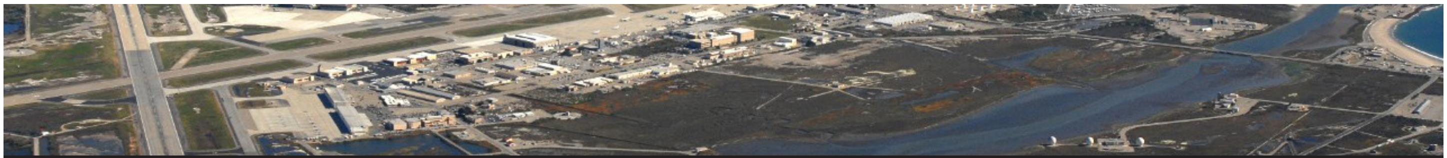
OPTIMIZED INTEGRATION OF LARGE-SCALE ENERGY STORAGE INTO MICROGRIDS

Energy Security for Military Installations

December 2021



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This white paper was prepared by EPRI.

Introduction

Microgrids generally employ diesel generators to improve the energy security of critical load facilities. This research effort is focused on showing that new microgrid design with large-scale energy storage can provide the same or better reliability than the traditional diesel generator (DG)-based microgrids. This study was supported by the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP). Microgrid design based on large energy storage integration was carried out at five military sites: Fort Bliss, Naval Air Station Corpus Christi, Naval Base Ventura County, Holloman Air Force Base, and March Air Reserve Base.

Objectives

This study focuses on integration of large-scale energy storage into microgrids for improving military installations' energy security using li-ion battery technology. The reliability performance targets and stacked grid services were investigated at five sites. The analysis constrained energy storage operations to ensure that the primary reliability service met or exceeded the baseline reliability target at each site. After meeting the reliability target, the modeling goals were set to maximize stacked benefits provided by energy storage at each site. Storage systems were re-sized to increase the cost-effectiveness of the microgrid, compared with the diesel-based microgrids.

Energy Storage Technologies and Sites Selected

The project investigated the viability of long-duration energy storage enabled microgrid in improving energy security, reliability, and providing continuity of service for critical loads during grid outages. In addition, the project evaluated opportunities to use storage simultaneously for multiple applications ("stacking benefits"). Li-ion technology characteristics considered in this study are summarized in Table 1.

Table 1. Storage Technologies and Design Variables Considered for Phase 1 Analysis

	Availability	Round-Trip Efficiency	Feasible Duration
Li-ion ES[1]	98.63%	91%	30 minutes to 4 hours

The analysis addressed five 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

Facility/Site Description

The five U.S. military bases site have seasonal load variations. The months June through September are considered summer months and October through May are considered winter for all five sites. A brief summary of the peak loads at the sites is provided in Table 2.

All sites have peak load during the summer months. Peak critical load that needs to be continuously powered is also included in Table 2. At each site, there is a designated number of diesel gensets. To account for PV variability, 20% of the PV output is considered as firm capacity that can serve the load during an outage.

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 estimation. 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 net present value (NPV) of the project, only the incremental value offered by the energy storage system (ESS) was considered because the PV was

1 Based on consultation with PowerSecure in 2019

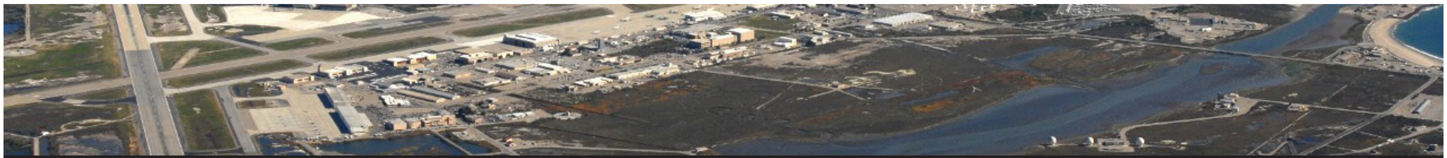


Table 2. Site Characteristics

Analysis Metrics		Naval Base Ventura County	March Air Reserve Base	Naval Air Station (NAS) Corpus Christi	Holloman Air Force Base	Fort Bliss
Peak load (MW)	Annual	14.9	7.9	23.9	15.9	67605
	Summer	14.9	7.9	23.9	15.9	67605
	Winter	14.7	7.9	23.7	13.8	57399
Critical Load (MW)		4	0.6	4.4	5.9	12.5
Max PV gen. (MW)		0.8	0.38	1.15	4.8	5.9
# 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

already a part of the baseline microgrid. For the California sites, no demand response was modeled for the baseline microgrid case.

Facility/Site Assumptions and Initial Conditions

For each site, storage was modeled based on critical load,[2] and available generation using the li-ion storage sizes varied between 0.5 hours and 4 hours in steps of 0.5 hours.

Performance Objectives and Metrics

The performance objectives for the analysis are shown in Table 3. These performance objectives were used as the primary criteria to evaluate the modeling of the li-ion battery-based microgrid. These objectives provided the basis for evaluating the energy security performance and the net costs of the technologies.

Reliability Curve Calculation

To calculate the probability of supplying the critical load during an outage of duration T, Monte Carlo-based simulation method is used. A total of 10,000 random scenarios of outage is modeled as part of this analysis. Every outage scenario is created considering variables such as the start time, load and PV profiles, failure models of the assets, and battery state of charge (SOC) at the start of an outage.

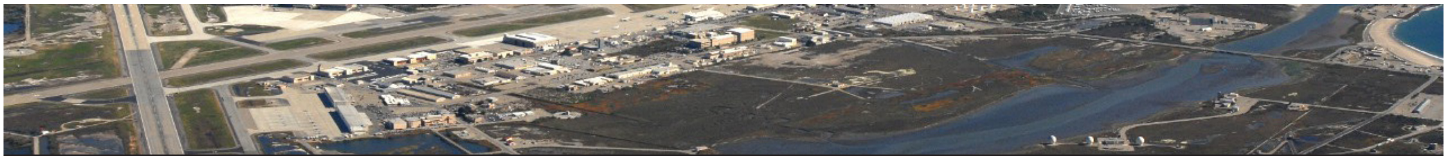
With the generated data for each scenario, the microgrid dispatch is calculated according to typical battery control strategy. At every time $t \in \{1, \ldots, T\}$, diesel generators are dispatched first to meet the net load. If there are not enough functional diesel gensets to meet the load, the storage system is then discharged to meet the fraction of the load that cannot be met by diesel generators. The storage system must have enough SOC to maintain the required power during the time interval t, which is 1 hour in this study. 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, the scenario is considered a failure. If the diesel gensets operational at time t have excess energy compared to the critical load, the battery system charges. If at all time t there is enough power to serve the critical load, the scenario is considered successful.

In this study, because 10,000 outage scenarios are created, a binary matrix of size 10,000 x 168 total outage scenarios is created. A value

Table 3. Performance Objectives Considered

Performance Objective	Metric	Requirements	Success Criteria
1. Reliability to Meet 100% of Installation Critical Load	Critical and ride-through load served during outage (that can begin at any time)	Performance measured for outages of any duration between 1 hour and 168 hours	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.
2. Net Life-Cycle Costs of Deployment and Operation (corresponding to Technical Objective 1 above)		Calculate per methodology distributed with baseline microgrid data and results	Net cost (per kW of critical load) is at or below level of baseline microgrid in current and future volatile scenarios

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



of 1 means success and 0 means 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, as illustrated in Figure 1. Therefore, 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 was 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 to or greater than the baseline performance curve.

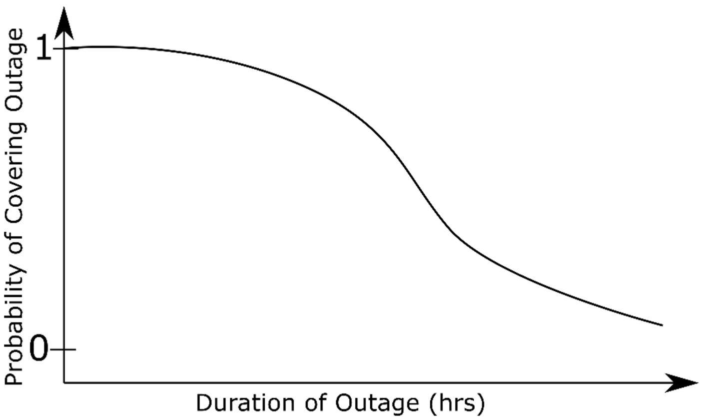


Figure 1. Example Critical Load Coverage Probability Curve

Critical Load Coverage Cost

The calculation of the critical load coverage cost provides an estimate of how expensive it is to serve the critical load. The cost for the DG-based microgrid is calculated and shown in Figure 2. The annual net cost of serving each kilowatt of peak critical load 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. March ARB has the highest critical

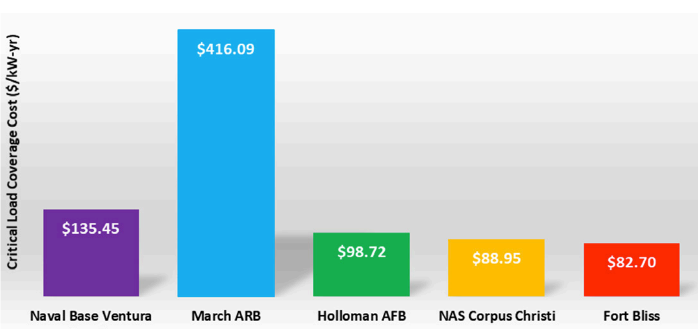


Figure 2. Baseline Microgrid Critical Load Coverage Cost

load coverage among all the sites due to the large upfront capital cost and small critical load it serves.

The major cost of the baseline microgrid includes the cost of owning and operating the microgrid, the diesel generators, and the UPS. The overall NPV (all costs) for the entire site ranges from $62M to $110M. The cost of covering the critical load for most of the sites is between $80/kW-year to $140/kW-year. The only exception to this is March ARB ($416/kW-year) due to extremely small critical load of 600 kW. For the two California sites and Fort Bliss, there is no possibility of providing demand response (DR) using diesel genset due to the nature of utility tariff and market rules. For the Corpus Christi and Holloman sites, some amount of DR value can be captured in the baseline case due to DG's participation in secondary services.

Methodology

Initially, a baseline analysis with a DG-based microgrid was performed for each site. After the baseline case was established, the storage-based microgrid investment case was designed for each site. The specific characteristics of the li-ion technology such as round-trip efficiency and probabilistic availability are considered for the analysis. Figure 3 illustrates this storage-enabled microgrid analysis work plan:

- **Step 1: Sizing and Reliability Analysis**. Monte Carlo[3] reliability analysis and storage sizing for a storage-enabled microgrid
- **Step 2: Iterative SOC Reservation Design**. StorageVET®[4] SOC analysis to assess secondary services while satisfying primary reliability targets
- **Step 3: Oversizing Sensitivity Analysis**. Increase power and energy capacity of storage and study the corresponding NPV
- **Step 4: Cost-Benefit Assessment**. Compare baseline microgrid with investment cases

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, informs decision makers across the electric grid, and is available at www.storagevet.com

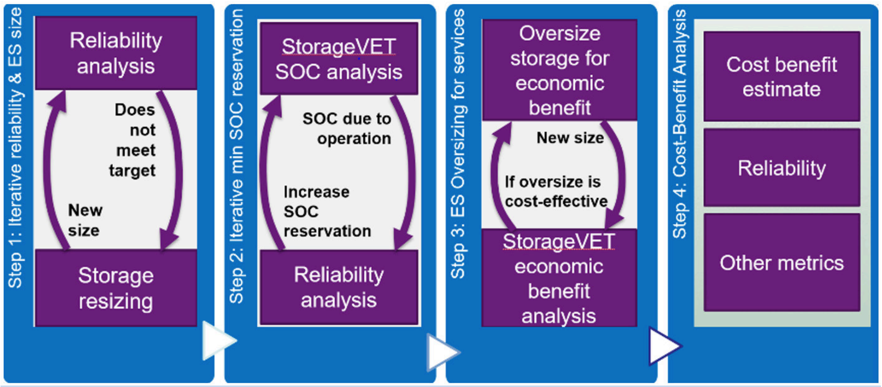


Figure 3. Illustration of the Technical Approach Developed for Phase 1 Analysis

Designed Microgrid Configuration

Energy storage–enabled microgrid configurations with the most feasible design and best financial performance for the five sites were determined using the four-step design methodology. The design configurations are listed in Table 4. 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 4. 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		7x750 kW = 5.25 MW	4x250 kW = 1 MW	7x750 kW = 5.25 MW	9x750 kW = 6.75 MW	8x2000 kW = 16 MW
Peak Critical Load		4 MW	0.6 MW	4.4 MW	6 MW	12.5 MW
ES Microgrid Configuration	Power and Duration	4375 kW 4 hr	1000 kW 4 hr	4600 kW 4 hr	3800 kW 4 hr	1255 kW 1 hr
	SOC Reservation	5.16%	0.23%	0.00%	0.78%	100%
	Number of Gensets	5	3	6	7	6
	Secondary Services	Bill reduction	Bill reduction	Wholesale market	Bill reduction	None

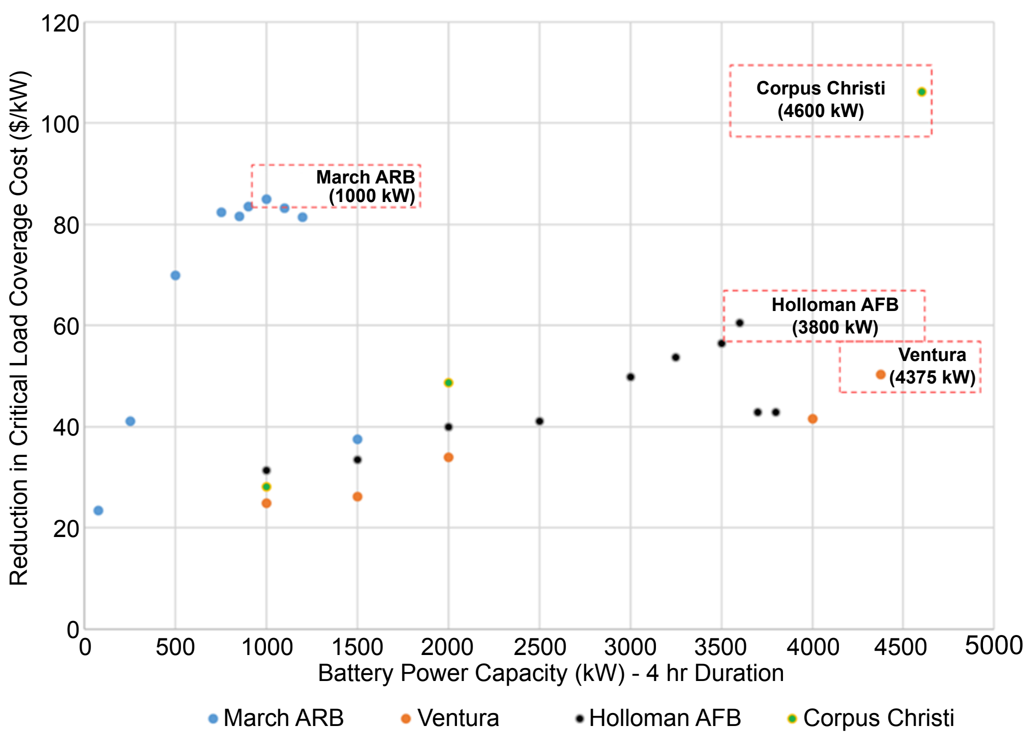
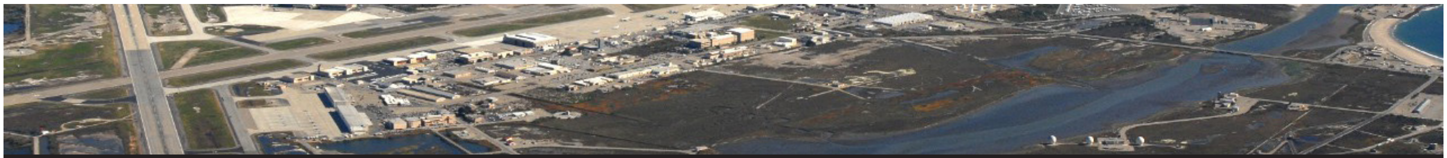


Figure 4. Improvement in Annual Net Cost of Serving each Kilowatt of Peak Critical Load ($/kW-yr) of the Investment case Compared to Baseline Microgrid for All Sites



Oversizing for maximizing value was carried out for all 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 (ES) was assumed to be 4 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 4.

For the sites at Ventura County and Corpus Christi, the critical load coverage cost reduced monotonically with an increase in energy storage size. Therefore, larger sized energy storage resulted in greater 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. Therefore, after a few iterative steps, the optimal energy storage size was determined to be 1000 kW, 4 hr and 3800 kW, 4 hr for March ARB and Holloman AFB, respectively.

Reliability Performance Assessment

The technical reliability targets and performance objectives for the li-ion based microgrid under different outage conditions are summarized in Table 5. The reliability metric is the probability of the microgrid serving 100% of the critical load at each site. The probability numbers are recorded for 24- and 168-hour outages as percentage numbers. It can be observed that the reliability performance is higher than the baseline at all sites.

Cost Assessment

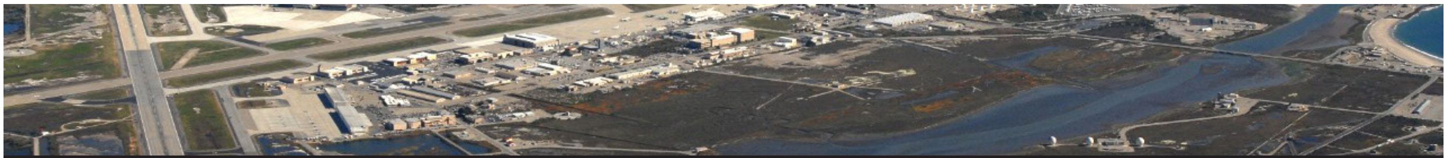
A baseline economic analysis of operating a diesel genset–based microgrid for each site was established. Inputs included capital expenditures (Capex) and operational expenditures (OpEx).

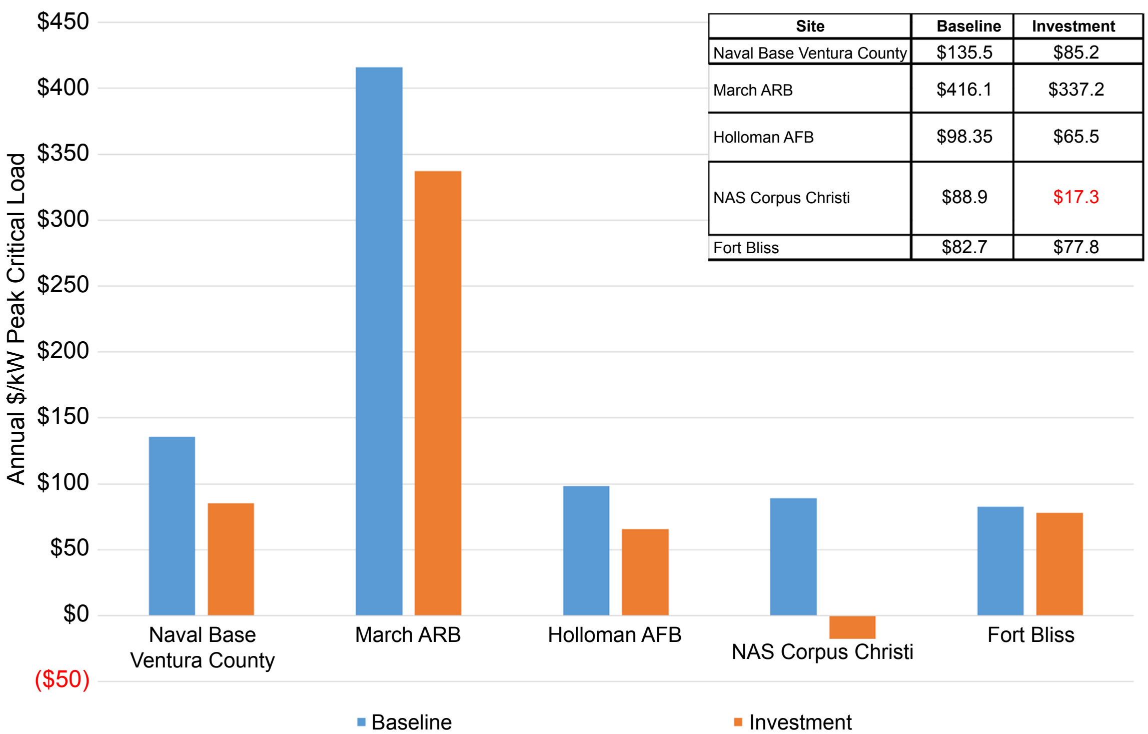
Table 5. Probability of Serving Critical Load Under Baseline and Investment Case

Performance Objective		Ventura		March		Corpus Christi		Holloman		Fort Bliss	
		Baseline	Investment	Baseline	Investment	Baseline	Investment	Baseline	Investment	Baseline	Investment
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%

Table 6. 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	$1084/kWh
Li-ion Cost (OPEX) ($/kWh)	$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**	**-$17.30**	**$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





Site	Baseline	Investment
Naval Base Ventura County	$135.5	$85.2
March ARB	$416.1	$337.2
Holloman AFB	$98.35	$65.5
NAS Corpus Christi	$88.9	$17.3
Fort Bliss	$82.7	$77.8

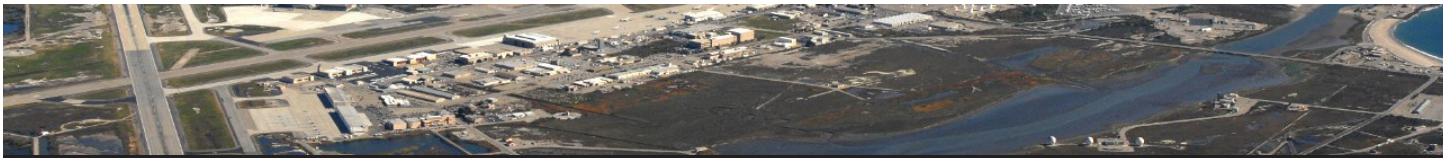
Figure 5. Annual $/kW Peak Critical Load Coverage Variations Across Five Sites

Then, the economics of operating a li-ion storage-enabled microgrid investment case were analyzed for each site. Table 6 includes 20-year NPV cost of the microgrid for both the base case and the investment case. Table 6 also includes improvement in NPV value for both cases. It can be observed that there is positive improvement at all sites; the maximum NPV improvement is 13.57% at Holloman AFB.

The annual net cost of critical load coverage ($/kW-yr) 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 5. For the sites Ventura, March ARB, and Holloman, the reduction in the number of generators and UPS systems in the investment case significantly reduced costs. In addition, the investment case designs resulted in lowering site utility bills through lowering energy demand.

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). Therefore, the battery was sized primarily for reliability alone, and this yielded a 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 6. The revenue was calculated using EPRI's optimization tool StorageVET®.



Study Conclusions and Outcomes

The microgrid analysis methodology using storage-enabled microgrids, as illustrated in the results shown in Table 5 and Table 6, indicated the following overall benefits:

- Optimized microgrid designs at five sites—consisting of diesel generators, UPS, storage, and solar PV—are capable of meeting baseline performance objectives and reliability targets as a function of outage durations between 1 hour and 168 hours. Reliability performance of the storage-enabled microgrid is equal to or greater than the reliability targets specified for each site for all outage durations ranging up to 168 hours.
- Storage-enabled microgrids enhance reliability and energy security by avoiding the cost of lost loads during outages, lower the cost of operations, enable power market participation, and result in a positive NPV compared to diesel-based microgrids.
- Storage-enabled microgrids reduce the "loss of critical load" risk during grid outages as well as the cost of serving critical load.
- Incremental values of using storage-enabled microgrids were found to include the following:
  - Avoided energy costs through self-generation and energy 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
- The annual cost of serving peak critical load ($/kW-yr) is lower for the proposed storage-enabled microgrid compared to the baseline microgrid. The maximum decrease in the cost is at Corpus Christi, and the minimum is at Fort Bliss. At Fort Bliss, the energy storage is not allowed to gain additional revenue from secondary services, and therefore the annual cost of serving the critical load is higher.
- The proposed microgrid design for the Corpus Christi site provided negative annual cost of serving peak critical load ($/kW-yr). It implies that there is a possibility of making profit by installing a storage-enabled microgrid.
- 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 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 5. At Corpus Christi and Ventura, large energy storage size meant more benefits—although the oversizing had to be capped to the site's minimum load. However, at the March and Holloman sites, the annual cost of serving peak critical load saturated and increasing the power capacity did not lower the cost.
- The SOC reservation for the final microgrid design was less than 5% for all sites and at Corpus Christi is 0%. A minimal energy storage reservation is sufficient for realizing the primary objective of meeting the reliability target. Excess energy from diesel generators is sufficient to charge the energy storage during an outage.
- Full report to this study is available here: https://www.serdp-estcp.org/content/download/51959/511266/file/EW19-5046%20Final%20Report.pdf

Cover photo: Naval Base Ventura County. https://www.cnic.navy.mil/regions/cnrsw/installations/navbase_ventura_county.html

Note

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EPRI RESOURCES

Suma Jothibasu, *Engineer/Scientist III*
650.855.7933, sjothibasu@epri.com

Arindam Maitra, *Senior Technical Executive*
704.595.2646, amaitra@epri.com

Ram Ravikumar, *Engineer/Scientist III*
650.855.8771, rravikumar@epri.com

Energy Storage and Distributed Generation (P94)

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com