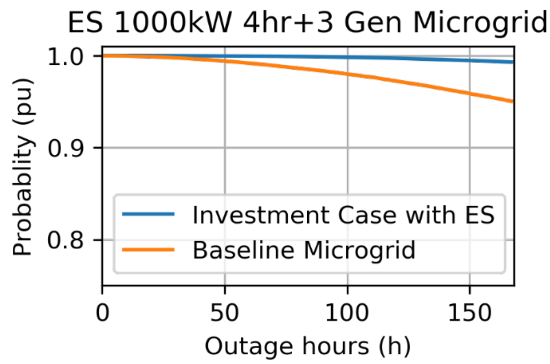
Microgrid configuration	ES Power Rating (kW)	ES Energy Rating (kWh)	Minimum SOC Reservation for Reliability		Baseline NPV Improvement ($)	
			Wholesale Market	Bill Reduction	Wholesale	Bill Reduction
Li-ion Technology						
N-2 Microgrid	450	225	-	50%	-	$1,396,920
Flow Battery Technology					**Total NPV of Benefits* ($)**	
N-2 Microgrid	475	2375	-	6.25%	-	$2,937,050

A3 PERFORMANCE APPENDIX

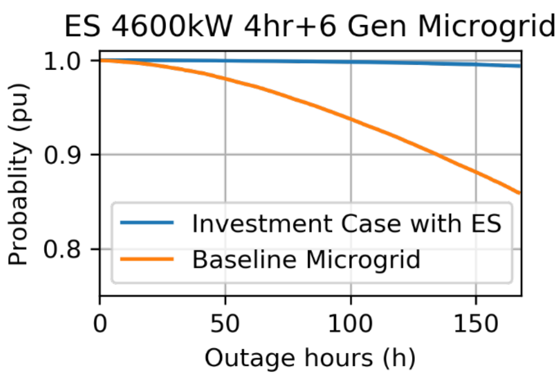
A3.1 Reliability Performance of Li-ion Based Microgrid to Meet 100% of Installation Critical and Ride-through Load



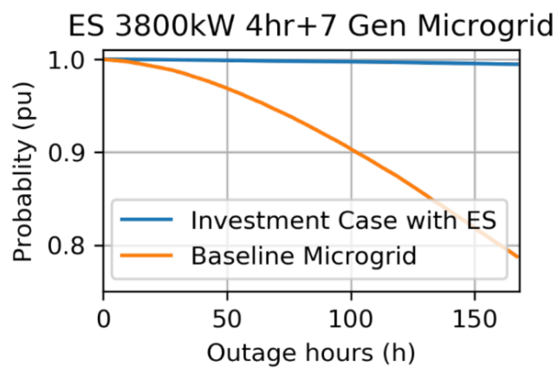
(a) Ventura



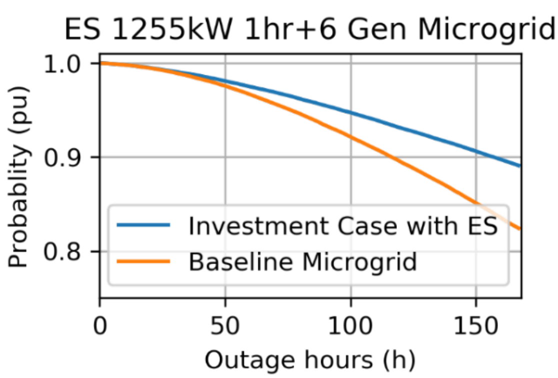
(b) March



(c) Corpus Christi



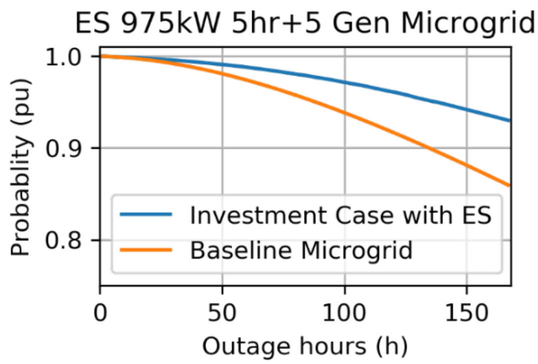
(d) Holloman



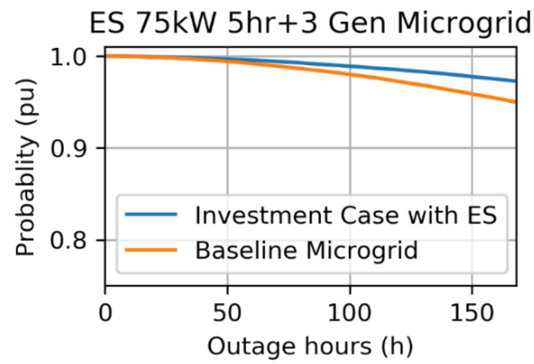
(e) Fort Bliss

Figure 18. Reliability Performance of Li-ion Based Microgrid to Meet 100% of Installation Critical and Ride-through Load

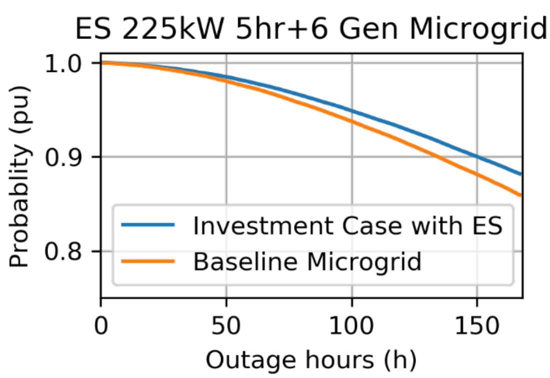
A3.2 Reliability Performance of Flow Battery Based Microgrid to Meet 100% of Installation Critical and Ride-through Load



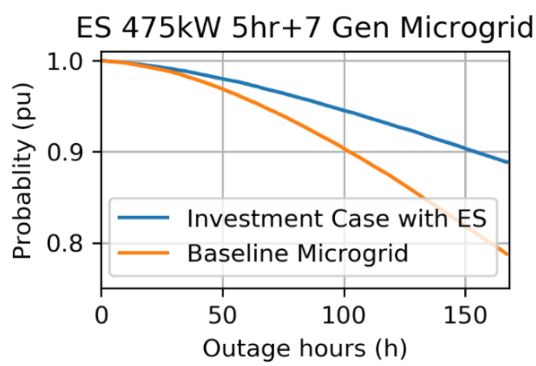
(a) Ventura



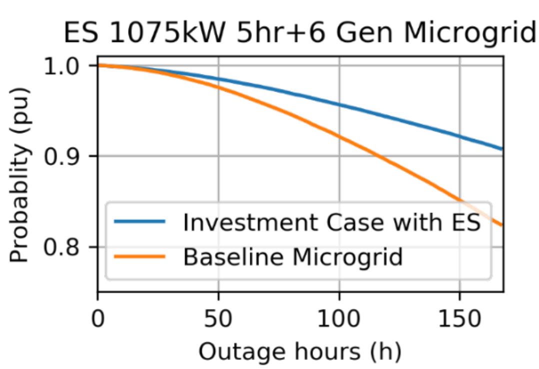
(b) March



(c) Corpus Christi



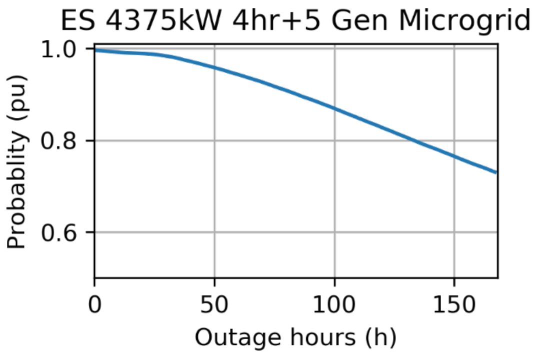
(d) Holloman



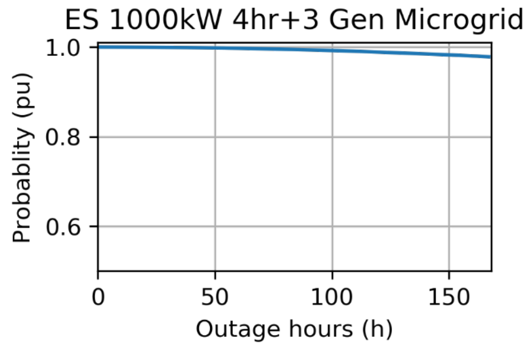
(e) Fort Bliss

Figure 19. Reliability Performance of Flow Battery Based Microgrid to Meet 100% of Installation Critical and Ride-through Load

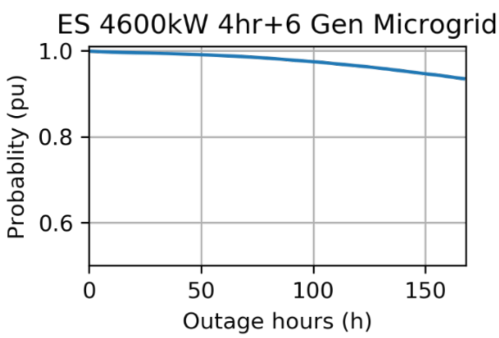
A3.3 Reliability Performance of Li-ion Based Microgrid to Meet 130% of Installation Critical and Ride-through Load



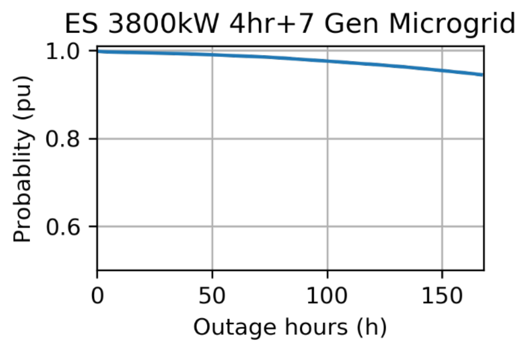
(a) Ventura



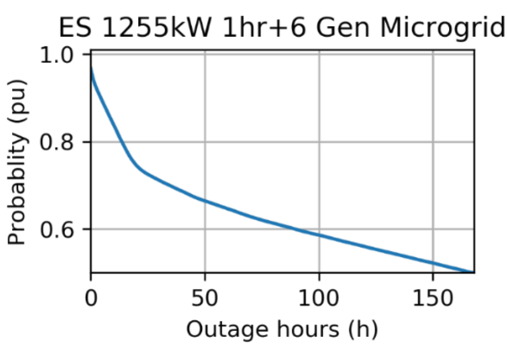
(b) March



(c) Corpus Christi



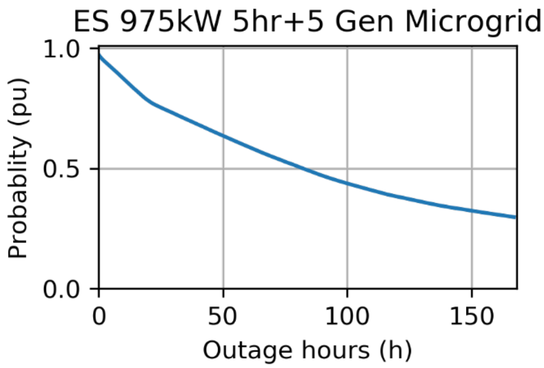
(d) Holloman



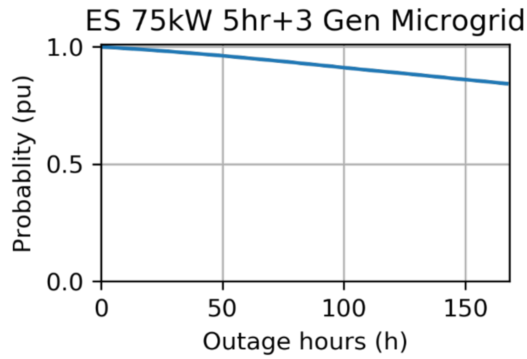
(e) Fort Bliss

Figure 20. Reliability Performance of Li-ion Based Microgrid to Meet 130% of Installation Critical and Ride-through Load

A3.4 Reliability Performance of Flow Battery Based Microgrid to Meet 130% of Installation Critical and Ride-through Load



(a) Ventura



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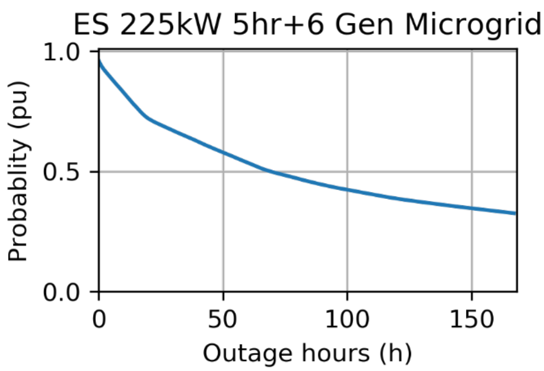
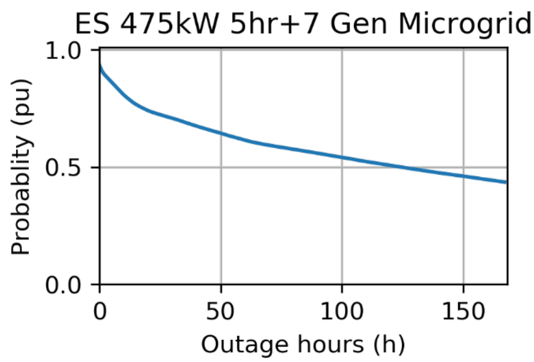


(c) Corpus Christi



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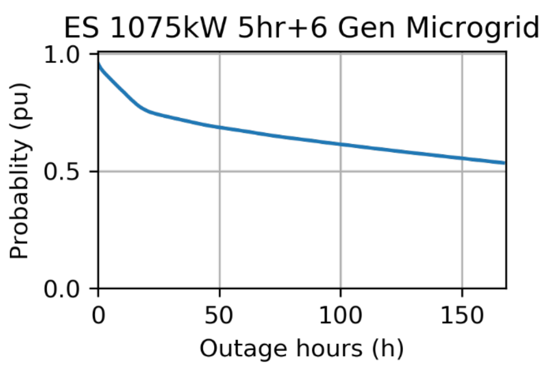
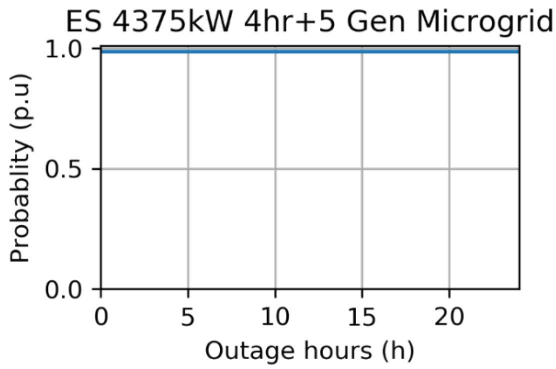


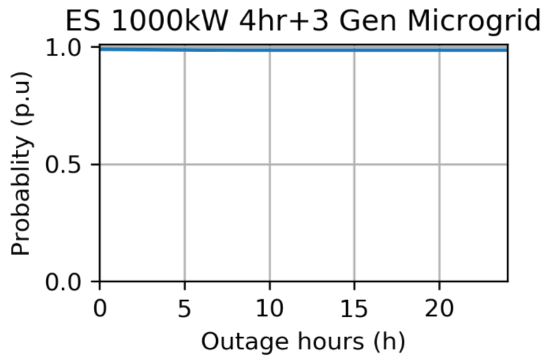
(e) Fort Bliss

Figure 21. Reliability Performance of Flow Battery Based Microgrid to Meet 130% of Installation Critical and Ride-through Load

A3.5 Reliability of Li-ion Based Microgrid to Meet 10% of Installation Critical and Ride-through Load When No Diesel Fuel is Available



(a) Ventura



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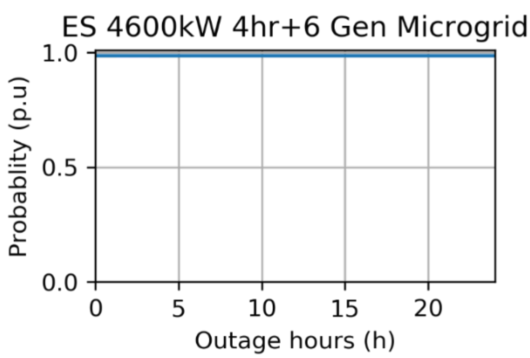
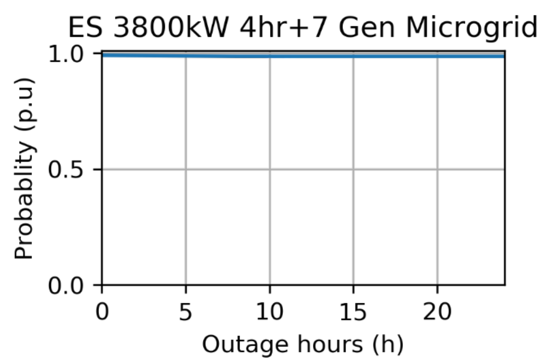
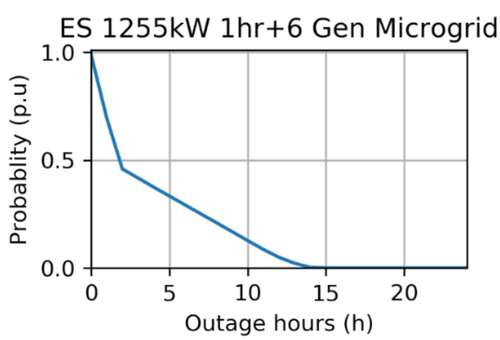


(c) Corpus Christi



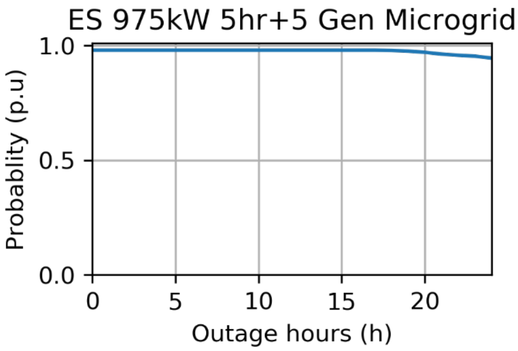
(d) Holloman



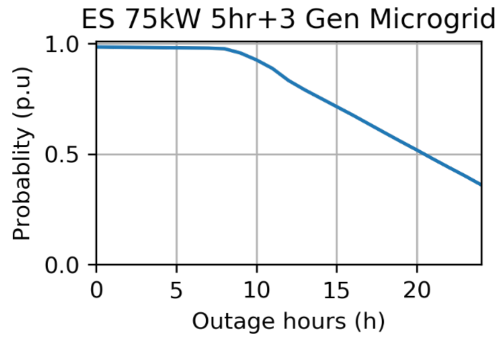
(e) Fort Bliss

Figure 22. Reliability of Li-ion Base Microgrid to Meet 10% of Installation Critical and Ride-through Load When No Diesel Fuel is Available

A3.6 Reliability of Flow Battery Based Microgrid to Meet 10% of Installation Critical and Ride-through Load When No Diesel Fuel is Available



(a) Ventura



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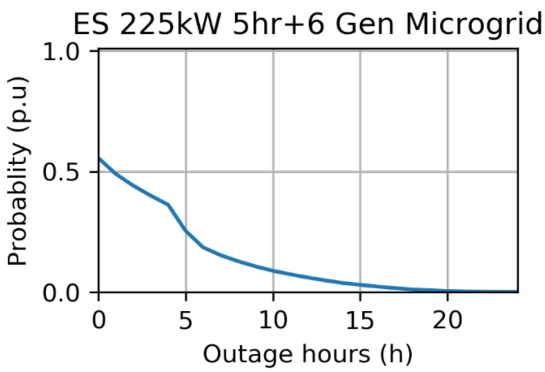
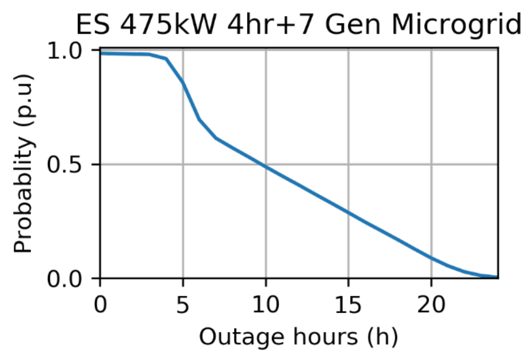
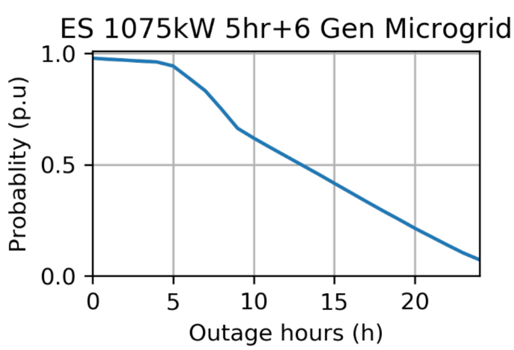


(c) Corpus Christi



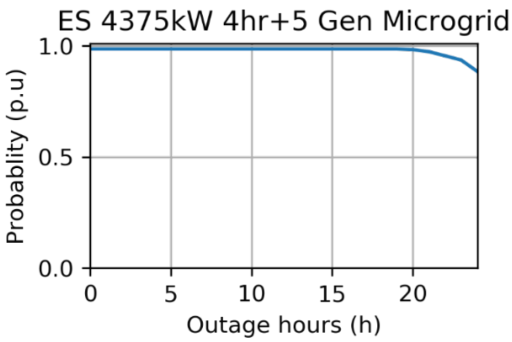
(d) Holloman



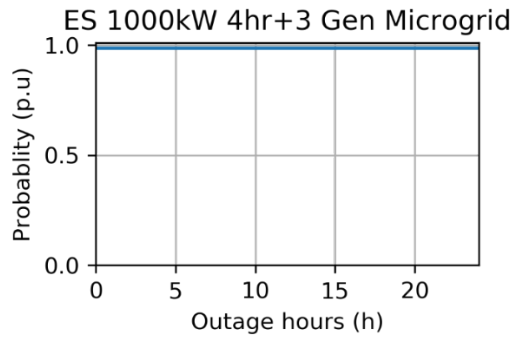
(e) Fort Bliss

Figure 23. Reliability of Li-ion Base Microgrid to Meet 10% of Installation Critical and Ride-through Load When No Diesel Fuel is Available

A3.7 Reliability of Li-ion Base Microgrid to Meet 30% of Installation Critical and Ride-through Load When No Diesel Fuel is Available



(a) Ventura



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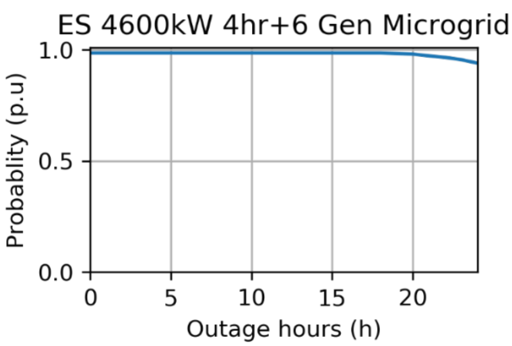
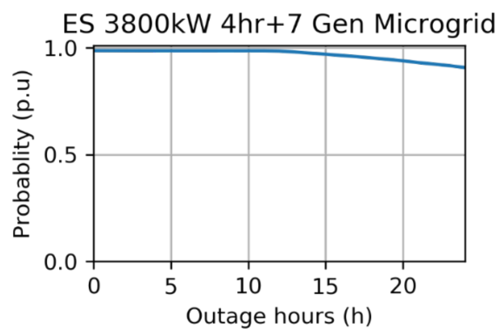
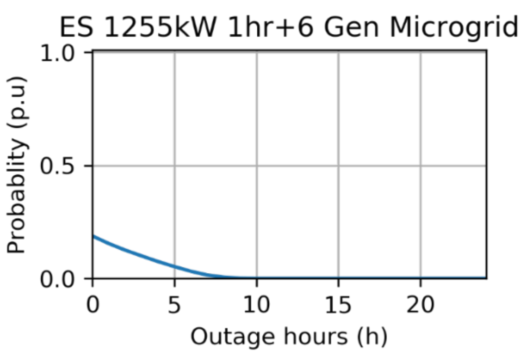


(c) Corpus Christi



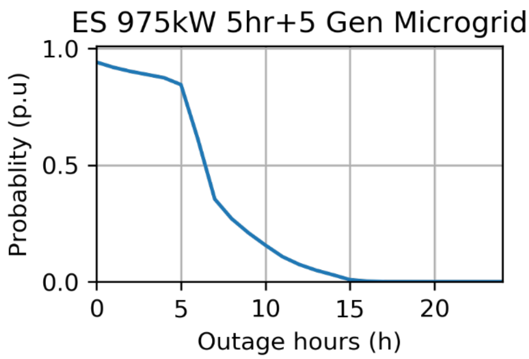
(d) Holloman



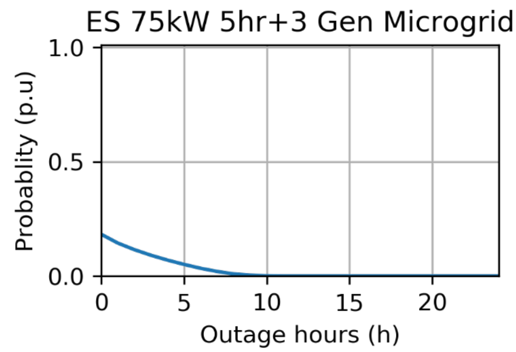
(e) Fort Bliss

Figure 24. Reliability of Li-ion Base Microgrid to Meet 10% of Installation Critical and Ride-through Load When No Diesel Fuel is Available

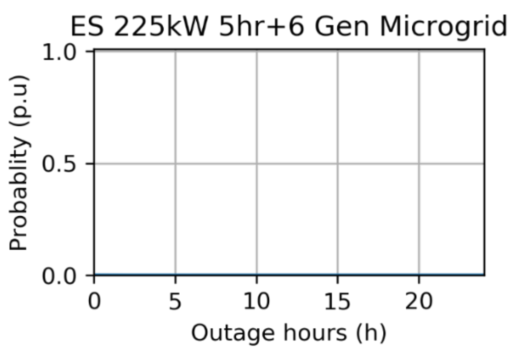
A3.8 Reliability of Flow Battery Based Microgrid to Meet 30% of Installation Critical and Ride-through Load When No Diesel Fuel is Available



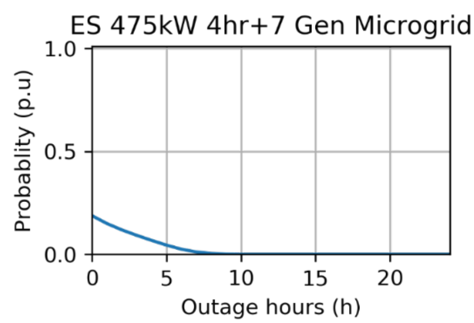
(a) Ventura



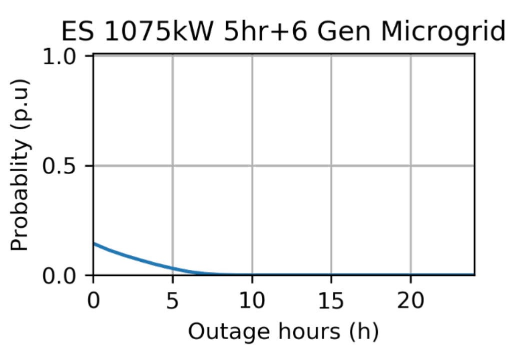
(b) March



(c) Corpus Christi



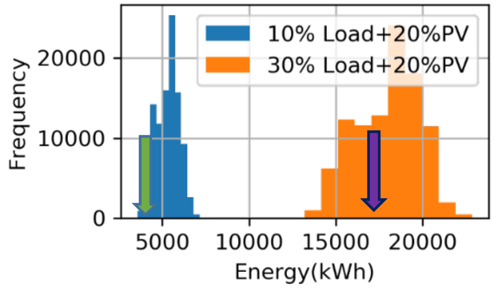
(d) Holloman



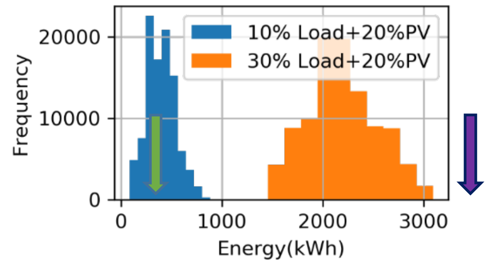
(e) Fort Bliss

Figure 25. Reliability of Flow Battery Based Microgrid to Meet 30% of Installation Critical and Ride-through Load When No Diesel Fuel is Available

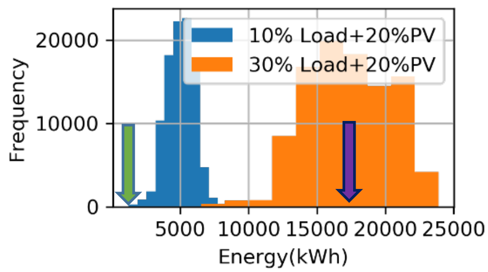
A3.9. Histogram On the Net Load (Load-PV generation) for 24 Hours



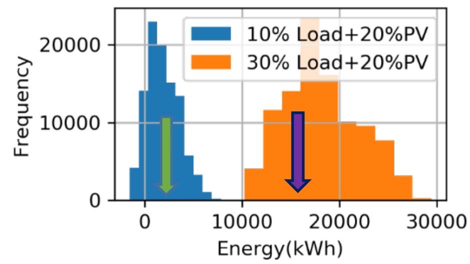
(a) Ventura



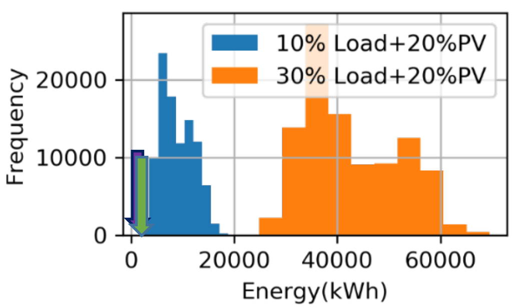
(b) March



(c) Corpus Christi



(d) Holloman



(e) Fort Bliss

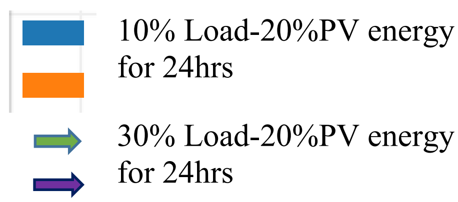


Figure 26. Histogram of 24-hour Net Energy and the Energy Rating of Li-ion and Flow Battery Technology

A4. COST APPENDIX

Table 25. NPV Improvement Due to Storage Installation for Naval Base Ventura County

Technology	Li-ion	Li-ion	Flow	Li-ion
Size	**875 kW, 1.5 h**	**875 kW, 5 h**	**975 kW, 5 h**	**4375 kW, 4 h**
Battery CapEx	($1,156,570)	($2,312,190)	$0.00	($7,787,500)
Battery Fixed O&M	($119,314)	($119,314)	$0.00	($596,569)
Avoided Energy Charge	$129,241	$1,078,159	$570,156	$4,850,519
Avoided Demand Charge	$478,319	$1,253,565	$1,268,815	$3,935,444
Avoided Cost due to Generator Reduction	$1,125,000	$1,125,000	$1,125,000	$1,125,000
Avoided Cost due to Generator O&M	$190,902	$190,902	$190,902	$190,902
Avoided Cost due to UPS Reduction	$485,250	$485,250	$485,250	$1,455,750
Avoided Cost due to UPS O&M	$139,699	$139,699	$139,699	$419,098
Demand Response	$61,539	$521,115	$320,047	$2,490,684
Battery Replacement	($356,960)	($713,625)	$0	($2,403,505)
Total NPV Improvement from baseline case	$977,106	$1,648,561	$4,099,869	$3,679,823

Table 26. NPV Improvement Due to Storage Installation for NAS Corpus Christi

Technology	Li-ion	Li-ion	Flow	Li-ion
Size	**225 kW, 0.5 h**	**225 kW, 5 h**	**225 kW, 5 h**	**4600 kW, 4 h**
Battery CapEx	($133,563)	($668,480)	$0	($8,184,320)
Battery Fixed O&M	($30,681)	($30,681)	$0	($627,249)
Wholesale Market Revenue	$705,383	$894,974	$803,413	18,175,974
Avoided Cost due to Generator Reduction	$562,500	$562,500	$562,500	$562,500
Avoided Cost due to Generator O&M	$95,451	$95,451	$95,451	$95,451
Avoided Cost due to UPS Reduction	$0	$0	$0	$1,455,750
Avoided Cost due to UPS O&M	$0	$0	$0	$419,098
Battery Replacement	($152,682)	($206,317)	$0	($2,525,976)
Total NPV Improvement from baseline case	**$1,046,408**	**$647,447**	**$1,461,364**	**$9,371,228**

Table 27. NPV Improvement Due to Storage Installation for Holloman AFB

Technology	Li-ion	Li-ion	Flow	Li-ion
Size	**450 kW, 0.5 h**	**3600 kW, 4 h**	**475 kW, 5 h**	**450 kW, 5 h**
Battery CapEx	($266,414)	($5,420,800)	$0	($1,249,030)
Battery Fixed O&M	($61,361)	($490,891)	$0	($61,361)
Avoided Energy Charge	$11,542	$1,187,483	$195,778	$219,287
Avoided Demand Charge	$267,953	$6,872,934	$1,214,027	$1,150,135
Avoided Cost due to Generator Reduction	$1,125,000	$1,125,000	$1,125,000	$1,125,000
Avoided Cost due to Generator O&M	$190,902	$190,902	$190,902	$190,902
Avoided Cost due to UPS Reduction	$161,750	$2,102,750	$161,750	$161,750
Avoided Cost due to UPS O&M	$46,566	$605,364	$46,566	$46,566
Demand Response	$12,271	$1,558,580	$0	$233,159
Battery Replacement	($82,224)	($1,673,060)	$0	($385,496)
Total NPV Improvement from baseline case	**$1,405,985**	**$6,058,262**	**$2,934,023**	**$1,430,912**

Table 28. NPV Improvement Due to Storage Installation for Fort Bliss

Technology	Li-ion	Li-ion	Flow
Size	**1255 kW, 1 h**	**1075 kW, 5 h**	**1075 kW, 5 h**
Battery CapEx	($1,189,740)	($2,828,594)	$0
Battery Fixed O&M	($171,130)	($146,585)	$0
Avoided Demand Charge	$0	$0	$0
Avoided Energy Charge	$0	$0	$0
Avoided Cost due to Generator Reduction	$2,400,000	$2,400,000	$2,400,000
Avoided Cost due to Generator O&M	$545,434	$545,434	$545,434
Avoided Cost due to UPS Reduction	$0	$0	$0
Avoided Cost due to UPS O&M	$0	$0	$0
Demand Response	$0	$0	$0
Battery Replacement	($367,197)	($873,006)	$0
Total NPV Improvement from baseline case	**$1,217,367**	**($902,751)**	**$2,945,434**

Table 29. NPV Improvement Due to Storage Installation for March ARB

Technology	Li-ion	Li-ion	Flow	Li-ion
Size	**75 kW, 0.5 h**	**75 kW, 4 h**	**75 kW, 5 h**	**75 kW, 5 h**
Battery CapEx	($38,414)	($240,750)	$0	($271,246)
Battery Fixed O&M	($10,226)	($10,226)	$0	($10,226)
Avoided Energy Charge	$2,616	$27,371	$99,650	$115,462
Avoided Demand Charge	$39,149	$107,627	$107,628	$107,627
Avoided Cost due to Generator Reduction	$275,000	$275,000	$275,000	$275,000
Avoided Cost due to Generator O&M	$88,633	$88,633	$88,633	$88,633
Avoided Cost due to UPS Reduction	$0	$0	$0	$0
Avoided Cost due to UPS O&M	$0	$0	$0	$0
Demand Response	$4,220	$43,611	$52,756	$54,866
Battery Replacement	($11,731)	($74,304)	$0	($83,716)
Total NPV Improvement from baseline case	**$349,247**	**$216,962**	**$623,667**	**$276,400**