EXECUTIVE SUMMARY

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

ESTCP Project EW19-5046

JANUARY 2020

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force base
ARB	Air Reserve base
CapEx	capital expenditures
DoD	Department of Defense
ES	energy storage
ESTCP	Environmental Security Technology Certification Program
kW	kilo-watt
Li-ion	Lithium ion
NPV	net present value
OpEx	operational expenditures
SOC	state of charge
UPS	uninterruptible power supply

ACKNOWLEDGMENTS

This material is based upon work supported by DoD ESTCP **EW19-B9-5046**.

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The authors wish to acknowledge the sponsorship and guidance provided by Timothy Tetreault, of DoD ESTCP. We would also like to extend our special appreciation to Sarah Medepalli from Noblis, Jeffrey Marqusee from NREL, and Craig Schultz from ICF for their guidance and directions throughout the methodology development and analysis.

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 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. 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.

2.0 OBJECTIVES

TextThe study focused analysis on the integration of large-scale energy storage into microgrids for military installations' energy security using two leading energy storage technologies—Lithium ion (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.

3.0 TECHNOLOGY DESCRIPTION

3.1 HEADING 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

The analysis addressed five DoD sites: **One Army Site** at Fort Bliss; **Two Navy Sites** at *Naval Air Station Corpus Christi and Naval Base Ventura County*; and **Two Air Force Sites** at *Holloman Air Force base (AFB) and March Air Reserve base (ARB).*

3.2 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

1 Based on consultation with PowerSecure in 2019
2 Based on consultation with Lockheed Martin by 2021
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 tool that is open source at no cost that informs decision-makers across the electric grid and is available at www.storagevet.com

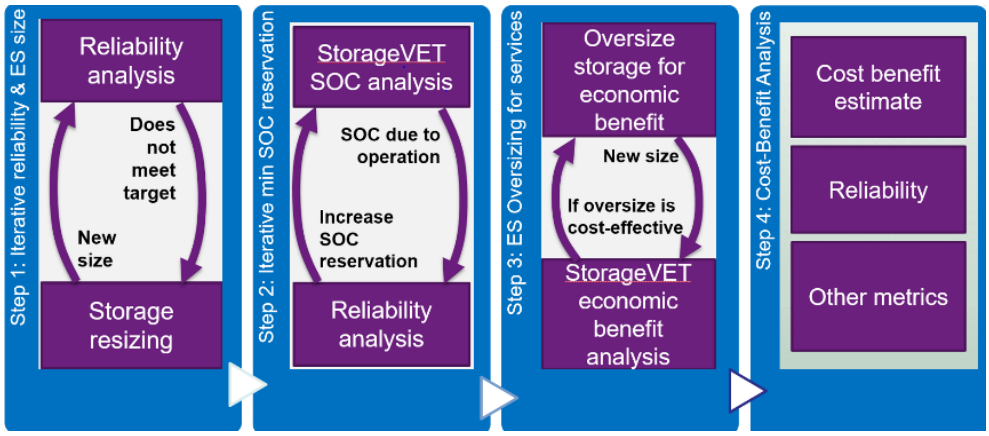

Figure ES-1. Illustration of the Technical Approach Developed for Phase 1 Analysis

3.3 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.

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= 1MW	7x750kW= 5.25MW	9x750kW= 6.75MW	8x2000kW= 16MW
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.

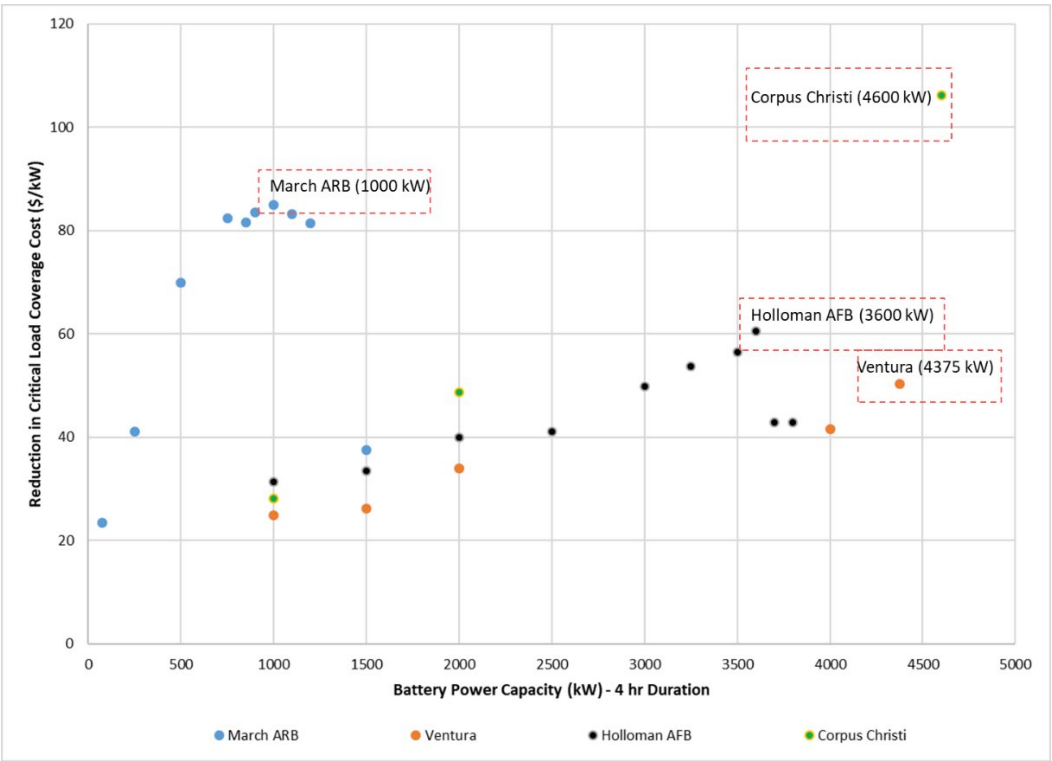

Figure ES-2. Improvement in Annual Net Cost of Serving each Kilowatt of Peak Critical Load ($/kW-yr) of the Investment Case Compared to Baseline Microgrid for All Sites

4.0 PERFORMANCE ASSESSMENT

4.1 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

(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%	99.85%	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%

(b) Flow Battery

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%

5.0 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 regard 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 three sites (Ventura, March ARB, and Holloman), the reduction in the number of generators and uninterruptible power supply (UPS) systems in the investment case significantly reduces costs. In addition, the investment case designs resulted in lowering DoD site bills through retail energy cost and demand charge reduction.

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**	**3600 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)(Millions of $)	$108.95	$62.45	$113.05	$96.14	$302.40
Investment Case NPV (20 Yr) (Cost)(Millions of $)	$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)	**$135.50**	**$416.09**	**$88.52**	**$98.35**	**$82.70**
Storage-Enabled Critical Load Coverage ($/kW-yr)	**$85.20**	**$337.42**	**-$17.30**	**$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

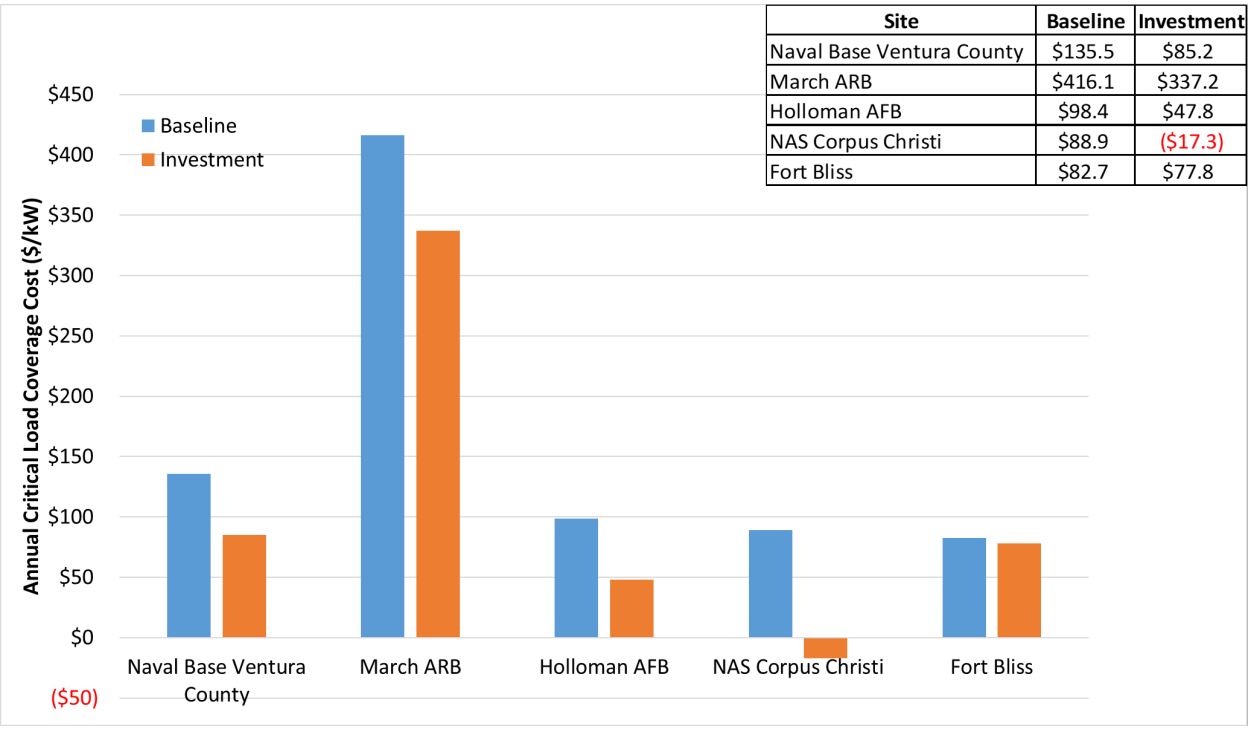

Figure ES-3. Annual $/kW Peak Critical Load Coverage Variations Across Five Installations

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 and 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

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 were 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

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.

6.0 IMPLEMENTATION ISSUES

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, by lowering cost of operations, by enabling power market participation, and therefore 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 the following:
   - 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 ($/kW-yr) is lower for the proposed storage-enabled microgrid compared to the baseline microgrid. The maximum decrease in the cost was at Corpus Christi and the minimum was at Fort Bliss. At Fort Bliss, the energy storage is not allowed to gain additional revenue from secondary services, and hence the annual cost of serving the critical load is higher.
6) The proposed microgrid design for Corpus Christi site provided negative annual cost of serving peak critical load ($/kW-yr). This implies that there is a possibility of making profit by installing storage-enabled microgrid.
7) Energy storage systems were 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 each site's minimum load. Whereas at the March and Holloman sites, increasing the energy storage system size beyond a certain value didn't necessarily result in a reduction of the annual cost of serving peak critical load ($/kW-yr).

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