# The Value of Battery Storage in Military Microgrids:

## An Assessment for ESTCP

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# List of Acronyms

| | |
|---|---|
| AC | Alternating Current |
| AFB | Air Force Base |
| ASU | Arizona State University |
| BESS | Battery Energy Storage System |
| CAISO | California ISO |
| CHIL | Controller Hardware-in-the-Loop |
| DC | Direct Current |
| DER | Distributed Energy Resources |
| DoD | U.S. Department of Defense |
| DR | Demand Response |
| EDG | Emergency Diesel Generator |
| EPRI | Electric Power Research Institute |
| ERCOT | Electric Reliability Council of Texas |
| ESIF | Energy Systems Integration Facility |
| ESTCP | Environmental Security Technology Certification Program |
| FTS | Failure to Start |
| FY | Fiscal Year |
| Holloman AFB | Holloman Air Force Base |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISO | Independent System Operator |
| ISO-NE | ISO New England |
| IT | Information Technology |
| kVA | Kilovolt-ampere |
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| Li-ion | Lithium Ion |
| March ARB | March Air Reserve Base |
| MTTF | Mean Time to Fail |
| MW | Megawatt |
| MWh | Megawatt-hour |
| NAS Corpus Christi | Naval Air Station Corpus Christi |
| NAS Patuxent River | Naval Air Station Patuxent River |
| NDAA | National Defense Authorization Act |
| NPV | Net Present Value |
| NREL | National Renewable Energy Laboratory |
| O&M | Operations and Maintenance |
| OEA | Office of Energy Assurance |
| OEI | Office of Energy Initiatives |
| PHIL | Power Hardware-in-the-Loop |
| PI | Principal Investigator |
| PJM | Pennsylvania, Jersey, Maryland Power Pool |
| PNNL | Pacific Northwest National Laboratory |
| PREP | Power Reliability Enhancement Program |
| PV | Photovoltaic |
| R&D | Research and Development |
| Raytheon | Raytheon Integrated Defense Systems |
| REPO | Resilient Energy Program Office |
| RTE | Roundtrip Efficiency |
| RTO | Regional Transmission Organization |
| SRI | Southern Research Institute |
| TOU | Time-of-Use |
| UPS | Uninterruptible Power Supply |
| USACE | U.S. Army Corps of Engineers |
| USAF | U.S. Air Force |
| Westover ARB | Westover Air Reserve Base |

# Executive Summary

Fixed military installations cannot function without a reliable supply of electricity. The U.S. Department of Defense's (DoD's) mission is under increasing threat as the power backbone of installations faces growing risk from grid power outages, especially as long-duration outages become more frequent.[1]

To address this increasing risk, DoD is pursuing the deployment of microgrid technologies. Microgrids are an alternative to the longstanding energy security paradigm of simply attaching a back-up generator to each building with a critical function. In parallel to its pursuit of microgrids, DoD also has been successfully working with the private sector to develop solar photovoltaic (PV) energy assets on installations. Although bringing economic value, PV assets are not a back-up power solution in the absence of energy storage or dispatchable power generation.

This report summarizes the results of recent Environmental Security Technology Certification Program (ESTCP) studies to isolate under what conditions battery energy storage systems (BESSs) can cost-effectively and materially enhance energy security within a military microgrid. ***Integrated into a microgrid, battery energy storage can play a key role in DoD energy assurance by providing increased energy reliability at lower lifecycle costs than a microgrid without battery storage.***

### ESTCP conducted assessments at seven installations:

- Fort Bliss;
- Naval Air Station Corpus Christi (NAS Corpus Christi);
- Naval Air Station Patuxent River (NAS Patuxent River);
- Naval Base Ventura County;
- Holloman Air Force Base (Holloman AFB);
- March Air Reserve Base (March ARB); and
- Westover Air Reserve Base (Westover ARB).

These installations cover the variability of critical power requirements, electricity rate structures, solar resources, PV assets, and local energy market conditions seen on military bases across the continental United States. They range from two air reserve bases (March and Westover) that are the smallest installations studied to three mid-sized installations (NAS Corpus Christi, Naval Base Ventura County, and Holloman AFB) and two large installations (Fort Bliss and NAS Patuxent River). The modeled performance at these seven installations provides DoD with an understanding of where and why battery storage can contribute effectively to an energy security solution. The body of the report focuses on the results for Fort Bliss, NAS Patuxent River, and Holloman AFB. These three installations represent mid-sized to large active military installations and illustrate the key conclusions of the ESTCP assessments. Full results for all seven installations are summarized in Appendices to this report.

Four teams competitively selected by ESTCP and led by Principal Investigators (PIs) from Ameresco, Electric Power Research Institute (EPRI), Raytheon Integrated Defense Systems (Raytheon), and Southern Research Institute/ Arizona State University (SRI/ASU) as well as the National Renewable Energy Laboratory (NREL) completed modeling assessments of simulated microgrids for these military installations.[2] The task for each team was to identify and quantify economic and reliability impacts of integrating battery energy storage at five of the seven installations of their choosing.[3,4]

1 See, for example, Larsen, Peter, et al. *Assessing Changes in the Reliability of the U.S. Electric Power System,* LBNL - 188741: Lawrence Berkeley National Laboratory, 2015.

2 The PI teams had the following members that are listed in parentheses, in addition to their lead organizations: Ameresco (2ndPath Energy); EPRI (Lockheed Martin, PowerSecure, and Southern Company); Raytheon (Customized Energy Solutions and PXiSE Energy Solutions); and SRI/ASU (350Solutions and XENDEE Corporation).

3 In instances where a team did not model a given military installation, no results from the team corresponding to that installation are shown on charts in this report. Similarly, data tables show "N/A" for instances where a team did not model an installation.

4 For more information on the distinct role of NREL's modeling in this study, see **Appendix G.**

The PI and NREL teams modeled and assessed microgrids without battery storage ("baseline microgrids") and microgrids with battery storage ("storage-enabled microgrids") to isolate the cost and performance impacts of storage. The teams were required to maintain, at a minimum, the reliability of the baseline microgrid with their proposed storage-enabled microgrid designs. This report summarizes the ESTCP "Phase I" techno-economic modeling of storage in microgrids that was completed in Q1 2020. ESTCP is investing in "Phase II" hardware-in-the-loop evaluations (described in **Appendix A**) beginning in Q2 2020 to build on the most promising Phase I results and intends to pursue "Phase III" field demonstrations beginning in fiscal years (FYs) 2021-2022.

To create a consistent and realistic foundation for analysis, ESTCP provided installation-specific data such as critical and non-critical power loads, PV energy production, utility rates, electricity market prices, and the number and size of the emergency diesel generators (EDGs) and uninterruptible power supply (UPS) units. The overall cost and system-level reliability for the baseline microgrid (containing EDGs, UPSs, and PV) was calculated for each installation.

System-level reliability depends on the quality of EDG maintenance as well as the number and connectivity of EDGs, and it varies dramatically between DoD's existing standalone, building-tied EDG paradigm and a microgrid with networked EDGs.

A single, well-maintained EDG has only a 90% probability of being up and running after a week-long power outage (it drops to 80% by two weeks), while a poorly-maintained EDG has less than a 10% probability of functioning after a week-long outage and is likely to fail within a few days of the start of the outage. So, it is essential for military installations to follow current maintenance guidance. It also means that the existing energy security paradigm of having a single, building-tied EDG per critical building will fail within a week – even with well-maintained EDGs – i.e., a 10% chance of losing a critical mission at every installation facility to the known risk of multi-day power outages should not be acceptable.

For the ESTCP assessments of microgrid alternatives to building-tied EDGs, only well-maintained EDGs were considered. The ESTCP baseline microgrids have networked EDGs in an N+1 configuration (referred to as an N+1 microgrid), where N generators would just satisfy each installation's annual peak critical load, and the "+1" provides a back-up EDG for redundancy. The baseline microgrids are not systems as currently-deployed at the installations, but are simulated systems.

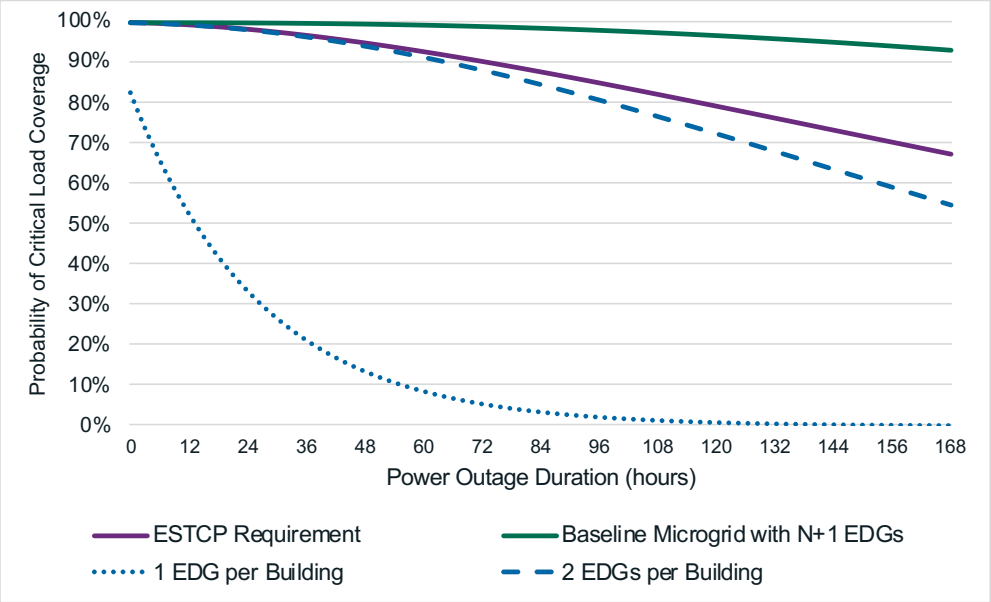


**Figure ES-1. Probability of Fully Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River: Systems without Battery Storage [5]**

5 The "1 EDG per Building" dotted line begins at 82.5% in this chart at hour 0 because there is a 17.5% chance that at least one EDG across NAS Patuxent River (in a standalone, building-tied configuration) will not start or be available at the beginning of the outage.

**Figure ES-1** shows the probabilities of building-tied EDG solutions (one EDG per building or two EDGs per building) and the N+1 microgrid without battery storage being able to support 100% of the critical loads at NAS Patuxent River over the course of a week-long outage.

The reliability "requirement" set by ESTCP at each installation was calculated by determining the performance of an N+1 microgrid for a fixed load equal to the annual peak load (occurring at the one hour annually with the highest load). "Baseline microgrid with N+1 EDGs" performance accounts for the effects of the variable load at each installation; i.e., the baseline microgrid must only serve the actual peak critical load occurring each hour.

As can be seen in **Figure ES-1**, the performance of a single EDG tied to each building with a critical load is poor – there is only a 10% chance that critical missions will be fully-served within two days of an outage beginning. This is not due to exhaustion of on-installation fuel supplies, which was not a constraint in the ESTCP analysis, but due to EDG performance.

The minimum ESTCP energy security requirement is higher than even a system placing two EDGs at every building with critical loads can attain. In contrast, a baseline N+1 microgrid exceeds the requirement. Ultimately, the choice on what level of reliability an installation requires is a function of the missions supported and its risk tolerance.

All ESTCP teams (four PIs and NREL) developed a conceptual design for a storage-enabled microgrid to exceed the minimum reliability performance metric (the "requirement" noted above) and to minimize microgrid lifecycle costs at each installation they analyzed. In determining how best to meet or exceed the minimum criteria, each team was free to make tradeoffs between costs and reliability in storage-enabled microgrids. These choices included selecting the BESS size, duration, and type; how many EDGs and UPSs could be eliminated when BESS was added to a microgrid; and how to use energy assets within the microgrid each hour of the year. Most teams focused on commercially available Lithium ion (Li-ion) BESS. Ameresco focused on the less mature and currently more expensive flow BESS[6] technology.

**Table ES-1** shows the variety of BESS sizes selected by the teams for three installations after they optimized the storage-enabled microgrids. In addition, the number of EDGs and UPSs eliminated varied between the teams.

**Table ES-1. BESS Power in Optimized Storage-Enabled Microgrids (all data in kW)**

| Assessment Team | Fort Bliss | NAS Patuxent River | Holloman AFB |
|---|---|---|---|
| **Ameresco** | 2,000 | 1,167 | N/A |
| **EPRI** | 1,225 to 1,255 | N/A | 3,600 to 3,800 |
| **Raytheon** | 1,700 | 3,000[7] | 2,400 |
| **SRI/ASU** | 2,700 | 900 | 1,800 |
| **NREL** | 600 | 800 | 800 |

To complement its reliability metric, ESTCP focused on a single cost metric that incorporates and nets all lifecycle cost and revenue impacts of microgrid investments and standardizes those impacts by what they are protecting – mission critical electricity loads at installations. The metric is the net annual cost of protecting each kilowatt (kW) of peak critical load. It represents energy security costs compared to having no protection whatsoever for critical loads and allows comparisons between energy security solutions. **Figure ES-2** shows the percent difference between the storage-enabled microgrid and the baseline (without storage) microgrid cost metric for three installations.[8] The NREL results labeled 1, 2, and 3 indicate the number of EDGs that NREL eliminated from the baseline microgrid in

6 The SRI/ASU team compared several BESS technologies, including pairings of BESS with ultra-capacitors, side-by-side. That team's primary results for a Li-ion solution are summarized in this report.

7 Raytheon also modeled a BESS with 29,400 kW of power at NAS Patuxent River to optimize ancillary service market revenues. To increase the comparability of results across PI and NREL teams, Raytheon's results for the 3,000 kW BESS are referenced throughout this report, unless otherwise noted.

8 EPRI did not model NAS Patuxent River, and Ameresco did not model Holloman AFB.

different scenarios. **Figure ES-2** only reflects cases where the elimination of EDGs met the minimum performance requirements.

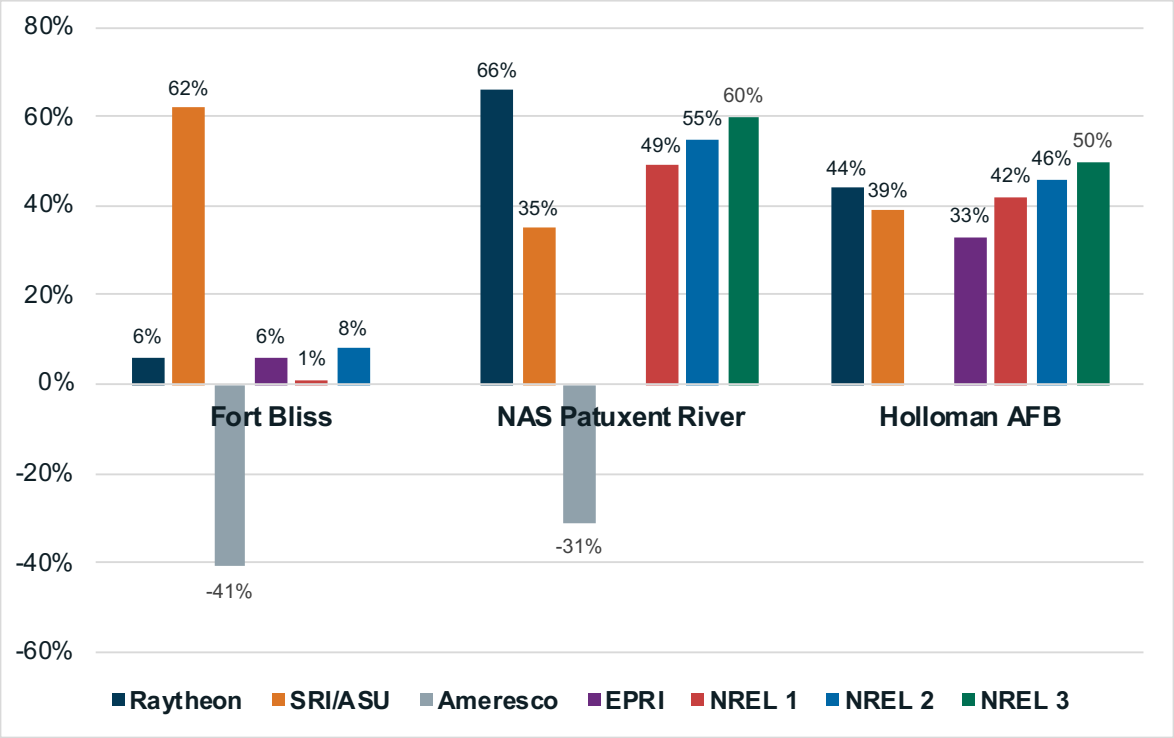


**Figure ES-2. Battery Storage-Enabled Microgrid Savings at Three Installations: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

Positive percentages in the figure above indicate lifecycle cost savings. These results show that Li-ion BESS consistently reduces the net costs of microgrids. For example, at Holloman AFB, adding battery storage improved the net cost of the microgrid by 33% to 50%, depending on the modeling team. Those savings are after paying the lifecycle costs for the battery system itself. Ameresco's reliance on the emerging flow battery technology led to a higher net cost relative to the baseline microgrid without BESS.

The net cost impacts of adding BESS to a microgrid can be broken down into three main categories: 1) retail and wholesale electricity market savings or revenues; 2) reductions in the number of EDG and UPS assets needed to deliver reliable power during grid outages; and 3) investment costs for the BESS itself. The contributions to microgrid economics calculated by the Raytheon, SRI/ASU, and NREL teams for these three categories at one example installation are shown in **Figure ES-3**. Negative numbers in the chart represent savings and positive numbers are added costs.

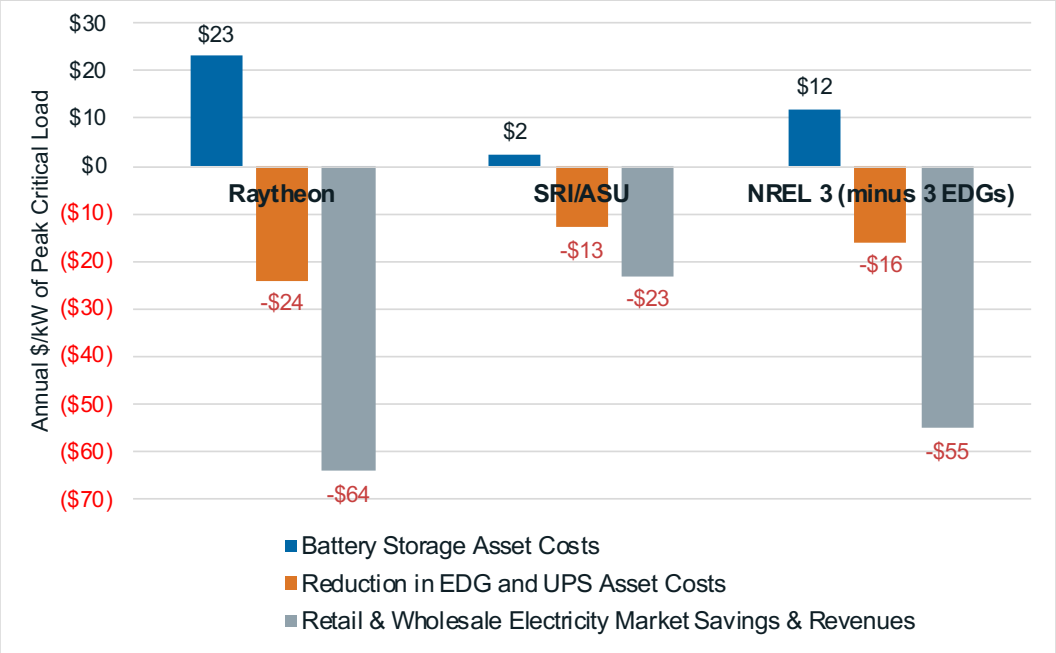


**Figure ES-3. Breakdown of Cost Additions and Savings in Lithium-ion Battery Storage-Enabled Microgrids at NAS Patuxent River**

At this example installation (NAS Patuxent River) as well as at the other six installations, the ESTCP assessments found that Li-ion BESS coupled to on-base PV and a microgrid can significantly lower energy security lifecycle costs compared to a microgrid without battery storage even accounting for the cost of the BESS.[9] Emerging battery technologies, such as flow BESS, are too expensive to justify their use today. The optimal BESS size and duration and the resulting cost savings depend on installation power reliability needs, local electricity market opportunities and utility rate structures, and solar resources, as well as the assumed BESS costs. ***A site-specific assessment should be undertaken that considers all of these factors in detail before deciding on what battery system size should be selected.***

While evaluating the cost-effectiveness of a storage-enabled microgrid is necessary, the most important characteristic of a microgrid or any other back-up power system is its ability to reliably provide power to critical loads. **Figure ES-4** illustrates the expected reliability performance that all five ESTCP assessment teams calculated at the end of a one-week outage for three installations.[10]

9 The greatest areas of savings were from operating the BESS to reduce retail (utility) electric bills and gain revenues from wholesale electricity market participation.

10 Where results are not shown for an assessment team (EPRI at NAS Patuxent River and Ameresco at Holloman AFB), that is because the team did not review the installation. Each team reviewed five of the seven installations, including at least one of each Service. NREL 3 results are not displayed for Fort Bliss because eliminating three EDGs at that installation causes reliability performance to be below the ESTCP requirement.

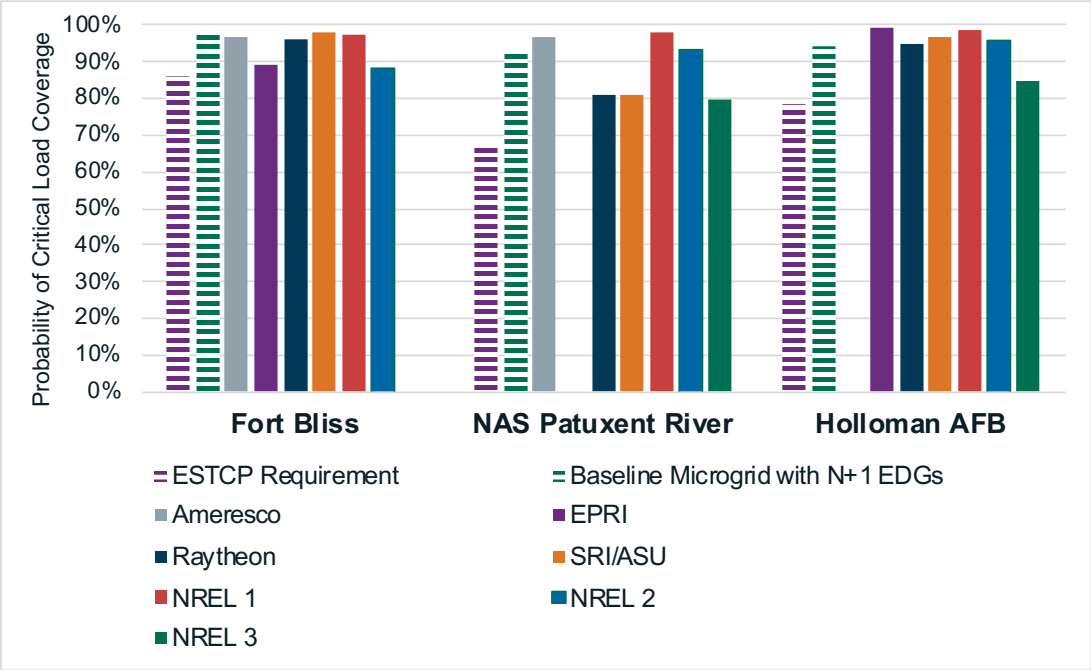


**Figure ES-4. Probability of Microgrids Fully Meeting Critical Loads by the end of One-Week (168-hour) Power Outages at Three Installations**

Depending on how many EDGs are eliminated (1, 2, or 3), the size and duration of the BESS, and critical load characteristics, the reliability performance of a storage-enabled microgrid may be higher or lower than a baseline microgrid (without storage), but storage-enabled microgrids outperformed the ESTCP requirement at each installation.[11] The strong performance occurs because ***integrating battery storage into a microgrid allows installations to introduce a very flexible asset type and increase exploitation of inside-the-fence, intermittent solar power for energy security purposes.***

In addition to reviewing reliability outcomes at the end of week-long outages as **Figure ES-4** does, it is important to review the full reliability performance curve over the duration of a power outage. **Figure ES-5** shows hourly microgrid reliability performance for one installation and includes the performance of building-tied systems (with one and two EDGs per building) for comparison.

11 The ESTCP requirement differs from installation to installation because it is calculated from the highest, single-hour peak critical load and the performance of the baseline microgrid with N+1 fossil fuel EDGs at each installation.

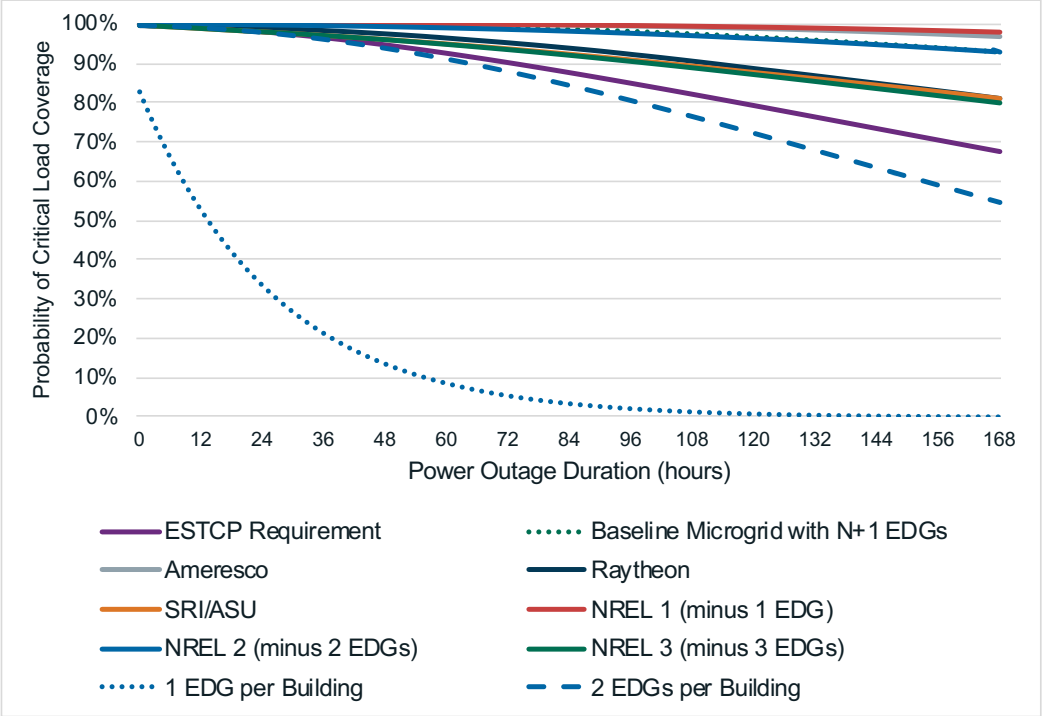


**Figure ES-5. Probability of Building-Tied EDG Systems, ESTCP Baseline Microgrid and Requirement, and Storage-Enabled Microgrids Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River**

All microgrid configurations outperformed a building-tied system, for outages of any duration. This is so even if one were to deploy two EDGs at each building with a critical load, which would be an expensive doubling of DoD's historical back-up power paradigm.

Battery storage provides flexibility in designing a microgrid, allows granular calibration of energy security performance and cost, and enhances the reliability advantages of microgrids compared to building-tied EDGs. The use of storage integrated into a microgrid also provides limited power in the absence of diesel fuel and can extend supplies of on-base diesel fuel. ***Ultimately, to design and procure an optimal storage-enabled microgrid requires comparing performance and cost trade-offs in the context of mission needs. It also requires a focus on buying performance and investing in sustainment, rather than simply buying equipment.***

# 1. Introduction

The U.S. Department of Defense (DoD's) fixed installations – or military bases – are a critical element of national security. Military bases have long supported the maintenance and deployment of weapons systems and the training and mobilization of combat forces. Increasingly, installations perform direct support to combat operations. Today, they cannot be assumed to be free from threats; as the recent *Summary of the 2018 National Defense Strategy* (1) noted, "the homeland is no longer a sanctuary."

Fixed installations rely on electricity to support critical missions and functions (2). The military's use of facility energy carries a hefty price tag, but more important for the military's mission is the operational risk that its reliance on energy entails. Installations depend on a commercial power grid that is vulnerable to disruption due to severe weather, physical attacks, cyberattacks, and aging infrastructure. Power outages are a fact of life. Outages can range in duration from minutes to weeks, and their impact can be geographically limited (a failure in a single utility circuit) or widespread (a failure in the bulk transmission system that affects hundreds of thousands of people in multiple states). The risks of blackouts and loss of electric power are not new. Outages of just a few hours are commonplace, but longer duration outages are becoming more frequent (3).

## 1.1. Rationale for Study: Military Installation Interest in Battery Storage

DoD is actively pursuing the deployment of microgrid technologies to provide improved energy security. DoD also has been working with the private sector to develop renewable generation assets on military installations. The primary source of renewable energy at installations, solar photovoltaic (PV), provides power intermittently based on available sunlight. Although of economic value, solar projects cannot be relied on as a backbone of an energy security solution in the absence of energy storage or dispatchable power generation. Given DoD's energy security requirements, its plans to deploy microgrids, and its existing and planned deployment of renewables, the potential to use battery storage to provide a better and more cost-effective energy security solution is significant. Although battery storage for military installations has been studied in connection to microgrids,[12] no systematic evaluation exists that looks at both the cost and performance advantages of battery storage in microgrids as a function of installation load profiles, size of renewable energy assets, the utility rate structure, and local electricity markets.

To inform DoD's cost-effective implementation of battery storage in microgrids, the Environmental Security Technology Certification Program (ESTCP) supported the work summarized in this report and the report itself. ESTCP is DoD's environmental technology demonstration and validation program, which promotes the transfer of innovative technologies that have successfully established proof of concept to field or production use.

## 1.2. Brief History of Installation Energy Security

The current default solution for energy assurance and resiliency at military installations relies on emergency diesel generators (EDGs). This is most often accomplished by either a single stand-alone EDG or, less frequently, two EDGs tied to an individual building containing critical missions. Also, less common, but with increasing frequency, installations are deploying microgrids with networked EDGs serving as the primary distributed energy resources (DER) within the microgrid.

### 1.2.1. Single Building-Tied Fossil Fuel Generators

At every building housing a critical load, a single (standalone) back-up EDG is hardwired directly to the building. For the highest priority critical loads, two standalone EDGs can be deployed to provide a back-up to the back-up and a higher degree of reliability. Back-up generators found on fixed installations are typically powered by diesel fuel.[13] A base typically has a centrally managed diesel fuel stockpile that contains enough fuel to allow the generators to run for two to fourteen days. **Figure 1** provides a simplified graphical representation of such a system.

12 For example, see ESTCP projects: EW-201242, EW-201246, EW-201350, and EW-201606, available at: https://www.serdp-estcp.org/.

13 Installations' back-up generators are sometimes powered by other fossil fuels, such as natural gas or propane. For simplicity and because diesel is the primary fuel for back-up generators, the label "EDGs" refers to all fossil-fuel back-up generators in this report.

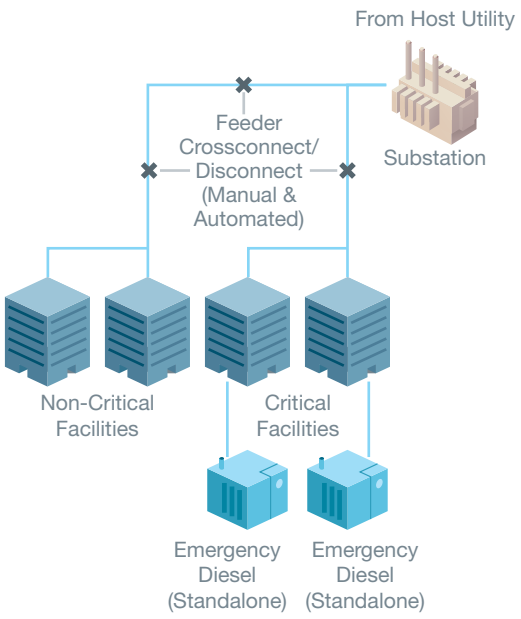


**Figure 1. Historical Energy Security Approach at Installations: Standalone Generators tied to Individual Buildings**

Standalone generators on installations tend to be diverse (non-uniform in scale, age, and manufacturer) and numerous. They can range in capacity from 10 Kilowatts (kW) to 2,000+ kW. Because the generators are disconnected from one another, each is sized to meet a building's peak critical load. DoD guidance directs generators to be sized to twice the current engineering estimate for their peak load (oversizing accommodates the uncertainty in the engineering estimate and possible increases in the building's future load). In practice, they are often sized even larger (2).

### 1.2.2. Microgrids

A microgrid is an alternative way to provide resilient power to a military base. A microgrid is a local system of DER and electrical loads that can operate as a single entity either in parallel to the commercial (macro) grid or independently (e.g., in "island" mode). Microgrid benefits include providing emergency back-up power during commercial grid outages and being a source of revenue and savings when connected to the grid. Any on-site power source can serve as a DER, including EDGs, prime generators, combined heat and power plants, renewables, battery systems, and other forms of energy. **Figure 2** provides a simplified graphical representation of a microgrid using centralized EDGs.

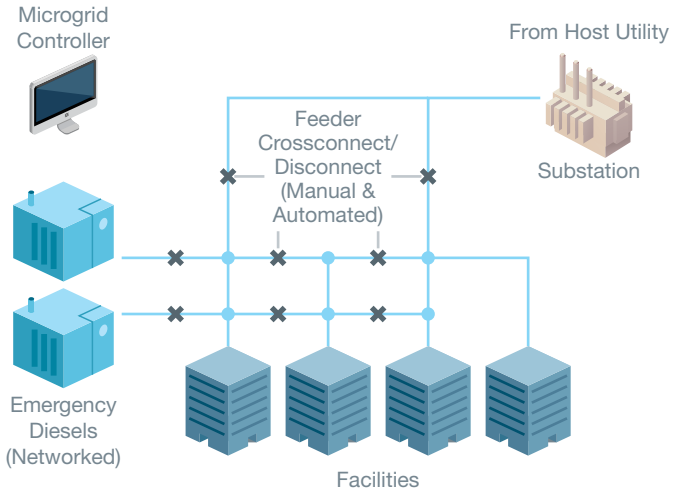


**Figure 2. Microgrid with Large Networked Generators**

## 1.3. Purpose of Study: Isolate Battery System Cost and Reliability Performance

The microgrid assessments supported by ESTCP were designed to determine if and under what conditions battery energy storage systems (BESSs) can cost-effectively and materially enhance energy security within a military microgrid. Previous work has shown that EDG-based microgrids have much higher power reliability performance than building-tied EDG systems (4) and lower lifecycle costs (2).

The ESTCP assessments found that integrating BESS into a microgrid can play a key role in DoD mission assurance by providing increased reliability for lower costs. Benefits of including BESS in military microgrids include:

- Minimal to zero underutilized energy generated from the renewable sources because the excess energy is either stored for future use for events such as grid outages or is fed back to the utility grid at optimal times;
- Seamless transition between alternative generation sources (e.g., PV to EDGs on a cloudy day) to provide a continuous source of energy;
- Savings obtained through reduction in utility peak demand and time-of-use (TOU) energy charges by load shaving and shifting;
- Revenue generated through participation in demand response (DR) and ancillary service programs;
- Reduced wear and improved fuel efficiency from EDGs by operating EDGs closer to manufacturer design-point conditions; and
- Enhanced microgrid reliability for power outages of at least one week.

Four teams – led by Principal Investigators (PIs) from Ameresco, Electric Power Research Institute (EPRI), Raytheon Integrated Defense Systems (Raytheon), and Southern Research Institute/Arizona State University (SRI/ASU) – were competitively selected by ESTCP to conduct design and modeling assessments of simulated battery storage-enabled microgrid technical and financial performance (5) (6) (7) (8).[14,15] In addition, the National Renewable Energy Laboratory (NREL) was selected to provide support and conduct an independent assessment. Seven installations were selected in coordination with the military Services for evaluation:

- Fort Bliss;
- Naval Air Station Corpus Christi (NAS Corpus Christi);
- Naval Air Station Patuxent River (NAS Patuxent River);
- Naval Base Ventura County;
- Holloman Air Force Base (Holloman AFB);
- March Air Reserve Base (March ARB); and
- Westover Air Reserve Base (Westover ARB).

The locations of the selected installations are shown in **Figure 3** on the next page. The figure also identifies the regions of the country (colored in the map) with regional transmission organizations (RTOs) and independent system operators (ISOs) and those without RTOs/ISOs (white in the map). RTOs/ISOs rely on competitive market mechanisms to a higher degree than non RTO/ISO markets, have more wholesale market participation options, and are called “structured” or “organized” markets for those reasons (9).

14 The PI teams had the following members that are listed in parentheses, in addition to their lead organizations: Ameresco (2ndPath Energy); EPRI (Lockheed Martin, PowerSecure, and Southern Company); Raytheon (Customized Energy Solutions and PXiSE Energy Solutions); and SRI/ASU (350Solutions and XENDEE Corporation).

15 Because the EPRI PI report was not published by the time this report was prepared, page number references herein to content from the EPRI report may differ from page numbers in the EPRI report after it is published.

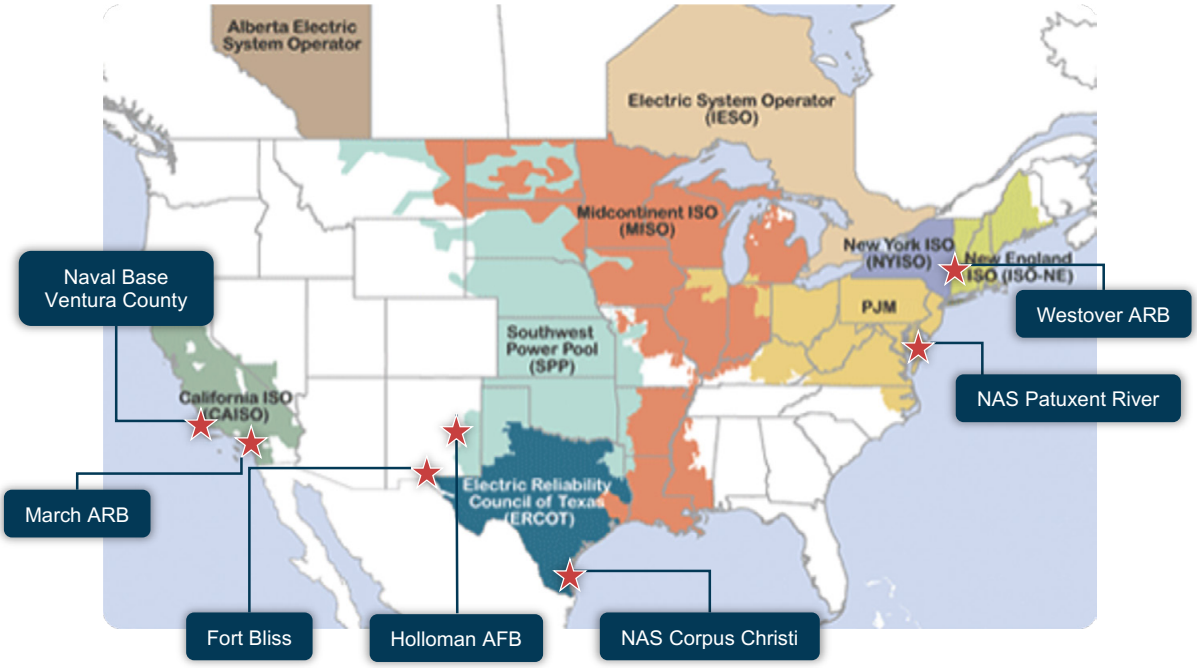


**Figure 3. Locations of Modeled Installations**[16]

The selected installations cover the variability of electricity loads, utility rate structures, solar resources, PV assets, and local electricity market conditions seen on military bases across the continental United States. The modeled performance at these seven installations provides DoD with an understanding of where and why battery storage can contribute effectively to an energy security solution.

Based on information from each of the seven installations, ESTCP provided the PI and NREL teams with site-specific data such as loads, installed PV capacity,[17] utility costs, and the assumed baseline microgrid configuration, including the number and size of the EDGs and uninterruptible power supply (UPS) units. This data helped ensure realistic and consistent modeling. In addition, ESTCP organized and provided data for a variety of electricity markets in which BESS and EDGs might participate to produce revenues for the installations.

16 The underlying map of regional transmission organization and independent system operator boundaries is from the Federal Energy Regulatory Commission and is available at: https://www.ferc.gov/industries-data/electric/power-sales-and-markets/rtos-and-isos.

17 It was assumed that a PV system had been installed already, independent of battery storage modeling decisions made by each PI and NREL team. Additional benefits can occur if the size of on-base PV and storage is jointly optimized.

## 1.4. Organization of Report

The remainder of this report provides a high-level overview of the results and lessons learned from the PI and NREL assessments.

- **Section 2:** Installation Microgrid Designs
- **Section 3:** Net Costs of Including Battery Storage in Microgrids
  - An energy security cost metric is defined, justified as a comprehensive and effective measure, and calculated for a "baseline" microgrid without storage. The economic results of the PI and NREL teams on their battery storage-enabled microgrids are then compared to baseline results, and each driver of microgrid costs and savings is examined.
- **Section 4:** Energy Security Results from Including Battery Storage in Microgrids
  - The key reliability metric is explained, and the performance of EDG-only systems are reviewed on that metric. ESTCP's minimum performance requirement is also defined on the key metric. The reliability of the PI and NREL teams' storage-enabled microgrids during power outages of up to one week is reviewed against the ESTCP requirement, and key lessons learned about installation energy security are highlighted.
- **Section 5:** Conclusion: Acting on Key Findings
- **Section 6:** References list
- **Appendices A-G:** Seven appendices provide additional details on assessment methods, assumptions, and findings at all seven military installations studied.
  - **Appendix A:** also describes subsequent battery storage microgrid research and development (R&D) that ESTCP is pursuing based on the most promising results from the PI assessments.

# 2. Installation Microgrid Designs

Each PI and NREL team independently designed a simulated, optimal battery storage-enabled microgrid. Using its own modeling tools and engineering insights, each PI designed a microgrid for five of the seven installations[18] that met the minimum technical reliability performance set by ESTCP and minimized the 20-year lifecycle costs after incorporating all battery system expenditures. Lifecycle costs could be lowered by reducing EDGs and/or UPSs (which in turn decreases capital and operations and maintenance [O&M] costs), reducing electric utility bills through peak shaving and shifting, and gaining revenue through electricity market participation. The inter-dependence of reliability and economic requirements in the modeling design of the PIs is depicted in **Figure 4.**

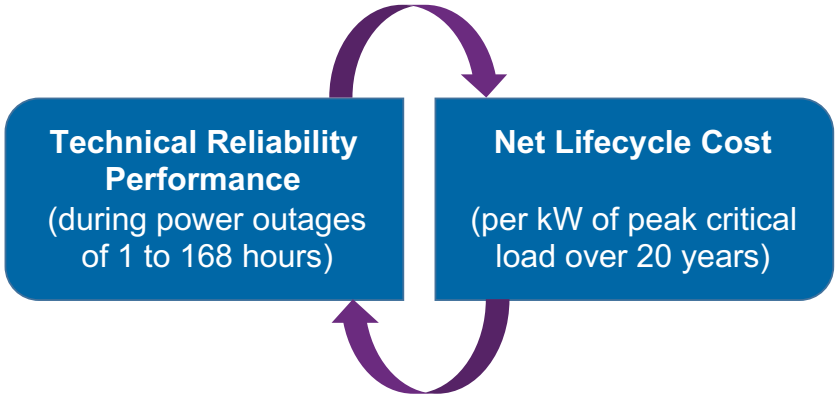


**Figure 4. Conceptual Microgrid Design Approach**

In the sub-section below and throughout the body of the report, three of the seven installations are emphasized: Fort Bliss, NAS Patuxent River, and Holloman AFB. These three installations represent mid-sized to large active military installations and illustrate the key conclusions of the ESTCP assessments.

Throughout this report's Appendices, data for all seven installations are provided. The PIs' published reports offer extensive additional details, including reviews of multiple battery technologies in several cases. This report focuses on the battery technologies selected as optimal by each team.

## 2.1. Baseline

The power requirements for each installation and the design of the baseline microgrid (with EDGs, but without storage) was defined by ESTCP to ensure consistency and serve as the reference point for battery storage-enabled microgrids. **Table 1** shows key electricity characteristics for Fort Bliss, NAS Patuxent River, and Holloman AFB. The "ride-through" loads identified in **Table 1** are covered by UPSs in the baseline microgrid.

**Table 1. Assumed Peak Electricity Loads at Three Installations (all data in kW)**

| Military Installation | Peak Critical Load | *Portion of Peak Critical Load Requiring Ride-Through* | Peak Non-Critical Load | Overall Peak Annual Load (Critical + Non-Critical) |
|---|---|---|---|---|
| **Fort Bliss** | 12,507 | *6,000* | 55,098 | 67,605 |
| **NAS Patuxent River** | 8,014 | *4,000* | 25,944 | 33,958 |
| **Holloman AFB** | 5,996 | *3,000* | 9,994 | 15,990 |

18 NREL designed and modeled microgrids for all seven installations.

These three installations span typical peak loads found in mid-size to large military installations; approximately 50% of the peak critical loads require ride-through capability (i.e., non-interruptible even for milliseconds).

**Table 2** lists the assumed DER, including the number of EDGs and UPSs, in the baseline (non-storage) microgrid.

**Table 2. Assumed Distributed Energy Resources at Three Installations in Baseline Microgrids**

| Military Installation | PV Size (kW-AC) | Size of Each EDG (kW-AC) | Number of EDGs | Size of Each UPS | Number of UPSs |
|---|---|---|---|---|---|
| **Fort Bliss** | 6,200 | 2,000 | 8 | 2,000 kVA<br>500 kWh | 4 |
| **NAS Patuxent River** | 2,000 | 750 | 12 | 250 kVA<br>63 kWh | 17 |
| **Holloman AFB** | 5,000 | 750 | 9 | 250 kVA<br>63 kWh | 13 |

The baseline microgrid was designed with N+1 EDGs, where N is the number of EDGs needed to meet the annual peak critical load and an EDG is added for higher reliability. The size of the EDGs for each modeled installation was chosen in accordance with common engineering trade-offs. Using smaller capacity EDGs will lead to more EDGs and, therefore, higher maintenance costs. Using larger EDGs can limit the ability to expand in a cost-effective manner to meet future growth in critical loads.

PV power was not considered in determining the size or number of EDGs in the baseline microgrid due to the intermittency of solar resources and the unpredictability of when a power outage will begin and end. PV power is not a reliable source of power, in the context of military mission protection, in the absence of battery storage or dispatchable generation.

## 2.2. Battery Storage-Enabled Microgrids

The PI and NREL teams' microgrid solutions at each installation varied due to the installations' physical and economic electricity conditions as well as teams' selected BESS and optimization choices with regard to use of microgrid assets. The DER selected by each team are summarized in this sub-section. The selection of battery chemistry was a key issue, and the main BESS technology reflected in each team's optimized results is listed in **Table 3**.

**Table 3. Primary BESS Technology in Results**

| Assessment Team | Primary BESS Technology |
|---|---|
| **Ameresco** | Vanadium Redox Flow Battery |
| **EPRI** | Generic Lithium-ion (Li-ion) |
| **Raytheon** | NMC Li-ion[19] |
| **SRI/ASU** | Blue Planet $LiFePO_4$ |
| **NREL** | Generic Li-ion |

19 Raytheon modeled a nickel manganese cobalt oxide (NMC) Li-ion battery, made by Samsung SDI or LG Chem, integrated into a DynaPower BESS (5), p. 8.

Based on these BESS technologies, each PI and NREL designed what it considered an optimal system based on its engineering calculations and modeling. The sizes of their BESS[20] are listed in **Table 4**, along with the number of EDGs that were removed in storage-enabled microgrids as BESS performed reliability functions.

**Table 4. Distributed Energy Resources in Storage-Enabled Microgrids at Three Installations**

| Assessment Team | Fort Bliss | NAS Patuxent River | Holloman AFB |
|---|---|---|---|
| BESS Power (kW) and Energy (kWh) | | | |
| **Ameresco** | 2,000 kW<br>12,000 kWh | 1,167 kW<br>7,300 kWh | N/A |
| **EPRI** | 1,225 to 1,255 kW<br>1,225 to 1,255 kWh | N/A | 3,600 to 3,800 kW<br>14,400 to 15,200 kWh |
| **Raytheon** | 1,700 kW<br>2,210 kWh | 3,000 kW<br>3,900 kWh | 2,400 kW<br>6,480 kWh |
| **SRI/ASU** | 2,700 kW<br>2,700 kWh | 900 kW<br>900 kWh | 1,800 kW<br>1,800 kWh |
| **NREL** | 600 kW<br>1,800 kWh | 800 kW<br>3,200 kWh | 800 kW<br>3,600 kWh |
| Number of EDGs Removed (from baseline microgrid) | | | |
| **Ameresco** | 1 | 1 | N/A |
| **EPRI** | 2 | N/A | 2 |
| **Raytheon** | 1 | 2 | 2 |
| **SRI/ASU** | 2 | 3 | 3 |
| **NREL** | 1 & 2 | 1, 2 & 3 | 1, 2 & 3 |

Each PI and NREL team made its own tradeoffs between lifecycle costs and reliability, while exceeding ESTCP's power reliability requirements. Further, each team had its own assumed installation costs for BESS and methods for exploiting market opportunities. The resulting variation between the teams in optimized systems is significant. For example, at Holloman AFB the BESS power differed by more than a factor of four and energy by a factor of eight. No one system design is optimal across-the-board, as the final decision on optimal design depends on an installation's mission, its risk tolerance, and actual costs.

20 BESS sizes are expressed in two measures: power (the maximum amount of instantaneous electricity that can be discharged) and energy (the stored volume of energy in the BESS). Power is shown in kW and energy in kWh. The "duration" of a BESS, in hours, is calculated by dividing energy by power. For example, NREL modeled a three-hour duration BESS at Fort Bliss (= 1,800 kWh / 600 kW).

# 3. Net Costs of Including Battery Storage in Microgrids

The threshold economic question in this study is whether adding battery storage will lower overall microgrid costs while meeting energy security needs. To address that threshold question, we examine economic results across seven installations, with a focus on one large installation in each Service. The results show that including Li-ion BESS lowers net microgrid costs by six percent to more than 60%, depending on the installation and the modeling approach taken.

After clearing that overall viability threshold, the next layer of economic questions identifies factors leading to better and worse outcomes for BESS in microgrids. Those questions include what battery chemistries, in what configurations and locations, and with what operational rules perform best? And for each factor, the last question is why is it associated with economic success? Answering the questions is necessary for isolating the energy security contributions of BESS and replicating those contributions within DoD.

This section uses a holistic metric for the net, lifecycle costs of microgrids to address its economic questions. The metric is the economic centerpiece of PI and NREL analyses. To isolate battery storage contributions, the central metric was calculated for a baseline microgrid (without storage) at each of the seven military installations studied and, then, for microgrids with BESS at each installation. The differences between baseline and "storage-enabled" microgrid economics are shown overall and decomposed into three drivers: opportunities for retail and wholesale electricity market savings; trimming unneeded energy assets; and adding costs for the battery systems.

## 3.1. Key Economic Metric

While there are many possible ways to review microgrid economics, this ESTCP study focuses on a single metric that incorporates and nets all lifecycle cost and revenue impacts of microgrid investments and standardizes those impacts by what they are protecting -- mission critical electricity loads at installations. The metric is the ***net annual cost of protecting each kW of peak critical load.***[21] It represents energy security costs compared to having no protection whatsoever for critical loads and allows comparisons between energy security solutions; e.g., microgrids with and without storage as well as non-microgrid solutions such as building-tied EDGs.[22]

The same metric concept applied in this study has been incorporated into National Defense Authorization Act (NDAA) (10) guidance and is being increasingly used by DoD officials because it nets and annualizes all revenues and costs of microgrid investments on a lifetime basis and standardizes by a proper measure of energy security scale. On the last point, DoD back-up power requirements are determined by the peak electricity needs of buildings or other assets containing critical missions. Therefore, energy security solutions should be measured by how they meet peak requirements (2). Like the central reliability metric described in the next section, this economic metric is also meant to support an emphasis on DoD "buying performance" for energy security, rather than "buying equipment."

21 The metric calculation starts with the military installation's overall, net electricity costs before implementing a microgrid. These include all costs of buying and self-generating retail electricity, plus any savings received from participation in demand response programs expected over a 20-year period. Then, the same installation-wide cost calculation is performed for a microgrid – adding lifetime net costs for centrally-controlled EDGs, UPSs, BESS (as applicable), and the microgrid itself as well as any additional retail electricity savings and wholesale electricity revenues that the microgrid can achieve. The post-microgrid, 20-year net present value (NPV) costs are subtracted from the pre-microgrid 20-year present value of electricity costs to determine the lifetime costs of adding the microgrid. That difference is divided by 20 years and by the peak critical load at the installation to arrive at the net annual cost of adding microgrid protection per kW of critical load. For example, if the net cost is $75/kW, that means that adding the substantial energy security of a microgrid would cost $75 per year for every kW covered, or $750,000 annually for a very large military installation with 10,000 kW (10 megawatts [MWs]) of peak critical load. That is the net cost compared to having no energy security solution (i.e., no EDGs nor UPSs).

22 Though installations have existing back-up power systems (usually building-tied EDGs), the capital and operating costs of those existing systems are not included in this report's analysis. The report compares baseline microgrids (without BESS) to storage-enabled microgrids (with BESS). For a comparison of baseline microgrid costs on this economic metric to building-tied EDG costs, see (2).

## 3.2. Performance Baseline: Microgrid Costs before Adding Battery Storage

Based on detailed data provided by each of the seven installations studied, ESTCP calculated the key economic metric for a baseline microgrid (without battery storage) at each installation.[23] **Table 5** shows total 20-year electricity costs pre- and post-microgrid for three installations, as well as the peak critical load used to standardize the cost difference into the key economic metric.[24] The formula for calculating the key economic metric in **Table 5** is:

$$\frac{Baseline\ Microgrid\ Cost - Pre\ Microgrid\ Cost}{Peak\ Critical\ Load\ in\ kW\ x\ 20\ (years)} = Net\ Annual\ Cost\ of\ Protecting\ Critical\ Load$$

or

$$\frac{a - b}{c\ x\ 20} = d$$

**Table 5. Aggregate Baseline (No Storage) Microgrid Costs at Three Installations**

| Military Installation | Baseline Microgrid 20-Year NPV of Energy Security Assets + Electricity Costs for Installation (a) | Pre-Microgrid 20-Year Present Value of Electricity Costs for Installation (b) | Peak Critical Load (c) | Baseline Microgrid Net Annual Cost of Protecting Critical Load ($/kW) (d) |
|---|---|---|---|---|
| **Fort Bliss** | $312.0 MM | $291.3 MM | 12,507 kW | $83 |
| **NAS Patuxent River** | $257.7 MM | $241.9 MM | 8,014 kW | $98 |
| **Holloman AFB** | $95.3 MM | $83.5 MM | 5,996 kW | $98 |

It is important to note that the *pre-microgrid* costs in **Table 5** do not include any energy security investments (i.e., these costs do not include the cost of building-tied EDGs or UPSs at the installation).[25]

23 Relevant data from the installations, as well the baseline microgrid calculations, were provided to the PIs and NREL to serve as a technical and economic foundation which they could reproduce and to which they added battery storage. Data provided by the installations and ESTCP's baseline microgrid methodology are described further in **Appendix A**.

24 Pre-microgrid costs cover all electricity purchases and differ among installations due to their existing (i) electricity consumption levels and patterns; (ii) retail electricity rate levels and structures; (iii) demand response participation; and (iv) power self-generation. Consumption levels refer to the amount of electricity consumed in a year (kilowatt-hour [kWh]), while consumption patterns refer to the hourly or sub-hourly shape of consumption and peak demand. The patterns create differences in costs when an installation's electricity rates have peak demand, energy TOU, or seasonal distinctions. Rate levels refer to unit prices per kWh, kW, and kilovolt-ampere (kVA) on electricity bills, while rate structures refer to the allocation of charges by rate type (e.g., energy by TOU designation, peak demand).

25 Because the purpose of this ESTCP study is to isolate the contributions of battery storage to microgrids, lifecycle cost comparisons of centralized microgrids versus non-microgrid solutions such as building-tied EDGs and UPSs were outside of the scope. However, other analyses have found that building-tied energy security solutions at large U.S. military installations tend to provide inferior energy security at added lifecycle cost compared to microgrids (2).

The baseline microgrid costs in **Table 5** reflect the pre-microgrid cost plus four factors. Values for these four factors are shown in **Table 6**,[26] and they are standardized into 20-year NPV costs per kW of peak critical load.[27] The formula for **Table 6** is:

$$EDG\ Cost + UPS\ Cost + Microgrid\ Cost + Savings\ from\ Demand\ Response\ \&\ Peak\ Shaving\ (if\ any) = Net\ Annual\ Cost\ of\ Protecting\ Critical\ Load$$

or

$$A + B + C + D = E$$

**Table 6. Individual Components of Baseline (No Storage) Microgrid Net Costs at Three Installations (all data in annual $/kW of peak critical load)**

| Military Installation | EDGs (A) | UPSs (B) | Microgrid Hardware, Software, & Support (C) | Demand Response & Peak Shaving Savings (D) | Annual Net Cost of Protecting each Kilowatt of Peak Critical Load[28] (E) |
|---|---|---|---|---|---|
| **Fort Bliss** | $47 | $18 | $18 | ($0) | $83 |
| **NAS Patuxent River** | $49 | $22 | $36 | ($10) | $98 |
| **Holloman AFB** | $49 | $22 | $36 | ($10) | $98 |

The costs in **Table 6** vary by installation due to differences in the number and size of EDGs and UPSs required, peak critical loads, and the opportunities for peak shaving and DR in local electricity markets.[29]

## 3.3. Overall Economic Performance of Battery Storage-Enabled Microgrids

The performance of microgrids with BESS, compared to baseline microgrids at three installations, is shown in **Figure 5**.[30] The chart displays results from the four PI teams that completed Phase I modeling and NREL's results using its REopt modeling tool.[31,32] Positive percentages in the chart represent improved economics.

26 Equivalent data from **Table 5** and **Table 6** are in **Appendix F** for the other four installations studied.

27 The first three factors (in columns A-C) reflect the necessity of including lifecycle capital and sustainment costs for back-up power (EDGs) sufficient to provide N +1 reliability for the peak critical load at each installation, UPSs sufficient for N + 1 reliability for the portion of critical loads requiring ride-through capability, and a fully-functional microgrid controller and associated components integrated with the EDGs, UPSs, PV, and critical loads on the installation. The fourth factor (in column D) is cost savings or added revenues from functions that the baseline microgrid can perform like peak demand shaving and increased participation in demand response programs.

28 Rounding causes $1/kW differences in totals in some cases.

29 The lack of peak shaving and DR savings at Fort Bliss is due to the combination of the installation's utility rate structure and its existing DR and peak shaving activities with on-installation natural gas generators.

30 An equivalent chart for the other four installations studied (NAS Corpus Christi, Naval Base Ventura County, Westover ARB, and March ARB) is in **Appendix F.**

31 NREL 1, NREL 2, and NREL 3 represent results when 1, 2, and 3 EDGs, respectively, are removed from an installation.

32 Where there is no bar on the chart for a given PI at an installation, that is because it was not one of the installations selected by that PI for modeling.

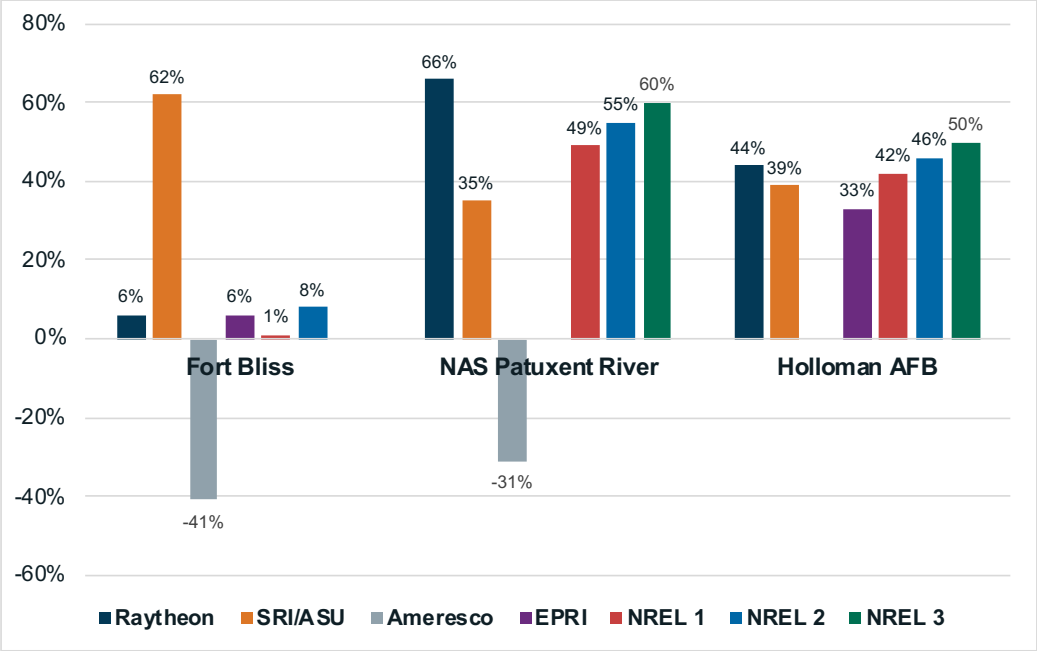


**Figure 5. Battery Storage-Enabled Microgrid Savings at Three Installations: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

These results, which are similar to those achieved for the other four installations, show that Li-ion BESS[33] consistently reduce the net costs of microgrids. For example, at Holloman AFB, adding battery storage improved the net cost of the microgrid by 33% to 50%, depending on the modeler.[34] Those savings are after paying the lifecycle costs for the battery system itself. More detailed results for all seven installations are in **Appendix E**.

## 3.4. Sources of Net Savings and Costs when Adding Battery Systems to Microgrids

**There are three main savings and cost categories when BESS are added to microgrids:**

- Retail and wholesale electricity market savings or revenues;
- Reductions in the number of EDG and UPS assets needed to deliver reliable power during grid outages;[35] and
- Investment costs for the BESS.

While the last category (BESS costs) occurs, by definition, at all installations implementing storage-enabled microgrids, the applicability of the other two categories varies widely depending on BESS technology selection, configuration, and operation as well as the size of critical loads at installations, their on-site PV, and their local electricity market conditions. The contributions to microgrid economics calculated by Raytheon, SRI/ASU, and NREL for these three categories at one example installation are shown in **Figure 6**. Negative numbers in the chart represent savings and positive numbers are added costs.

33 The Ameresco results in this chart are for a vanadium redox flow BESS, which is an emerging technology with higher costs than mainstream Li-ion systems.

34 The savings in **Figure 5** at Holloman AFB are equivalent to $32/kW to $49/kW of critical load per year (= 33% to 50% x $98/kW baseline microgrid cost). They translate into annualized savings of approximately $190,000 to $290,000 at Holloman AFB (= $32/kW to $49/kW x 5,996 kW of peak critical load at the installation).

35 The PI and NREL teams were provided capital and O&M costs for EDGs and UPSs by ESTCP. This ensured standard treatment of costs. See **Appendix A** for a listing of these costs.

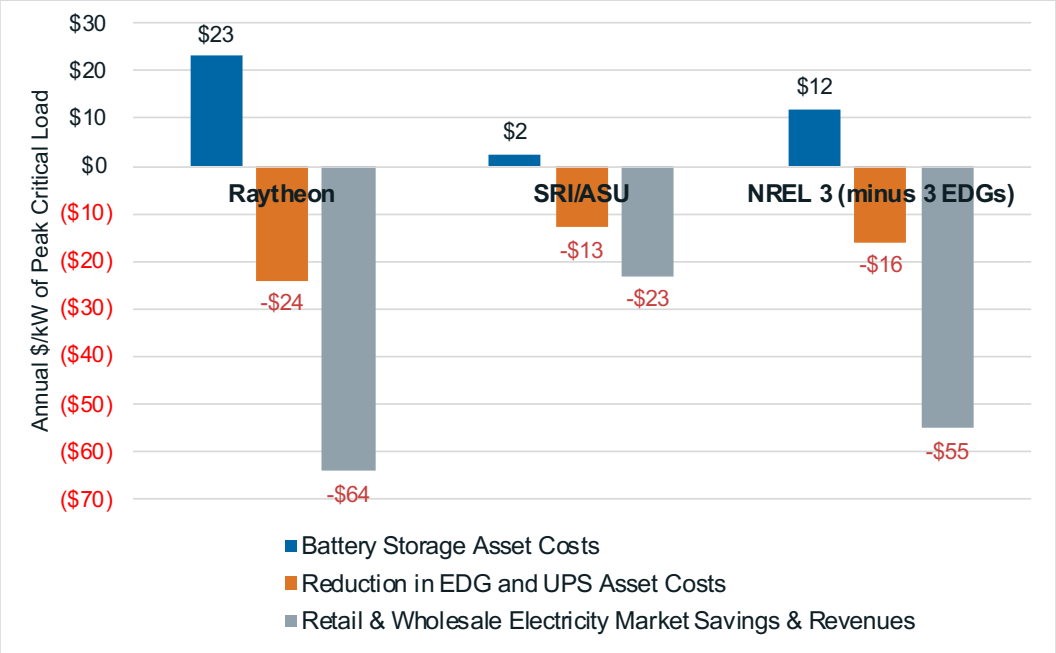


**Figure 6. Breakdown of Cost Additions and Savings in Lithium-ion Battery Storage-Enabled Microgrids at NAS Patuxent River**

From this example installation, one can see that while retail and wholesale electricity market activities are the largest positive contributor to microgrid economics, reductions in EDGs and UPSs are also important contributors and can pay for all of the added costs of the battery storage technology.[36] A similar pattern occurs at the other installations studied, except Fort Bliss.[37]

Below, each of the three categories of savings and costs is described and, then, its importance to overall economic results is illustrated with additional examples from the military installations modeled.

### 3.4.1. Electricity Market Savings and Revenues

Economic value can be obtained from microgrids through retail and wholesale market activities. In some cases, that value can be obtained simultaneously in both types of markets.

#### Retail Markets

The most widely available source of savings from BESS was on retail electric bills. PIs and NREL were able to obtain some level of retail bill savings at each installation compared to the ESTCP baseline. Often, that is because large portions of military installations' bills (e.g., 40% at Holloman AFB) are from peak demand charges. Battery systems are very effective at peak shaving, or reducing monthly demand, by discharging power during the hours of peak need on-installation and re-charging at times of low demand or when excess PV power is available.

**Retail and Wholesale Electricity Markets Defined**

Retail electricity costs are those paid by the end-user (e.g., military installation) on its monthly power bills. End-users can manage their retail costs by changing their level or pattern of consumption, by switching rates, or by self-generating power.

Wholesale electricity costs are those incurred by power resellers such as utilities and competitive generation suppliers for energy, capacity, and ancillary services. End-users can participate in wholesale markets if they have power generation or energy storage assets, or the ability to control their loads for demand response and have been registered to participate in such markets themselves or through intermediaries.

36 The NREL 1 and NREL 2 results are not shown in **Figure 6**. The only significant differences between the NREL 1, 2, and 3 cases for this installation are that eliminating each additional EDG contributes about $5.50/kW in annual savings, without any change in battery storage costs and only minimal reductions in retail savings. Therefore, the "Reduction in EDG and UPS Asset Costs" bar in the chart would be -$5 for the NREL 1 case and -$11 for the NREL 2 case.

37 At Fort Bliss, the absence of wholesale market opportunities in its utility territory, the utility's rate structure, low average utility rates, and the installation's existing use of peak shaving and DR techniques greatly limit cost savings opportunities from BESS.

In addition to peak demand savings, some of the installations studied have TOU energy rates that include higher prices during certain (on-peak) hours each weekday. BESS also tend to be effective at creating TOU savings by charging the battery during off-peak (low-cost) periods each day and discharging the battery (and thereby reducing utility electricity purchases) during on-peak periods. This is commonly called "energy arbitrage." The savings from shifting the installation's consumption pattern are especially large when off-peak vs. on-peak price differentials are large, such as during the summer in many southern states.[38,39]

#### Wholesale Markets

In contrast to retail bill savings, installation opportunities for ***participation in wholesale markets*** are not uniformly available. Installations in vertically integrated utility markets[40] typically have limited wholesale opportunities, unlike installations in regions with structured markets for energy, capacity, and ancillary services (9) (11).

Among installations in this ESTCP study, the PI and NREL teams obtained the greatest wholesale revenues from frequency regulation markets, a type of ancillary services. That is not surprising because frequency regulation requires fast-response (e.g., in reaction to two- to four-second signals), a particularly strong characteristic of BESS. This was particularly the case at NAS Patuxent River in the Raytheon study and Westover ARB in the SRI/ASU study. There can be additional wholesale revenues from storage participation in other ancillary service markets (e.g., spinning reserve) as well as in energy and capacity markets.

### 3.4.2. Reductions in Unneeded Energy Assets

An often-overlooked category of cost savings from adding BESS to a microgrid is the reduction in EDGs and UPSs it can allow. If the BESS can, at high reliability, serve critical loads and the subset of critical loads requiring ride-through capability,[41] then the number of EDGs and UPSs can be reduced with no loss of reliability performance.

Eliminating even one 750 kW EDG avoids about $560,000 in upfront capital costs and $7,000 in annual costs for O&M. Similarly, removing a single 250 kVA, 63 kWh UPS avoids about $160,000 in one-time capital costs and $3,400 in annual O&M costs.[42]

On the basis of the key economic metric, reducing EDGs and UPSs decreased the cost of protecting critical loads by about $5/kW to $30/kW each year at the mid-sized to large installations studied, with placement in the range dependent on installation conditions and the PI's BESS configuration. For example, Raytheon calculated $11/kW in annual EDG savings and $16/kW in annual UPS savings, for total annual savings of about $160,000 from reducing unneeded back-up power assets at Holloman AFB.

#### Emergency Diesel Generators

The PIs and NREL found that at least one EDG could be eliminated from each installation. They also found that, at maximum, and only by some of the PIs and only at the large bases NAS Patuxent River and Holloman AFB, that it was possible to eliminate three EDGs while meeting reliability requirements.

#### Uninterruptible Power Supply Units

Reductions in UPS units were not as prevalent as for EDGs because typical BESS, without specialized configurations and supplementary technologies, will not reliably handle the micro-second frequency and voltage

38 For example, military installations in Southern California can have differentials of more than $0.20/kWh between their highest on-peak prices and their off-peak prices in the summer. At Holloman AFB in New Mexico, there is a large, year-round TOU differential: an on-peak rate above $0.11/kWh compared to an off-peak rate below $0.04/kWh.

39 The only instance where meaningful retail bill savings were not available from BESS use in a microgrid was at Fort Bliss. That is because the installation already captured almost all savings through its own load management and power generation activities. The savings shown from the SRI/ASU PI at Fort Bliss are an outlier.

40 Vertically integrated markets are those in which the electric utility provides generation, transmission, and distribution to its end-use customers. Among the seven installations in this ESTCP study, Fort Bliss and Holloman AFB are in vertically integrated markets.

41 Ride-through is necessary for electricity loads that cannot withstand a power loss of more than several milliseconds without losing important functionality, such as computer systems. See **Appendix A** for additional information.

42 O&M costs identified in this report are for the first year of system operation. Such costs are assumed to rise annually at the rate of inflation.

requirements of ride-through transitions for sensitive power consuming equipment. However, through the pairing of high-speed phasor-based control technologies (by Raytheon) or ultra-capacitators (by SRI/ASU) with Li-ion battery systems, the two PIs found UPS unit reductions to be viable. For example, Raytheon determined that its storage-enabled microgrid allowed for the elimination of all three 250 kVA UPSs at March ARB and all nine 250 kVA UPSs at Naval Base Ventura County, but no elimination of the larger 2,000 kVA UPSs at Fort Bliss.[43]

### 3.4.3. Added Battery Storage Investment Costs

This cost category covers the capital and annual O&M costs of the battery systems themselves. These costs depend on the battery chemistry selected (e.g., Li-ion vs. flow) as well as the size (in power [kW] and energy [kWh]) and configuration of the BESS. Though there were wide ranges on all of these factors among PIs, and between installations, most BESS were Li-ion chemistries with sizes of 1,000 to 3,000 kW in power and 2,000 to 8,000 kWh in energy.

Each PI's assumed capital costs for these systems in the ESTCP Phase I reports were generally $475 to $775/kWh, with fixed annual O&M costs at the modest level of about $10/kW-year. There is also a cost to replace the battery itself of approximately $200 to $238/kWh occurring every five to 10 years of operation to substitute for degradation of the original battery.[44]

On the key economic metric, BESS costs generally added $10 to $30 per kW of peak critical load to annualized microgrid costs at the mid-sized to large installations studied.[45] The annual BESS costs amounted to $100 to $200 per kW of peak critical load at the two reserve bases (Westover and March) in some analyses because BESS costs are amortized over much smaller critical load volumes at U.S. Air Force (USAF) reserve bases, and relatively larger capacity BESS are needed to replace EDGs.

For additional details on battery system chemistries, costs, sizes, and performance characteristics, see **Appendix B** and **Appendix E** of this report.

## 3.5. Characteristics of Installations with Best Economic Outcomes

On the study's key economic metric (annual cost of protecting each kW of peak critical load), there are two characteristics associated with the best outcomes for battery storage – presence in a structured ISO/RTO market and larger critical loads.

Being ***located in a structured wholesale electricity market*** allows battery systems to capture significant revenues by providing frequency regulation, in particular, as well as other ancillary services, energy, and capacity. That is a main reason why installations in the Pennsylvania, Jersey, Maryland Power Pool (PJM[46]) (NAS Patuxent River), Electric Reliability Council of Texas (ERCOT) (NAS Corpus Christi), and ISO New England (ISO-NE) (Westover ARB) markets had the lowest annual costs for storage-enabled microgrids per-kW, depending on the investigator. Microgrid costs are even negative is some instances

**Economic Considerations for Small Military Bases**

The economic results for the two USAF reserve bases in this study (Westover and March) are directionally similar to those for larger installations. Specifically, adding battery storage decreases overall microgrid costs materially without hindering energy security, EDGs and UPSs can be eliminated to contribute to economic savings, and the greatest savings are from retail and wholesale electricity market operations.

However, the smaller bases have a unique barrier: they must amortize the large fixed cost of implementing a microgrid itself, and to a lesser extent EDGs and UPSs, over critical loads that are 7 to 20 times smaller than at Fort Bliss. That leads to much higher costs per kW to protect critical loads at reserve and other small bases with microgrids. The implication is not that the small bases should avoid storage-enabled microgrids, but that they should explore simpler, more standardized microgrid configurations to realize the energy security benefits at more attractive net costs.

43 See (5), p. ES-5.

44 Within that five- to 10-year period, more frequent use of BESS leads to faster degradation and replacement (or "capacity enhancement") of the battery.

45 In the case of SRI/ASU, its methodology led to the deployment of relatively small BESS, leading to much lower annualized BESS costs of approximately $3 to $7/kW of peak critical load at four installations.

46 Though PJM's acronym includes three states, this transmission organization serves all or parts of 13 states and the District of Columbia.

(e.g., NAS Corpus Christi in EPRI's and NREL's modeling). Investing in a storage-enabled microgrid at that installation is less expensive than providing no back-up power whatsoever, due mostly to BESS-derived savings from retail and wholesale market activities.

The ***scale of peak critical loads*** was also a major contributor to economic success. Larger critical loads allow the installation to spread the high fixed cost of the microgrid controller and related hardware and software over a larger volume. BESS, EDGs, and UPSs are also more cost-effective at larger scales. The smallest installations, two USAF reserve bases, had by far the highest costs of protecting each kW of critical load in most of the PIs' analyses (see box on the prior page), though in relative terms they benefitted in roughly the same manner as larger installations from the addition of BESS.

In addition to the two factors profiled above, ***sharp distinctions in retail TOU electric rates*** between on-peak and off-peak periods is another important contributor to economic success as is a ***high peak*** demand ***rate*** on the retail bill. Weather conditions themselves (heating and cooling degree days, or amount of sunlight) were not major predictors of economic success. Adding BESS to microgrids aided economic performance in every geography, and the top performers were as likely to be in Texas as Maryland.

# 4. Energy Security Results from Including Battery Storage in Microgrids

The most important characteristic of a back-up power system is its ability to provide power to critical loads. Reliability metrics indicating the likelihood that critical loads will be supported for the full duration of a grid outage are the most suitable gauge of performance.

Multiple system-level reliability metrics can be calculated to characterize the expected lost load or probabilities that all or some portion of the critical load is supported. The metrics are not independent of each other, but they can be used to highlight different reliability vulnerabilities. Although they vary numerically, outcomes are consistent across such metrics. ESTCP chose to focus on the most sensitive of these metrics -- the probability that all the critical load will have available power as a function of outage duration ranging from one hour to one week (168 hours).

This section begins with a brief performance review of building-tied EDG systems (without microgrids) and defines the minimum reliability performance requirement of the ESTCP assessment. Next, the performance of battery storage-enabled microgrids is compared to the ESTCP performance requirement, baseline microgrid performance with only EDGs, and the performance of building-tied EDGs at three installations representing a cross-section of mid-sized to large installations studied. The section concludes with commentary on other reliability performance characteristics.

## 4.1. Emergency Diesel Generator Systems

The performance of an on-installation EDG system depends on the reliability of the individual EDGs which serve the critical loads. Based on recent analysis of EDG reliability (12) (see **Appendix C**), ESTCP established an EDG performance benchmark for all PI and NREL teams to use. The reliability of a well-maintained[47] EDG was selected.[48] **Figure 7** compares the reliability of a single well-maintained EDG over a one-week power outage to a poorly-maintained EDG.

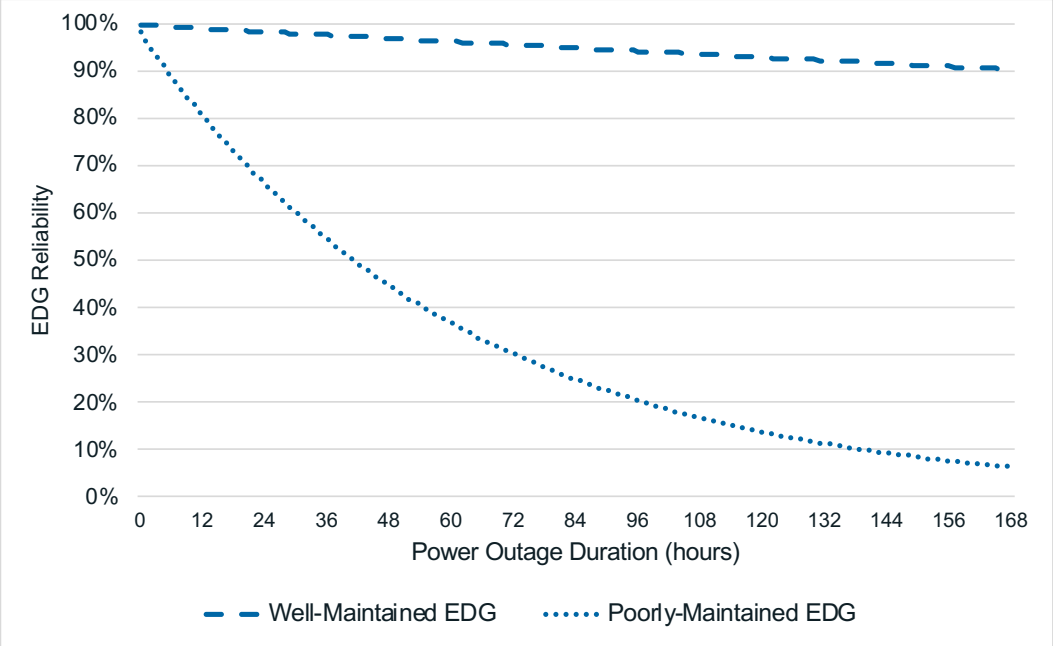


**Figure 7. Probability of a Single EDG Meeting Critical Loads for Power Outages of up to One Week**

47 Well-maintained means that the EDG maintenance and testing program rigorously follows Unified Facility Criteria guidance (UFC 3-540-07).

48 Reliability is equivalent to one minus the cumulative probability of a failure.

A well-maintained EDG has a 90% probability of being up and running after a week-long outage (it drops to 80% by two weeks), while a poorly-maintained EDG has less than a 10% probability of being up at the end of a week and is more likely than not to fail within a few days of an outage starting. These results are why it is so important for military installations to follow current maintenance guidance.

System-level reliability depends on the number and connectivity of EDGs and varies dramatically between building-tied and microgrid networked EDGs (4). Building-tied EDGs are sized to exceed the peak critical load of their buildings; therefore, the reliability of a well-maintained, EDG-based system does not depend on the underlying load profile, but only on the number of buildings.

In contrast, the total capacity of EDGs supporting a microgrid is sized to ensure there is sufficient power to meet the annual peak critical load of all interconnected loads combined. ESTCP baseline microgrids have N+1 back-up generators (referred to as an N+1 microgrid) where N generators would just satisfy the annual peak critical load.[49] The EDGs in a microgrid can supply power to any building on the microgrid network. Thus, the amount of redundancy at each hour depends on the critical load at that hour. Critical loads vary with season, day of week, and time of day. For most of the year, the N+1 microgrid has much higher redundancy than N+1 when critical loads are much lower than their annual one-hour peak.

**Figure 8** shows the predicted performance at NAS Patuxent River of three different back-up power systems with EDGs[50] and the minimum required performance established by ESTCP.[51]

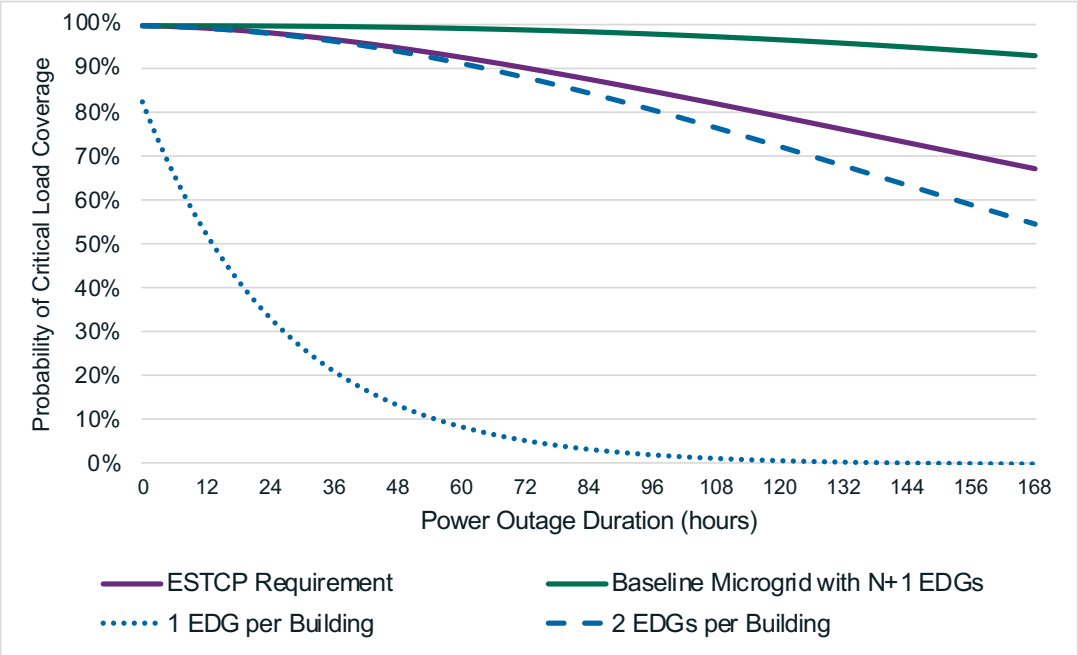


**Figure 8. Probability of Fully Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River: Baseline Microgrid vs. Single and Double Building-Tied EDG Systems[52]**

The ESTCP minimum requirement was based on the performance of an N+1 microgrid for a fixed load equal to the annual peak critical load and provided a common performance floor for the PI and NREL teams. As seen in **Figure 8**,

49 The "+1" EDG provides redundancy to improve microgrid reliability performance during periods of peak demand.

50 The three systems are: baseline microgrid with networked EDGs (but no battery storage); one standalone, building-tied EDG per building; and two standalone, building-tied EDGs per building.

51 This ESTCP study used a fault tree methodology to calculate the performance for building-tied EDGs and a microgrid supporting a fixed critical load. A Markovian matrix approach was used to calculate the reliability for a microgrid supporting a variable load (4).

52 The "1 EDG per Building" dotted line begins at 82.5% in **Figure 8** at hour 0 because there is a 17.5% chance that at least one EDG across NAS Patuxent River (in a standalone, building-tied configuration) will not start or be available at the beginning of the outage. That installation-wide outcome in **Figure 8** is distinct from **Figure 7**, which shows the probability that a single EDG will not perform over the course of an outage. The probability of a single, poorly-maintained EDG being available and starting at hour zero is 98.2%.

the performance of a single EDG per building is poor. The minimum ESTCP performance requirement is higher than a system of two EDGs per building achieves, but not as high as the expected performance for a baseline microgrid when one considers the benefits of load variability to reliability.[53] Baseline microgrid results for NAS Patuxent River in **Figure 8** are similar to results seen for the other six installations in **Appendix E**.[54]

**Figure 9** shows the performance at the end of week-long power outages for different EDG-based systems at three installations. Results for the other four installations are similar.

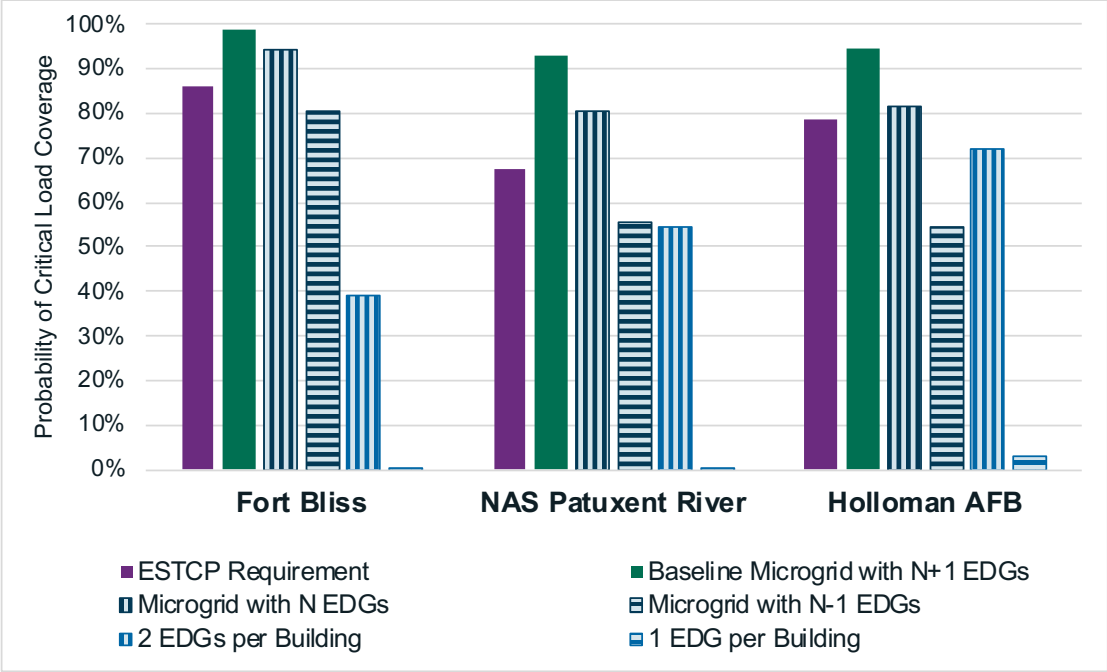


**Figure 9. Probability of Building-Tied EDGs and Baseline Microgrids Fully Meeting Critical Loads by the end of One-Week (168-hour) Power Outages at Three Installations**

The likelihood that a system with single EDGs at each critical load building will be able to serve loads throughout a week-long outage is vanishingly small. The minimum ESTCP performance requirement at one week is between 67% and 86% at these three installations, which exceeds even what a system with two EDGs per building (39% to 72%, denoted by blue, vertically striped bars that are second from the right at each installation) can achieve. The expected performance for an N+1 microgrid (93% to 99%) and an N microgrid[55] (80% to 94%) surpasses the minimum ESTCP requirement when one considers the load variability at all three installations. A microgrid with only N-1 EDGs fails to meet the ESTCP minimum requirement at one week for all three installations.

53 The failure during an outage of a single networked EDG in a microgrid will not lead to a loss of load if the load is sufficiently below its annual peak during the outage.

54 The PI and NREL teams independently calculated the reliability of the baseline (no storage) microgrid as a starting point for their storage-enabled microgrid modeling. In so doing, Ameresco and EPRI used a Monte Carlo approach to achieve the same baseline microgrid results as displayed in **Figure 8**, while SRI/ASU used a Markovian matrix approach very similar to NREL's and achieved similar results. However, Raytheon used a conservative, restricted Markovian matrix approach which provides a lower bound for the probability of serving critical loads and, thus, underestimates the true probability.

55 An N microgrid is one where the number of EDGs is selected to just exceed the annual peak critical load. An N-1 microgrid has one less EDG than an N microgrid.

## 4.2. Battery Storage-Enabled Microgrids

As with the prior section, this one focuses on results from three of the seven installations: Fort Bliss, NAS Patuxent River, and Holloman AFB.[56] To understand the different reliability performance of storage-enabled microgrids at the installations, it is useful to compare the sizing and number of DER in the microgrids. **Figure 10**, **Figure 11**, and **Figure 12** provide such DER information and are supplemented by information in **Section 2** and **Appendix E** of this report and in the PIs' published reports.

**Figure 10** illustrates the size of on-installation PV compared to the average critical load.[57]

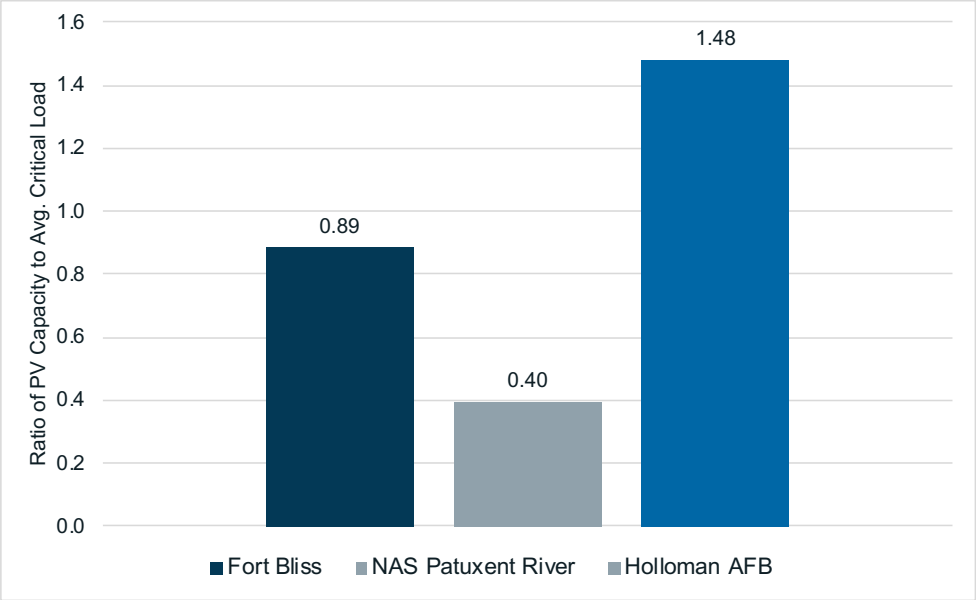


**Figure 10. Ratio of PV Capacity to Average Critical Load at Three Installations**

PV capacity varies from just 40% of average (not peak) critical load at NAS Patuxent River to almost 150% at Holloman AFB. Other factors equal, higher ratios indicate that more solar power generation can contribute to energy security at the installation.

The size of the BESS and the number of EDGs eliminated are critical in determining the storage-enabled microgrid system reliability. The BESS size is driven by the economic opportunities at the installation, the battery technology chosen, and the optimization process used. **Figure 11** displays the BESS power level in relation to the size of each EDG in the microgrid.

56 In **Appendix E**, reliability results for all seven installations are provided.

57 Average critical load is the mean of the 8,760 hourly critical load levels throughout the year.

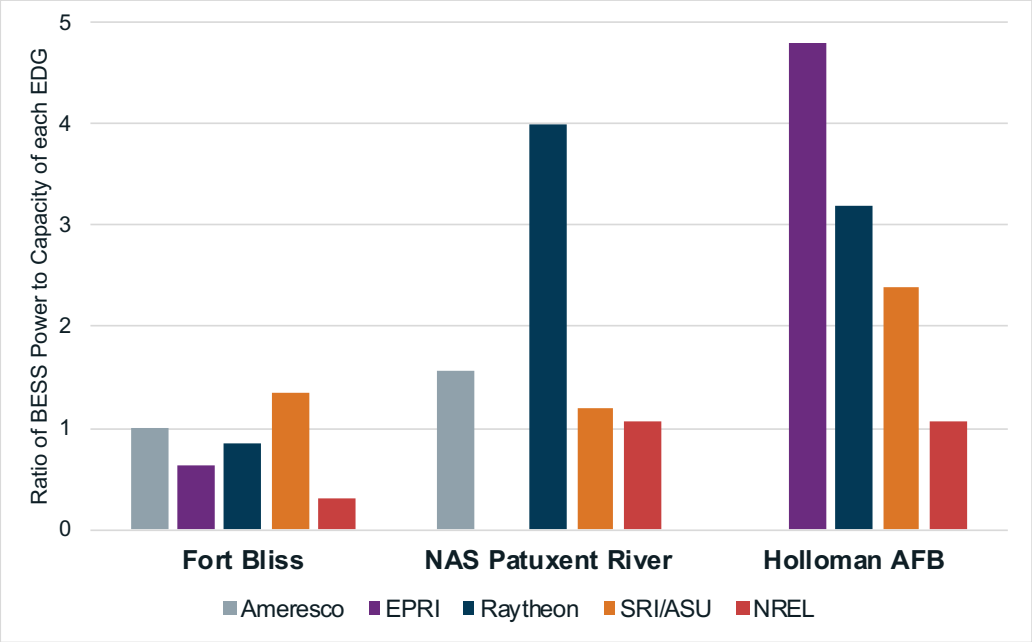


**Figure 11. Ratio of BESS Power to Individual EDG Capacity at Three Installations[58]**

From **Figure 11**, one can see that the PI and NREL teams sized BESS at Fort Bliss, where there are limited market participation opportunities and larger individual EDGs, at roughly the same or less capacity than a single EDG. There was more diversity in BESS choices among teams at the other installations, driven by the complex interplay of market opportunities and optimization processes that each team pursued. The results shown in **Figure 11** are for Li-ion BESS for all PIs except Ameresco, which has a flow BESS portrayed.

**Figure 12** shows the number of EDGs each team chose to eliminate from the baseline microgrid.

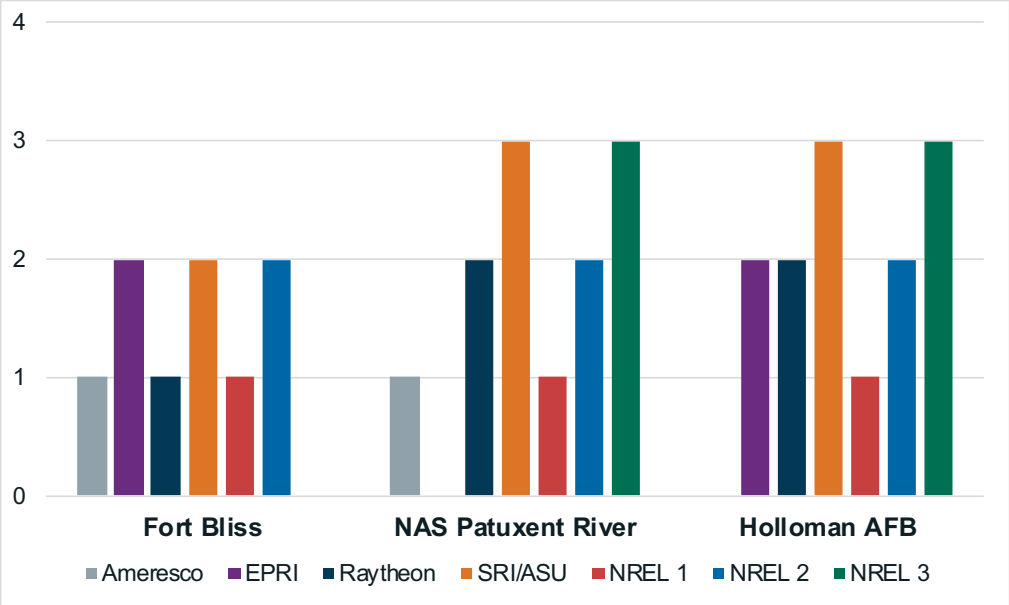


**Figure 12. Number of EDGs Eliminated in Storage-Enabled Microgrids at Three Installations**

58 Holloman AFB and NAS Patuxent River were modeled with 750 kW EDGs, while Fort Bliss was modeled using 2,000 kW EDGs. EPRI did not model NAS Patuxent River and Ameresco did not model Holloman AFB, which is why bars are not shown for those contractors at the installations. For EPRI's ratios in this chart, BESS power of 1,255 kW at Fort Bliss and 3,600 kW at Holloman AFB were used (EPRI's report has a range from 1,225 to 1,255 kW of BESS power at Fort Bliss and 3,600 to 3,800 kW of BESS power at Holloman AFB).

NREL modeled removal of one, two, and three EDGs for each installation.[59] The four PIs were free to make tradeoffs between cost and reliability as long as the reliability performance surpassed the ESTCP requirement. There is no correct or best solution. Ultimately, each installation will need to decide on the value of cost reduction versus reliability depending on its mission and risk tolerance.

The reliability performance curves that result from the DER asset and optimization choices of the PI and NREL teams for NAS Patuxent River are shown in **Figure 13** and **Figure 14**. **Figure 13** is plotted on a scale of 0% to 100% to show a comparison with single EDG, building-tied systems. All microgrid configurations outperform a building-tied system even if two EDGs are deployed at each building. **Figure 14** shows the results on a scale of 80% to 100% to illustrate more clearly the differences between the various storage-enabled microgrids. On this scale the results for a single EDG tied to each building are not visible.

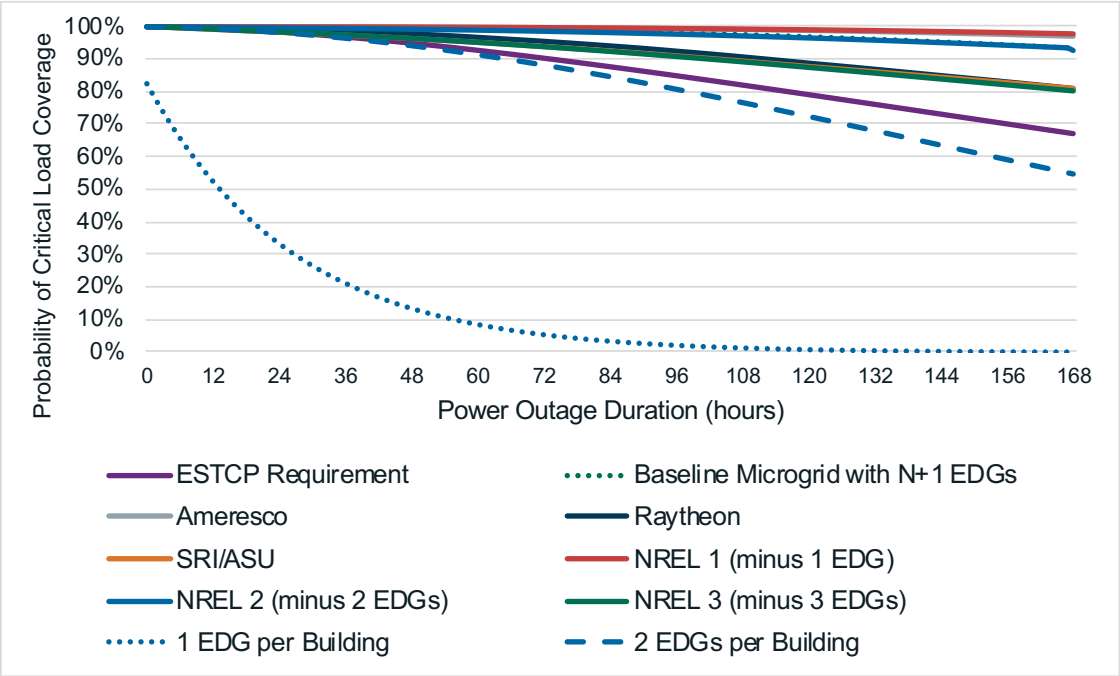


**Figure 13. Probability of Fully Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River: Baseline and Storage-Enabled Microgrids vs. Single and Double Building-Tied EDG Systems (probability scale of 0% to 100%)**

59 Because removing three EDGs caused reliability performance to be below the ESTCP requirement at Fort Bliss, "NREL 3" results are not displayed for that installation.

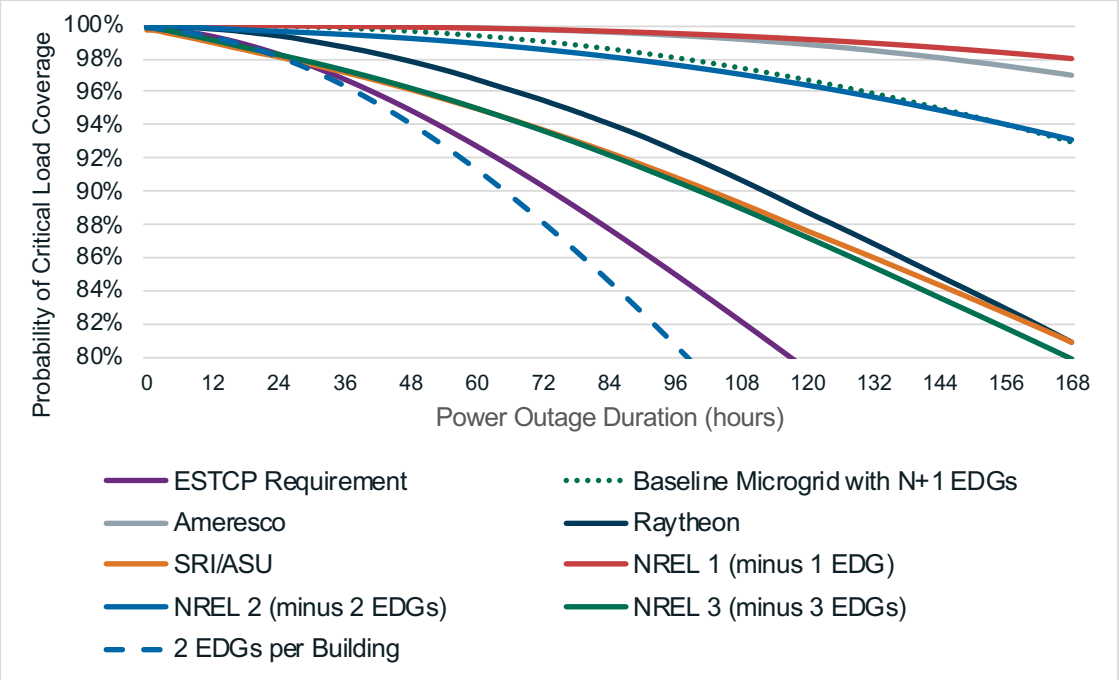


**Figure 14. Probability of Fully Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River: Baseline and Storage-Enabled Microgrids vs. Double Building-Tied EDG Systems Only (probability scale of 80% to 100%)**

**Figure 13** and **Figure 14** indicate that all battery storage-enabled microgrids exceeded the ESTCP performance requirement.

The NREL 1 system, which eliminated only a single EDG at the installation, showed the highest reliability performance, consistently exceeding baseline microgrid performance (and doing so a lower lifecycle cost as described in **Section 3** of this report). NREL 1 optimized performance, at the expense of further cost reductions.[60]

The NREL 2 system, which eliminates two EDGs, essentially matches the performance of the baseline microgrid. The Raytheon storage-enabled microgrid eliminates two EDGs at NAS Patuxent River and has lower reliability performance than the baseline microgrid due to Raytheon's conservative calculation methodologies.

The NREL 3 and SRI/ASU systems both eliminate three EDGs, yet still exceeded the ESTCP requirement. They do not, however, perform as well as the baseline microgrid (which has three more EDGs, but no BESS). In the NREL 3 and SRI/ASU cases, microgrids with BESS were optimized for greater cost savings over higher performance.

The BESS power sizes selected by SRI/ASU, Ameresco, and NREL for NAS Patuxent River were similar. Raytheon's larger BESS was selected largely for economic reasons, to gain revenues from PJM ancillary service markets and allow elimination of some UPS units. The strong reliability performance of all storage-enabled microgrids was achieved even with the modest PV capacity assumed for NAS Patuxent River

### Reliability Considerations for Small Military Bases

The three bases discussed in this section have peak critical loads of 6, 8, and 12 MWs. Small bases often have peak critical loads on the order of only 1 MW. March and Westover ARBs are typical of such smaller bases and require only four EDGs to support a diesel-only microgrid. When the number of buildings with critical loads becomes small, the performance difference between a microgrid and a building-tied system narrows (4).

ESTCP's microgrid performance requirements for these small bases are higher than the larger bases, 95%+ coverage of critical loads at one week. Combined with the small number of EDGs at these bases, that means that more than one EDG cannot be removed while still meeting the reliability requirement. Nevertheless, it is possible to design a storage-enabled microgrid with lower lifecycle cost than the baseline microgrid, as all teams relying on Li-ion BESS as their primary technology did.

60 Ameresco also eliminated only one EDG at NAS Patuxent River and, in so doing, achieved high reliability performance. Due to its use of an emerging BESS flow technology and for other modeling reasons, it did not identify cost savings from including BESS in the microgrid.

relative to the installation's critical load. In contrast to the microgrids, building-tied EDG systems are unable to meet the ESTCP performance requirement.

**Figure 15** displays reliability performance at the end of a 168-hour outage for NAS Patuxent River, as well as for Fort Bliss and Holloman AFB.

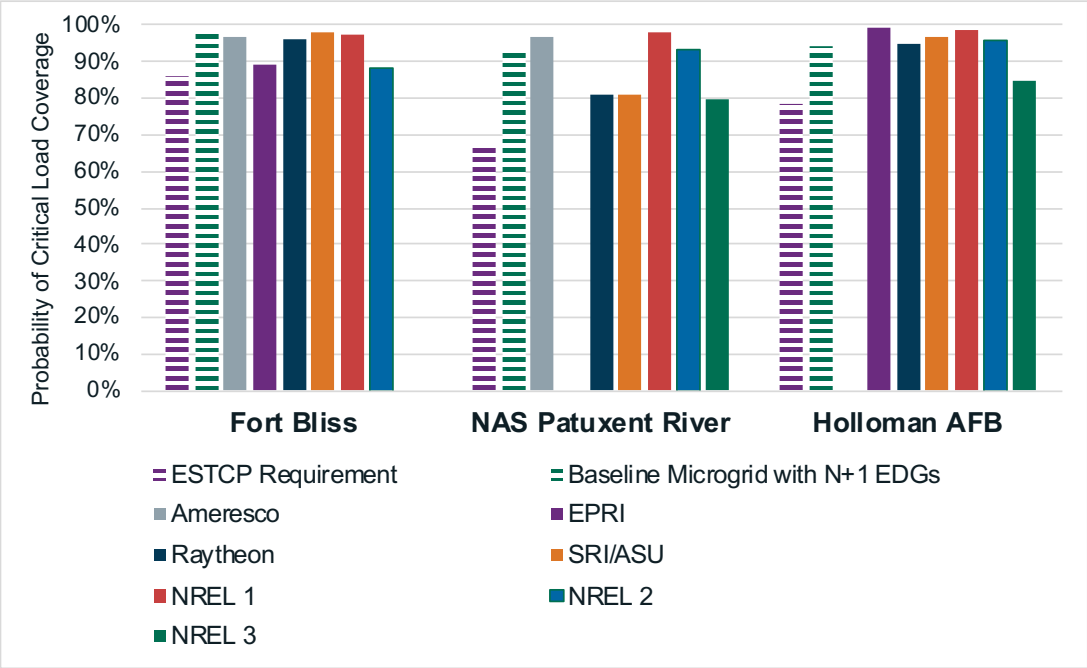


**Figure 15. Probability of Microgrids Fully Meeting Critical Loads by the end of One-Week (168-hour) Power Outages at Three Installations**

By design, all microgrids shown exceeded the ESTCP performance requirement (the purple striped bars in this chart).[61]

At Holloman AFB, all storage-enabled microgrids except NREL 3 also exceeded baseline microgrid performance (green striped bar in the chart) at a lower lifecycle cost. This is partly because the ratios of (i) PV capacity to critical loads, and (ii) BESS to EDG capacity are higher at Holloman AFB than at the other two installations.

In contrast to Holloman AFB, none of the storage-enabled microgrids performed as well as the baseline microgrid at Fort Bliss. This is largely due to the BESS being sized smaller than an EDG (which was done for economic reasons to minimize BESS costs in the face of limited electricity market savings opportunities at Fort Bliss).

61 The NREL 3 system, which eliminates 3 EDGs, was unable to meet the minimum ESTCP requirement at Fort Bliss and is not shown.

## 4.3. Additional Performance Benefits

Battery storage-enabled microgrids provide performance benefits beyond improved reliability. Although not the focus of the ESTCP assessments, battery storage allows greater exploitation of on-installation solar power to both extend diesel fuel supplies (that would otherwise be used by EDGs) and provides limited support for critical loads after diesel fuel supplies have been exhausted. Both of these issues can be important if installations are faced with long-term grid outages and re-supply of diesel fuel is constrained.

The reduction in diesel fuel consumption during a power outage is directly correlated with the ratio of PV assets to installation critical loads. So, at an installation such as Holloman AFB with considerable PV capacity relative to its critical loads, a significant amount of diesel fuel can be conserved, allowing missions to be served longer.

By the time that all diesel fuel is depleted at an installation, it is likely that many missions will have been transferred to other installations, and critical loads will be significantly smaller than at the start of the outage. Microgrids with very long duration energy storage could be designed for that contingency.

Though the storage-enabled microgrids in the ESTCP assessments were not designed for that contingency (diesel fuel exhaustion), ESTCP did request that PIs examine how their systems would perform under such circumstances. Specifically, PIs calculated the probabilities of supporting 10% and 30% of installation critical loads for up to 24 hours without any fuel for EDGs. The results were that storage-enabled microgrids could reliably serve 10% to 30% of critical loads for the first few hours, but the probability drops quickly at installations with modest-sized PV assets. Results at 24 hours varied widely between PIs and installations.

At installations such as Holloman AFB with a relatively large amount of solar power in the simulated microgrids, some PIs' microgrids sustained 10% of the critical load for 24 hours. At a large installation such as Fort Bliss with modest PV assets relative to its scale, storage-enabled microgrids were not able to cover 10% of critical loads for 24 hours. These results are not surprising given that microgrids were not designed for a fuel exhaustion contingency, but the results point to the fact that storage-enabled microgrids allow for a more orderly ramp down and transfer of critical loads during an extended grid outage when diesel fuel supplies are limited.[62]

Though ESTCP fixed the amount of PV at each installation for modeling consistency, the SRI/ASU team performed additional analyses showing that increasing PV capacity, paired with larger BESS, led to even better reliability performance and greater economic savings at a sample installation.[63]

62 Including battery storage in a microgrid also reduces wear on EDGs and allows these assets to operate closer to manufacturer's design conditions, which can extend EDG system life and improve fuel efficiency.

63 See (6), pp. 64-68.

# 5. Conclusion: Acting on Key Findings

Fixed military installations cannot support their critical mission without reliable power. Multi-day utility grid outages are becoming more frequent and represent an increasing risk to the DoD mission. To address this risk, DoD is pursuing the deployment of microgrid technologies to provide improved energy security. In parallel, DoD also has been working with the private sector to develop solar power assets on military installations. Although of economic value, solar assets cannot be the backbone of an energy security solution in the absence of energy storage or dispatchable generation. This report summarizes the results of recent ESTCP assessments to isolate under what conditions battery storage can cost-effectively and materially enhance energy security within a military microgrid. ***Integrated into a microgrid, battery storage can play a key role in DoD energy assurance by providing increased energy reliability at lower lifecycle costs than a microgrid without battery storage.***

Li-ion battery storage systems on the order of a few MWs added to on-installation solar power, EDGs, UPSs, and a microgrid can significantly lower energy security lifecycle costs. There are three main savings and cost categories when battery systems are added to microgrids: 1) retail and wholesale electricity market savings or revenues; 2) reductions in the number of EDG and UPS assets needed to deliver reliable power during grid outages; and 3) investment costs for the battery storage systems. Emerging battery systems such as flow batteries are too expensive to justify their use today. That may change as the technology matures and prices decrease. Optimal battery power levels and duration, and resulting cost savings, depend on the installation power reliability needs, local electricity market opportunities and utility rate structures, and solar resources. ***A site-specific assessment should be undertaken that considers all these factors in detail before deciding on what battery system size should be selected.***

Back-up power systems should be judged on their ability to provide power to critical loads for the full duration of grid outages. ESTCP focused on a performance metric allowing that judgment -- the probability that all critical loads will have power across outages of one hour to one week. Depending on how many EDGs are eliminated (1, 2, or 3), battery system size and duration, and load characteristics, the ESTCP assessments found that microgrids with storage may perform better than a baseline (EDG-only) microgrid, but always outperform the ESTCP requirement and significantly outperform any building-tied EDG system. ***Integrating battery storage into a microgrid allows installations to introduce a very flexible asset type and increase exploitation of inside-the-fence, intermittent solar power for energy security purposes.***

Battery storage provides flexibility in designing a microgrid and facilitates trade-offs between performance and cost. The use of storage integrated into a microgrid also can extend supplies of on-base diesel fuel. Additional system reliability metrics can easily be calculated to aid in design, such as the expected lost load or probabilities that different tiered priority critical loads will be supported as a function of outage duration. Reliability metrics should be combined with projections on the frequency and duration of future power outages to calculate impacts on various missions. ***Ultimately, to design and procure an optimal storage-enabled microgrid requires comparing performance and cost trade-offs in the context of mission needs. It also requires a focus on buying performance and investing in sustainment, rather than simply buying equipment.***

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# Appendix A: Methodologies and Limitations of Analysis

The Phase I research for ESTCP was structured so that all PIs had the same realistic set of starting conditions and the same performance requirements. Their responsibility was to dedicate their technical, analytic, and market expertise to demonstrate if and precisely how adding battery storage to a military microgrid can meet or exceed the cost and performance requirements of a microgrid without storage.

Below is a brief overview of the shared starting conditions, cost and performance requirements, and limitations of the Phase I work. Individual PI reports describe their methodologies in detail.

## A1. Selection of Installations

ESTCP coordinated within DoD and individual Service organizations, including the U.S. Army Office of Energy Initiatives (OEI), the USAF Office of Energy Assurance (OEA), and the U.S. Navy Resilient Energy Program Office (REPO), to identify and engage seven installations that are a representative cross-section of the size, mission, geography, and electricity markets of installations nationwide and that had the interest and data required to serve as test sites for the analysis.

These seven installations range from two air reserve bases (Westover and March), that are the smallest installations studied, to three mid-sized installations (Naval Base Ventura County, Holloman AFB, and NAS Corpus Christi), and two large installations (NAS Patuxent River and Fort Bliss). The peak critical and non-critical electricity load (or "demand"), along with annual total peak load, for each installation are listed in **Table A-1**. The table also identifies the subset of critical loads requiring "ride-through" at each installation.[1]

**Table A-1. Electricity Loads Assumed for Military Installations Studied (all data in kW)**

| Military Installation | Peak Critical Load | *Portion of Peak Critical Load Requiring Ride-Through* | Peak Non-Critical Load | Overall Peak Annual Load (Critical + Non-Critical) |
|---|---|---|---|---|
| **March ARB** | 600 | *350* | 7,398 | 7,998 |
| **Westover ARB** | 1,707 | *900* | 1,707 | 3,414 |
| **Naval Base Ventura County** | 4,003 | *2,000* | 10,989 | 14,992 |
| **NAS Corpus Christi** | 4,410 | *2,000* | 19,555 | 23,965 |
| **Holloman AFB** | 5,996 | *3,000* | 9,994 | 15,990 |
| **NAS Patuxent River** | 8,014 | *4,000* | 25,944 | 33,958 |
| **Fort Bliss** | 12,507 | *6,000* | 55,098 | 67,605 |

PIs were each required to analyze five of the seven installations that were the best test cases for their solutions, including at least one installation from each Service.

1 For the PIs' **reliability analyses**, only the critical load and the subset of that critical load requiring ride-through were relevant. Ride-through is necessary for electricity loads that cannot withstand a power loss of more than several milliseconds without losing important functionality, such as computer systems. Ride-through loads are typically backed-up by UPS, though some of the battery systems analyzed by the PIs are configured to perform ride-through themselves, enabling the reduction in the number of UPSs at installations. For PIs' **economic analyses**, the total electricity consumption and peak demand for the installations were also relevant.

## A2. Data on Starting Conditions

**The installations provided ESTCP with data to use in the analyses including:**

- Hourly or sub-hourly electricity consumption data for at least one year;[2]
- Electricity costs and utility rate structure;
- Aggregate amounts of critical load (backed up by EDGs) and critical ride-through load (backed up by UPSs);
- Existing and planned solar PV projects; and
- Demand response program participation.

ESTCP masked the electricity consumption information into hourly data for a typical year, using random statistical variation while preserving realistic consumption patterns, before providing it to the PIs.

In addition to the installation data, ESTCP provided PIs with two sets of hourly prices for physical energy and various ancillary services in the California ISO (CAISO), ERCOT (Texas), PJM (Mid-Atlantic), and ISO-NE wholesale electricity markets. PIs used a set of "current" market prices to simulate how much their storage-enabled microgrids would earn from market participation and a set of "future volatile" prices to gauge how their microgrid economics would differ in years when electricity market prices have a more spiked (volatile) pattern and, therefore, more high-value opportunities for storage participation. Both sets of prices were established by ESTCP from historic prices in the individual markets.

ESTCP also provided data on regional diesel fuel prices, demand response program rules, and baseline asset (EDG, UPS, and microgrid) cost and performance as part of the starting conditions for the PI simulations and created detailed baseline microgrid economic and reliability results (described in **Section 3** and **Section 4** of this report) against which the PIs' storage-enabled microgrid results were compared. The DER -- EDG, UPS, and PV -- unit sizes and quantities assumed for each installation are displayed in **Table A-2**, and the EDG and UPS cost assumptions are in **Table A-3**.[3,4]

**Table A-2. Distributed Energy Resources Assumed for Baseline (No Storage) Microgrids**

| Military Installation | PV Size (kW-AC) | Size of each EDG (kW-AC) | Number of EDGs | Size of each UPS | Number of UPSs |
|---|---|---|---|---|---|
| **March ARB** | 400 | 250 | 4 | 250 kVA<br>63 kWh | 3 |
| **Westover ARB** | 2,000 | 750 | 4 | 250 kVA<br>63 kWh | 5 |

2 Hourly electricity loads were taken as fixed. PIs were not allowed to change the starting load shape nor annual electricity consumption by introducing energy efficiency or other demand-side energy measures (though PIs can and did dispatch EDGs and BESS to alter net load shapes post-microgrid). This limitation on starting loads was included to isolate the value of BESS in a microgrid and avoid any cross-subsidization of demand-side measures with BESS. The PV capacity and hourly output profiles at installations were also fixed (not able to be changed by PIs) for the same reason.

3 For data availability and modeling consistency reasons, PV power was assumed to be purchased by the installations at the same average electricity costs as grid power.

4 In addition to the costs of DER, the baseline microgrid requires costs for the microgrid itself. Based on industry research and calibration to the characteristics and scale of each installation, that capital cost was assumed to be $2 million (at the two reserve bases) to $4 million (at NAS Patuxent River) depending on the installation scale and number of DER, with additional fixed annual O&M costs beginning at $67,000 (at the two reserve bases) to $133,000 (at NAS Patuxent River) in year 1 and escalating 2.2% annually thereafter. The other four installations (Naval Base Ventura County, NAS Corpus Christi, Holloman AFB, and Fort Bliss) had assumed microgrid capital costs of $3 million and starting annual O&M costs of $100,000. The microgrid capital costs cover: microgrid controller and other required information technology and operational technology; switchgear upgrades; electricity market participation software; communications, monitoring, and metering improvements; upgraded inverter/power control system that meets standards; necessary building enclosures; grid interconnection engineering; system integration; permitting; testing and commissioning; and training.

| Military Installation | PV Size (kW-AC) | Size of each EDG (kW-AC) | Number of EDGs | Size of each UPS | Number of UPSs |
|---|---|---|---|---|---|
| **Naval Base Ventura County** | 830 | 750 | 7 | 250 kVA<br>63 kWh | 9 |
| **NAS Corpus Christi** | 1,200 | 750 | 7 | 250 kVA<br>63 kWh | 9 |
| **Holloman AFB** | 5,000 | 750 | 9 | 250 kVA<br>63 kWh | 13 |
| **NAS Patuxent River** | 2,000 | 750 | 12 | 250 kVA<br>63 kWh | 17 |
| **Fort Bliss** | 6,200 | 2,000 | 8 | 2,000 kVA<br>500 kWh | 4 |

**Table A-3. Distributed Energy Resources Cost Assumptions (applicable to baseline and storage-enabled microgrids)**

| Distributed Energy Resource Type | Capacity | Capital Cost | Annual O&M Cost (in year 1) | Variable O&M Costs |
|---|---|---|---|---|
| **EDG** | 250 kW | $1,100/kW | $6,500 | N/A |
| **EDG** | 750 kW | $750/kW | $7,000 | |
| **EDG** | 2,000 kW | $600/kW | $20,000 | |
| **UPS** | 250 kVA<br>63 kWh | $647/kVA | $13.66/kVA | $4.39/MWh |
| **UPS** | 2,000 kVA<br>500 kWh | $486/kVA | $5.98/kVA | $1.21/MWh |

As a basis for comparison to storage-enabled microgrids of PIs funded under ESTCP's fiscal year (FY) 2019 Large-Scale Storage and Microgrids topic, NREL utilized its REopt model to produce economic results for all seven military microgrids. NREL also performed reliability modeling on storage-enabled microgrids at the installations. The NREL assumptions and results are shown throughout the report alongside the PIs' information, and NREL's analytic process is briefly described in **Appendix G**.

## A3. Limitations

The Phase I analysis involved detailed hourly simulation of storage-enabled microgrid performance over a 20-year period compared to an ESTCP-provided baseline microgrid without battery storage. It involved largely desktop analysis conducted with sophisticated modeling tools and approaches by PIs and NREL with practical experience. The limitations of the approach are those inherent to desktop analyses – they cannot fully simulate mechanical and information technology (IT) system integration and performance nor the physical and behavioral constraints of field deployment. An additional limitation was the exclusion of on-installation electric distribution system constraints from the Phase I analysis.

To address those limitations and build on the Phase I analysis, ESTCP is investing in two subsequent R&D phases, shown on **Figure A-1**. In that figure, "CHIL" refers to (microgrid) controller hardware-in-the-loop testing, while "PHIL" refers to power hardware-in-the-loop testing.[5]

Phase II is being conducted by the three PI teams with the most promising Phase I results and strongest plans to test key storage system components and their integration with actual microgrid controllers and other DER in NREL's hardware-in-the-loop Energy Systems Integration Facility (ESIF) in Colorado.[6] That testing, beginning in FY 2020, will validate or expose weaknesses of key simulation factors and thereby inform and de-risk field tests at one or more military installations in Phase III beginning in FY 2021 or FY 2022 to reach full fidelity in the technology validation process.

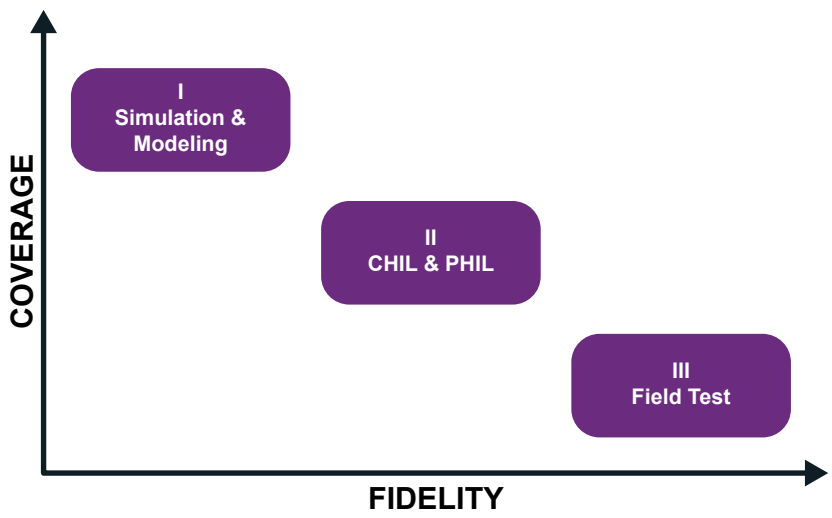


**Figure A-1. Schematic of Three-Phase R&D Approach for Storage-Enabled Microgrids**

5 PHIL involves interconnecting power hardware (e.g., EDG, PV inverter, battery storage [UPS and non-UPS]) to a simulated, real-time electric grid to perform rigorous tests of hardware and system performance. PHIL can include simulated integration of power hardware with a microgrid controller. CHIL is similar to PHIL, but necessarily includes use of a microgrid controller and does not include the physical connection of power hardware to the simulation. In CHIL testing, power hardware performance is represented by signals exchanged from its information ports to the controller. For more information on the distinctions between PHIL and CHIL, see (26).

6 The three PIs selected for Phase II projects are led by Ameresco, ASU, and Raytheon.

# Appendix B: Battery Storage System Cost and Performance Data

A secondary benefit of the Phase I analyses by PIs was their research on the cost and performance of BESSs appropriate for military microgrids. This research, which was informed by direct outreach to leading BESS providers in several cases, is particularly valuable because data on these systems tailored to military applications are rarely published.

In this appendix, key BESS costs (capital and O&M) and performance metrics are summarized from PIs completing their Phase I reports to date and are compared to other sources where appropriate.

## B1. Capital Costs of Initial System Deployment

Capital costs (also called "installed costs") cover the full cost of designing, engineering, financing, procuring, permitting, constructing, interconnecting, and integrating all components of the BESS.[1] Components include the direct current battery itself, associated racking, and battery and energy management systems as well as a power conversion system with an inverter to convert direct current (DC) to alternating current (AC) power, inverter controls, and a container with environmental control (e.g., Heating, Ventilation, and Air Conditioning [HVAC]) and fire suppression systems.

The PI reports had a wide range of capital costs depending on system size, duration (the ratio of energy to power), chemistry, and configuration. In **Table B-1**, a sample of the PI capital costs for Li-ion BESS is provided along with two additional sources.[2]

These capital costs, however, *exclude* replacement of the battery itself. Battery replacement is a function of both time and the number and depth of use cycles and often occurs every five to ten years. Battery replacement costs are identified in the next section on O&M and sustainment.

**Table B-1. Sample of Lithium-ion BESS Capital Costs (Pre-Incentive)**

| Research Source | Capital Costs ($/kWh of Energy) |
|---|---|
| **Raytheon[3]** | $554 |
| **SRI/ASU[4]** | $693 (Li-ion) $993 ($LiFePO_4$) |
| **Ameresco[5]** | $771 |
| **EPRI[6]** | $477 |
| **NREL REopt[7]** | $550 |
| **Lazard[8]** | $377 to $831 |
| **PNNL[9]** | $469 |

1 BESS costs can be expressed on both power ($/kW) and energy ($/kWh) bases.

2 Because flow system capital costs are not comparable to Li-ion costs (due to the much longer average durations of flow systems), they are not included in this table. Flow BESS cost details are provided in the Ameresco, EPRI, and SRI/ASU reports.

3 See (5), p. 60. Data are for a 2.50 MW, 3.25 megawatt-hour (MWh) BESS at Naval Base Ventura County, which does not include interconnection, communication, permitting, commissioning, ISO scheduling, and engineering design cost elements.

4 See (6), p. 9. The All Cell Li-ion BESS in SRI/ASU's report has the chemistry that is most directly-comparable to the BESS modeled by other PIs and NREL. In its economic analysis, SRI/ASU found that the Blue Planet $LiFePO_4$ battery combined with ultra-capacitors was the best choice at four of the five installations analyzed, and an Avalon flow battery combined with ultra-capacitors or an Eos Aqueous Zinc battery with ultra-capacitors was the best choice at the fifth installation (Westover ARB) See (6), pp. ES-6, 37-39.

5 See (7), p. A-31. Data are for a 3.5 MW, 7 MWh BESS at March ARB, not including 15% internal management and overhead cost nor pre-pay of battery replacement, but adding back incentives to make it a pre-incentive cost.

6 See (8), p. vi. Data are an unweighted average price across four installations with four-hour duration BESS, which have battery power of 1 MW to 4.6 MW.

7 NREL REopt data are for a two-hour duration BESS, such as the 1 MW, 2 MWh system at Naval Base Ventura County that it modeled.

8 Lazard data are for a 1 MW, 2 MWh BESS; see (22), p. 6.

9 Pacific Northwest National Laboratory (PNNL) data are for a 1 MW, 4 MWh BESS; see (25), p. 4.4.

## B2. O&M Costs and Sustainment

A frequent point of failure in military microgrids is lack of long-term investment in O&M. Due to DoD sustainment funding limitations on many microgrid components as well as lack of planning and staff training, some military microgrids have ceased to operate fully after their first several years. Therefore, it is essential to understand the O&M costs of important microgrid components, including BESS. For BESS, there are ongoing fixed and variable O&M costs as well as periodic costs for replacing the batteries themselves after they are depleted.

**Fixed O&M** costs are irrespective of battery use, cover planned and unplanned maintenance, and are typically expressed as an annual dollar amount per kW of battery system power.[10] Fixed O&M costs for the first year of system operation from the ESTCP PI reports, NREL's modeling, and a PNNL study are displayed in **Table B-2**.[11] These costs typically rise each subsequent year with general price inflation.

**Table B-2. Sample of BESS Fixed O&M Costs in Year 1 of Operation**

| Research Sources | Battery System Type | Annual Fixed O&M Cost ($/kW of Power) | Annual Fixed O&M Cost ($/kWh of Energy) |
|---|---|---|---|
| **Raytheon**[12] | Li-ion | $7.50 | $5.77 |
| **SRI/ASU**[13] | Li-ion | Up to $6.67 (Li-ion)<br>$4.00 ($LiFePO_4$) | Up to $10.00 (Li-ion)<br>$4.00 ($LiFePO_4$) |
| **Ameresco**[14] | Li-ion | $4.80 | $2.40 |
| **EPRI**[15] | Li-ion | $10.00 | $2.50 |
| **NREL REopt**[16] | Li-ion | $12.50 | $6.25 |
| **PNNL**[17] | Li-ion | $10.00 | $2.50 |
| | | | |
| **Ameresco** | Flow | $19.20 | $2.40 |

**Variable O&M costs** depend on how often the battery system is used and are expressed on an energy basis in $/kWh. A reasonable estimate of their cost is $0.0003/kWh.[18]

The largest sustainment cost for most Li-ion battery systems is the **replacement of the battery itself** every five to ten years depending on use patterns. This cost is estimated at $200/kWh to $238/kWh from a sample of installations in the ESTCP PI reports.[19]

10 These costs are also displayed on an energy basis ($/kWh) in the table for comparison.

11 For example, the Raytheon study O&M cost of $7.50/kW-year means that a 1 MW (1,000 kW) battery system would have a fixed O&M cost of $7,500 in its first year.

12 See (5), p. 60. Data are for a 1.3-hour duration BESS.

13 See (6), p. A-1. Consistent with the SRI/ASU BESS configurations, data were converted from $/kWh to $/kW for a 45-minute duration Li-ion BESS and retained as a 1-hour duration BESS for the $LiFePO_4$ chemistry.

14 See (7), pp. A-31 and A-35. Data are for two-hour duration Li-ion BESS and an eight-hour duration flow BESS at March ARB, excluding wholesale curtailment service provider costs and electrolyte replacement costs (for the flow battery).

15 See (8), p. vi. Data are for the four-hour duration BESS modeled at four of the five installations in the report.

16 NREL REopt data are for a two-hour duration BESS, like that modeled at Naval Base Ventura County.

17 PNNL modeled a four-hour duration BESS; see (25), p. 4.4.

18 See (25), p. 4.4.

19 Specifically, Raytheon estimates this cost at $200/kWh in year 10 of operation; see (5), p. 60. EPRI estimates that replacement will occur in year 7 of operation and cost half of the initial capital cost, or $238/kWh, on average, for the 4-hour duration BESS reviewed; see (8), pp. vi and 15. Battery replacement costs (also called "capacity enhancement costs") will vary based on battery power and duration. NREL used a replacement cost of $150/kWh in year 10 of operation for its REopt analysis.

## B3. Performance

Among the aspects of BESS performance, two key measures are profiled here: availability and roundtrip efficiency (RTE). Both measures were incorporated into PIs' and NREL's Phase I economic and reliability results.

**Availability** is the percentage of time annually that the BESS can perform. Typically, availability ranges between 95% and 99% depending on system specifics and location. While availability calculations often exclude planned maintenance, there are several other reasons that a battery system's availability can be below the maximum of 100%.

For systems using the most common battery chemistry (Li-ion), a common reason for availability reduction is temperature. The warrantees and standard operating procedures for BESS may not cover operating outside of certain temperature ranges. Unavailability can also be caused by ground faults, HVAC system outages (in conditioned spaces housing BESS for safe operation), and other factors.

The lower the availability of a BESS, the more installations will require traditional sources of back-up power supply (EDGs and UPSs) to maintain reliability during outages. Unavailability also lowers the potential for BESS participation in market activities (e.g., dispatch for frequency regulation or demand response events).

**RTE** describes the percentage of electricity that is turned into productive purposes through a full discharge and recharge cycle of the BESS. The simplified formula for RTE is 1 – (% average loss on discharge + % average loss on recharge).

RTE is important because it both reflects a cost[20] (beyond traditional O&M) of each BESS use and affects the sizing of electricity generation assets that supply the battery and of the battery itself. The lower the battery RTE, the larger generating assets need to be in a microgrid to offer the same level of microgrid capability. Due to its economic importance, BESS component manufacturers and integrators continue to seek technical and operational innovations to improve RTE.

The availability and RTE of BESS in the PI reports are listed in **Table B-3**, alongside these metrics from other recent studies. RTE tends to be higher for Li-ion than flow battery systems.

**Table B-3. BESS Performance Measures: Availability and RTE**

| Research Sources | Battery System Type | Availability | Roundtrip Efficiency |
|---|---|---|---|
| **Raytheon[21]** | Li-ion | 95% | 90% |
| **SRI/ASU[22]** | Li-ion | >99% (Li-ion)<br>99% ($LiFePO_4$) | 90% (Li-ion)<br>98% ($LiFePO_4$) |
| **Ameresco[23]** | Li-ion | Not provided | 85% |
| **EPRI[24]** | Li-ion | 98.6% | 91% |
| **NREL REopt** | Li-ion | 97% | 81.3% |
| **Itron[25]** | Li-ion | Not provided | 81% |

20 This cost represents what is paid for imported utility power or on-site generated power used by the BESS, but that is lost in the charge and discharge cycle. For example, if a BESS has RTE of 90%, then 10% of the power it receives is lost. The cost of that loss is essentially another type of operating cost.

21 See (5), p. 20.

22 See (6), p. A-1.

23 See (7), p. ES-5.

24 See (8), p. i.

25 See (23), p. 4.4.

| Research Sources | Battery System Type | Availability | Roundtrip Efficiency |
|---|---|---|---|
| **Sandia National Labs**[26] | Li-ion | Not provided | 81.6% to 82.9% (range for half-rated to full-rated performance; includes auxiliary load) |
| **PNNL**[27] | Li-ion | Not provided | 86% |
| **PNNL**[28] | Li-ion | Not provided | 83% to 91% (wo./ auxiliary load)[29] 70% to 87% (w./ auxiliary load) |
| | | | |
| **Ameresco**[30] | Flow | 93% | 76% |
| **EPRI**[31] | Flow | 98% | 71% |
| **PNNL**[32] | Flow | Not provided | 66% to 75% (wo./ auxiliary load) 58% to 65% (w./ auxiliary load) |

26 See (24), p. 3.

27 See (25), p. 4-4.

28 See (27), p. 21.

29 "Auxiliary load" refers to the electricity required for the BESS to operate. For Li-ion systems, this is often a modest issue and is often not explicitly referenced in RTE calculations. Because flow batteries have relatively large pumping systems, auxiliary loads are a more material issue in their performance, and it is useful to distinguish whether RTE includes or excludes the electricity consumption of these loads for flow systems.

30 See (7), p. 46 (for availability) and p. ES-5 (for roundtrip efficiency).

31 See (8), p. i.

32 See (27), p. 21.

# Appendix C: Reliability Data for Assets in Microgrids

## C1. Asset Reliability Overview

The performance of a microgrid depends on the reliability of its major assets, including the on-base DER which power the critical loads. Three types of DER are considered in this report: EDGs,[1] PV systems[2], and BESS.

To ensure a common baseline for the PIs' analyses, ESTCP established reliabilities for both EDGs and PV systems. Different BESS technologies and configurations were considered by each PI and, thus, each PI individually determined the reliability of its BESS. In this appendix, we review the component reliability assumptions used for modeling EDGs and PV systems.[3]

Unlike typical EDG and PV reliability assessments that estimate annual uptime or total asset lifetime to determine revenue potential and replacement cycles, reliability in this report pertains to DER performance during short, infrequent periods (hours to weeks) when grid power outages occur. That is, this study focuses on DER reliability when the microgrid system is in islanded mode.

**To model DER performance during microgrid islanded events requires up to four metrics:**

1. Operational availability: probability that a DER is available to provide power when an outage starts;[4]
2. Failure to start (FTS) probability: percentage of time that a DER fails to start in a manner that can supply electrical loads at the beginning of an outage;[5]
3. Mean time to fail (MTTF): average duration until a DER stops functioning after it starts operating; and
4. Repair duration: average time to repair a DER that fails (at start or during operation).

The formulae for these asset reliability metrics are below.

$$Operational\ Availability = \frac{Lifetime - Time\ offline\ due\ to\ repairs, maintenance, etc.}{Lifetime}$$

$$Failure\ to\ Start\ Probability = \frac{number\ of\ failures\ to\ start}{number\ of\ attempts\ to\ start}$$

$$Mean\ Time\ to\ Fail = \frac{total\ runtime}{number\ of\ failures\ while\ running}$$

$$Repair\ Duration = \frac{sum\ of\ time\ to\ complete\ all\ repairs\ after\ failure\ is\ detected}{number\ of\ repairs}$$

1 An EDG includes all components required to output electrical power, including the transfer switch.

2 A PV system includes PV modules, inverters, and the balance of system. Inverters are the component that converts DC power collected by the module into AC power used by the military installation.

3 BESS reliability metrics are described in **Section 4** and **Appendix B** of this report.

4 A DER can be offline (i.e., unavailable) for reasons including general maintenance, repairs, or operating conditions being outside of DER design or engineering parameters.

5 EDGs, which are typically operated infrequently, sit in "cold states" most of the year until they are operated for routine testing and emergency operations.

# C2. Emergency Diesel Generator Reliability

## C2.1. Approach Tailored to ESTCP Analysis

Because EDG reliability is a key component of military energy security performance, within and apart from microgrids, ESTCP supported a new analysis of existing U.S. Army Corps of Engineers (USACE) Power Reliability Enhancement Program (PREP) (13) data and a Navy-sponsored data set (14). This analysis, performed by NREL, was based on thousands of EDG-years of fielded commercial data collected by the U.S. Army and Navy. The NREL analysis found that new EDGs of 10 kW to 2,000 kW in capacity should have the values in **Table C-1** if they follow proper maintenance and testing protocols. These are the values used in all of the PI studies, as well as NREL's independent analysis of microgrid performance.

**Table C-1. EDG Reliability Assumptions for ESTCP PI Microgrid Studies**

| Reliability Metric | Value |
|---|---|
| **Operational Availability** | 99.9%[6] |
| **FTS** | 0.2% |
| **MTTF** | 1,700 hours |
| **Repair Duration (during islanded operation)** | N/A[7] |

A poorly-maintained EDG will have much worse reliability than in the above table. Such EDGs can have an MTTF of only 61 hours and FTS of nearly two percent (15).

## C2.2. Standard Industry Approach and its Limitations for Analyzing Performance During Power Outages

The standard source for reliability data for equipment used in industrial and commercial power systems is the Institute of Electrical and Electronics Engineers' (IEEE's) Gold Book (16), recently updated in IEEE's *3006.8 Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems* (17). The IEEE reports are based on data from two major data collection efforts conducted by PREP (13), with reliability data identical to that reported in the *U.S. Army Technical Manual* (18). The data reported by IEEE and the U.S. Army for EDG reliability are inadequate and inappropriate for assessing EDG back-up power performance during grid outages (12) for three reasons:

- IEEE and PREP only report annual failure rates, which are not relevant for assessing the run time failure rate of an EDG during a grid outage;
- The probability of an EDG failing to start and carry the load is a well-recognized failure event, but IEEE and the underlying PREP data do not provide this key reliability statistic; and
- The repair duration reported by IEEE does not include the logistics (e.g., failure notification, parts acquisition, staff scheduling, transportation of parts and labor to site) associated with a repair. It reports only the time required to make the repair once the needed parts and labor are on-site.

Due to these shortcomings in existing data sources, ESTCP followed the *EDG* reliability approach described in sub-section C2.1 above. None of the external sources reviewed (IEEE references, *U.S. Army Technical Manual,* or PREP) contain reliability data for *PV systems* or large-scale *BESS*.

6 The very high operational availability reflects the both the limited usage of EDGs during a year (the opportunities to fail and require a repair are infrequent) and typical short times for maintenance. EDG maintenance time has a mean value of 1.7 hours (13). For assessing the performance of an EDG to provide power *during extended outages*, this ESTCP analysis assumes that unavailability due to scheduled maintenance is not relevant (15).

7 For this ESTCP analysis, it was assumed that an EDG failing to start or failing after operating in an islanded event will not be repaired until grid power is restored. That is because, during extreme grid events (multi-hour to multi-day outages), it is unlikely that EDG parts and technical staff will be readily available to diagnose the failure and repair the EDG. For reference, the mean time to repair an EDG is 37 hours (12), with the vast majority of repairs not occurring during long grid outages.

# C3. PV System Reliability

## C3.1. Reliability Concepts Applicable to PV Generation

For the Phase I modeling, the seven military installations had on-site PV arrays between 400 $kW_{AC}$ and 6,200 $kW_{AC}$ in capacity, which are typical sizes for large commercial-scale or small utility-scale PV. For the modeling, it was important to determine if downtime of these PV arrays due to system failures should be considered a meaningful factor during grid outages. Existing literature on PV system reliability was reviewed for this purpose.

Downtime (i.e., reliability) calculations for the PV system are not connected to availability of sunlight. Local solar conditions, on an hourly basis, are already part of the PV electricity production profiles provided to PIs for Phase I analysis. Rather, PV reliability is the likelihood that the system can produce the expected power for the given local solar condition at any time.

## C3.2. PV Reliability Assumption for ESTCP Phase I Analysis

The same four reliability metrics (operational availability, FTS, MTTF, and repair duration) discussed for EDGs can be reviewed for PV systems.

The *operational availability* of a PV system depends on both the rate of system failures and the time it takes to make repairs. A system that is repaired quickly will still have a high availability even if the failure rate is high. One can estimate the availability by measuring the actual, systemwide energy yield in the field divided by the ideal energy yield. This is a more empirically accurate approach than using guaranteed availability stipulated in solar power contracts (19) (20).[8]

Unlike an EDG, unavailability of a PV system is not typically an all-or-none proposition. A PV system with multiple inverters would only lose partial power if a single inverter failed.[9] Likewise, failure among a string of panels would not eliminate all electricity production, but only the portion served from that string. The infrequent, modest availability losses typical of PV systems means that it is highly likely that these systems will have sufficient generating capacity available if a grid outage occurs. Thus, ESTCP assumed the PV systems should be treated as having 100% operational availability at the start of an outage.

Because PV systems are meant to be continuously operational (except during the very small number of hours per year they are taken off-line for maintenance or safety reasons), the *FTS* metric is not applicable.

To predict the *MTTF* of a PV system as a function of the outage duration requires estimates of system component failure rates and explicit information on the design of the PV system (21). For this report, the issue was simplified by reviewing only the main cause of large-scale failures, the inverters. This is justified by the extremely low frequency of failures for PV modules and balance of system components (20). Conservative estimates were applied: centralized inverters have failure rates of $7.4 \times 10^{-5}$ per hour, and string inverters have failure rates of $1.5 \times 10^{-5}$ per hour (21). Using those inverter MTTF rates, fault tree analysis for two common PV configurations was conducted. The analysis showed that the PV system will lose less than 1% of its rated capacity by the end of a one-week outage.

Because it is assumed that PV systems have 100% availability, the *repair duration metric* is not relevant during a grid power outage.

8 Contractually-guaranteed availability is typically between 97% and 99%. Contract guarantees reflect not what is commonly-achieved, but what is safe to guarantee and transact against with high confidence.

9 The most common cause of significant PV failures are inverter failures (17). Mid-sized to large PV systems like those modeled in this Phase I analysis often have multiple inverters, though they could have a single, central inverter.

# Appendix D: Highlighting Additional Content in PI Reports

While this study focuses on the economic and reliability metrics seen as central to BESS and microgrid decision-making for military installations, there are many other elements from the PIs' published analyses that advance the state of knowledge for battery storage in military microgrids.

Some of these elements are shared across the reports – for example, all PIs reviewed how long the microgrid could supply power during outages if peak critical loads were 30% above historic peaks and if on-installation diesel fuel supply was exhausted. Likewise, all PIs conducted extensive research into BESS cost and performance. Highlights of that cost and performance research are profiled in **Appendix B** of this study and more details are in the individual PI reports.

In varying ways, the PIs produced economic results for additional metrics, such levelized cost of energy, internal rate of return, and NPV. They also ran additional scenarios beyond the standard case summarized in this report. The scenarios describe how outcomes differ if electricity market prices, storage cost incentives, and solar production change from baseline values provided by ESTCP. Other unique and noteworthy elements of PI reports are identified in **Table D-1**.

**Table D-1. Selected Unique Elements in PI Analyses**

| Lead PI[1] | ESTCP Project # | Project Title | Example Elements of Analysis |
|---|---|---|---|
| **Ameresco** | EW19-5312 | *Demonstrating the Benefits of Long-Duration, Low-Cost Flow Battery Storage in a Renewable Microgrid* | Detailed review of flow battery system operation in comparison to Li-ion system and deconstruction of flow system cost and performance into granular detail. |
| **EPRI** | EW19-5046 | *Energy Security for Military Installations through Optimized Integration of Large-Scale Energy Storage into Microgrids* | Detailed battery system state of charge analysis for Li-ion and flow systems and inclusion of flow system costs from four vendors of this emerging technology. |
| **Raytheon** | EW-19-5163 | *Advanced Phasor-based Control of Energy Storage Micro-grids* | Utilizing high-speed, phasor-based control and switchgear to improve microgrid performance while de-centralizing storage systems to bolster resilience and allow reduction of redundant UPS investments. |
| **SRI/ASU** | EW19-5277 | *Design, Modeling, and Control of Hybrid Energy Storage System for Defense Installation Microgrids* | Side-by-side analysis of six battery storage chemistries/types and review of combining ultra-capacitors with other battery types. |

For more information, readers are encouraged to review the PIs' full reports on the ESTCP website: **https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/(list)/1/.**

1 The PI teams had the following members that are listed in parentheses, in addition to their lead organizations: Ameresco (2ndPath Energy); EPRI (Lockheed Martin, PowerSecure, and Southern Company); Raytheon (Customized Energy Solutions and PXiSE Energy Solutions); and SRI/ASU (350Solutions and XENDEE Corporation).

# Appendix E: Installation-Level Results

To supplement the comparisons in **Section 3** and **Section 4** of this report, below are results for the key economic and reliability metrics at seven individual installations. For each installation, there is a:

- Bar chart with the percentage cost savings of the storage-enabled microgrid versus the baseline microgrid without battery storage. Positive chart percentages designate improved economics;[1,2]
- Table with cost metric data as well as sizing of the BESS and the number of EDGs eliminated after inclusion of storage in the microgrid;[3,4] and
- Graph indicating reliability performance of storage-enabled microgrids for outages of 1 to 168 hours vs. the ESTCP requirement and baseline microgrid performance without storage.[5]

Because each PI analyzed only the five installations (including at least one from each Service) that best met its modeling framework, PI data available for each installation differ per **Table E-1**.

**Table E-1. Installations Modeled by each PI and NREL**

| Military Installation | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| Westover ARB | | ✓ | ✓ | | ✓ |
| NAS Patuxent River | ✓ | ✓ | ✓ | | ✓ |
| NAS Corpus Christi | | | ✓ | ✓ | ✓ |
| Fort Bliss | ✓ | ✓ | ✓ | ✓ | ✓ |
| Holloman AFB | ✓ | ✓ | | ✓ | ✓ |
| March ARB | ✓ | | ✓ | ✓ | ✓ |
| Naval Base Ventura County | ✓ | ✓ | | ✓ | ✓ |

1 Data are displayed for Li-ion BESS throughout this appendix, except that flow BESS results are displayed from Ameresco because flow BESS were emphasized in that PI's work. Since flow BESS are an emerging technology that is not as widely-deployed as Li-ion systems, the economics of flow systems are often worse than Li-ion systems.

2 Data are based on the "current" electricity market pricing scenario, not the "future volatile" pricing scenario. SRI/ASU data are from its post-incentive scenario. Percentage changes shown for the cost metric are in comparison to ESTCP-provided costs for the baseline (no storage) microgrid. In some cases, PIs calculated baseline costs that were different than the ESTCP values, but the differences (noted in their published reports) were minimal. However, NREL did calculate materially different baseline costs for several installations, largely due to the optimization algorithm of its REopt software that dispatched EDGs more frequently to reduce net retail electricity costs. NREL's baseline values are noted in **Appendix G**.

3 These data were obtained from: (5), pp. 36, 39-44, and 60; (6), pp. 36-38; (7), p. 57; and (8), pp. vi-vii.

4 Though not as common as reduction in the number of EDGs, Raytheon and SRI/ASU were able to reduce the number of UPSs in some instances, due to the configuration and operation of BESS they modeled. Descriptions of the number of and rationale for UPS elimination, as well as the resulting cost savings are in their individual reports.

5 NREL calculated separate reliability results for removal of 1, 2, and 3 EDGs in storage-enabled microgrids. These results are labeled as "NREL 1", "NREL 2", and NREL 3." NREL reliability results are only shown for cases when EDG removal allows for improving on the ESTCP requirement. For example, if removing 2 EDGs drove reliability performance below the requirements (as it did at the two USAF reserve bases), then NREL reliability results are only displayed for removal of 1 EDG. NREL 1 economic results are shown for all installations, while NREL 2 and NREL 3 economic results are shown for Ft. Bliss, NAS Patuxent River, and Holloman AFB, as applicable.

## E1. Westover ARB

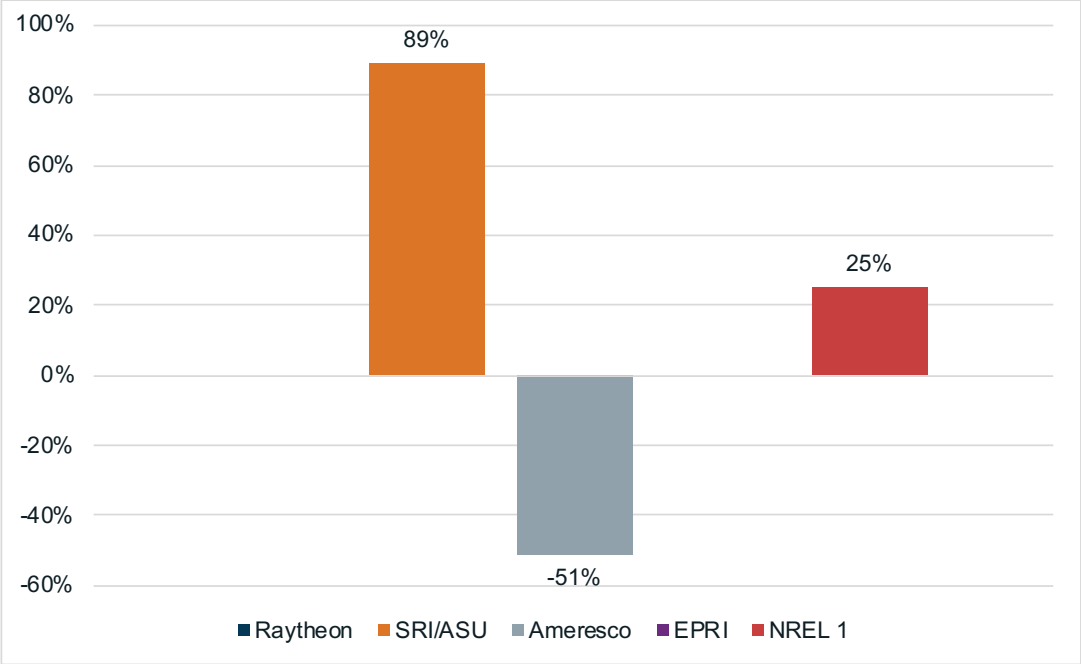


**Figure E-1. Battery Storage-Enabled Microgrid Savings for Westover ARB: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-2. Microgrid Net Cost and Asset Sizing Data for Westover ARB**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW) | $166.00 | | | | |
| PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW) | Not Modeled | $18.67 | $251.00 | Not Modeled | NREL 1: $125.00 |
| PI BESS Power (kW) | | 2,100 | 750 | | 250 |
| PI BESS Energy (kWh) | | 8,400 | 4,500 | | 500 |
| PI BESS Duration (Hours) | | 4 | 6 | | 2 |
| PI Number of EDGs Removed in Storage-Enabled Microgrid | | 2 | 1 | | 1 |

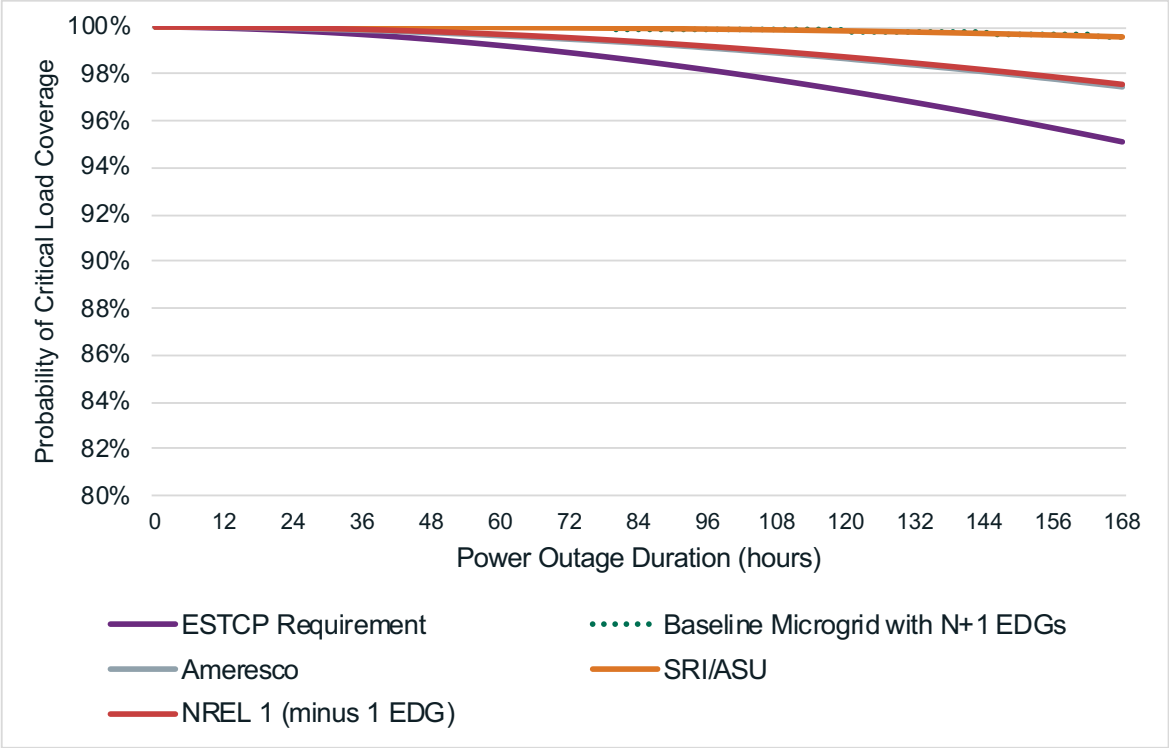


**Figure E-2. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at Westover ARB**

## E2. NAS Patuxent River

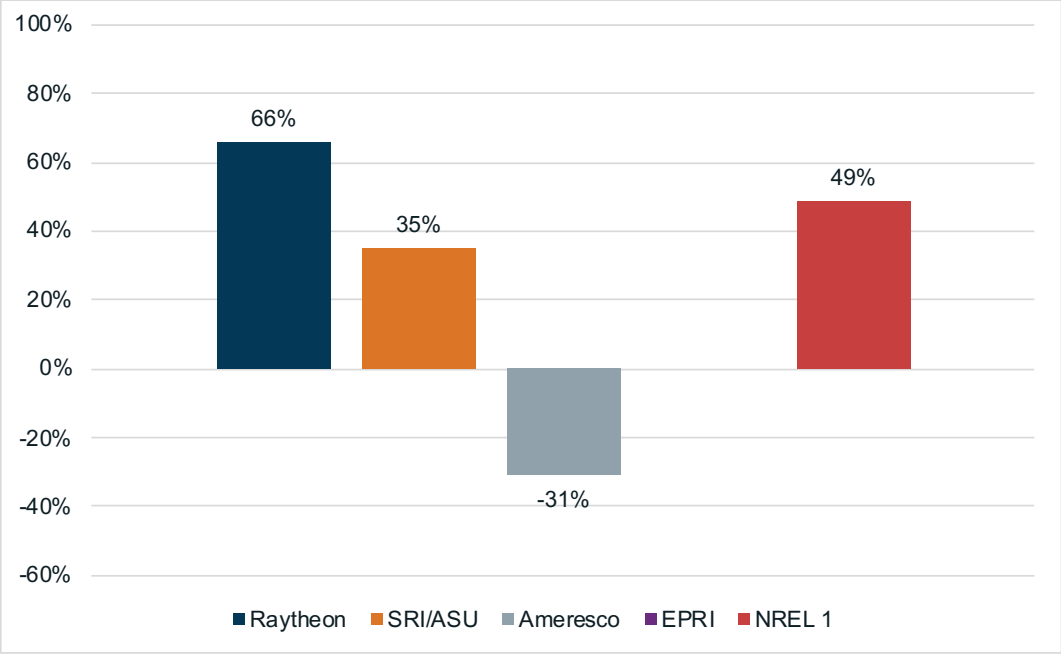


**Figure E-3. Battery Storage-Enabled Microgrid Savings for NAS Patuxent River: % Improvement in Net Cost of Protecting Critical Load vs. Baseline[6]**

**Table E-3. Microgrid Net Cost and Asset Sizing Data for NAS Patuxent River**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW) | $98.00 | | | | |
| PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW) | $33.00 | $64.12 | $128.00 | Not Modeled | NREL 1: $50.00 NREL 2: $44.50 NREL 3: $39.00 |
| PI BESS Power (kW) | 3,000 | 900 | 1,167 | | 800 |
| PI BESS Energy (kWh) | 3,900 | 900 | 7,300 | | 3,200 |
| PI BESS Duration (Hours) | 1.3 | 1 | 6.26 | | 4 |
| PI Number of EDGs Removed in Storage-Enabled Microgrid | 2 | 3 | 1 | | 1, 2, & 3 |

6 Raytheon modeled two battery system sizes for this installation: 3 MW of power and 29.4 MW of power. In this report, results from the smaller system are used to improve comparability of results across PIs.

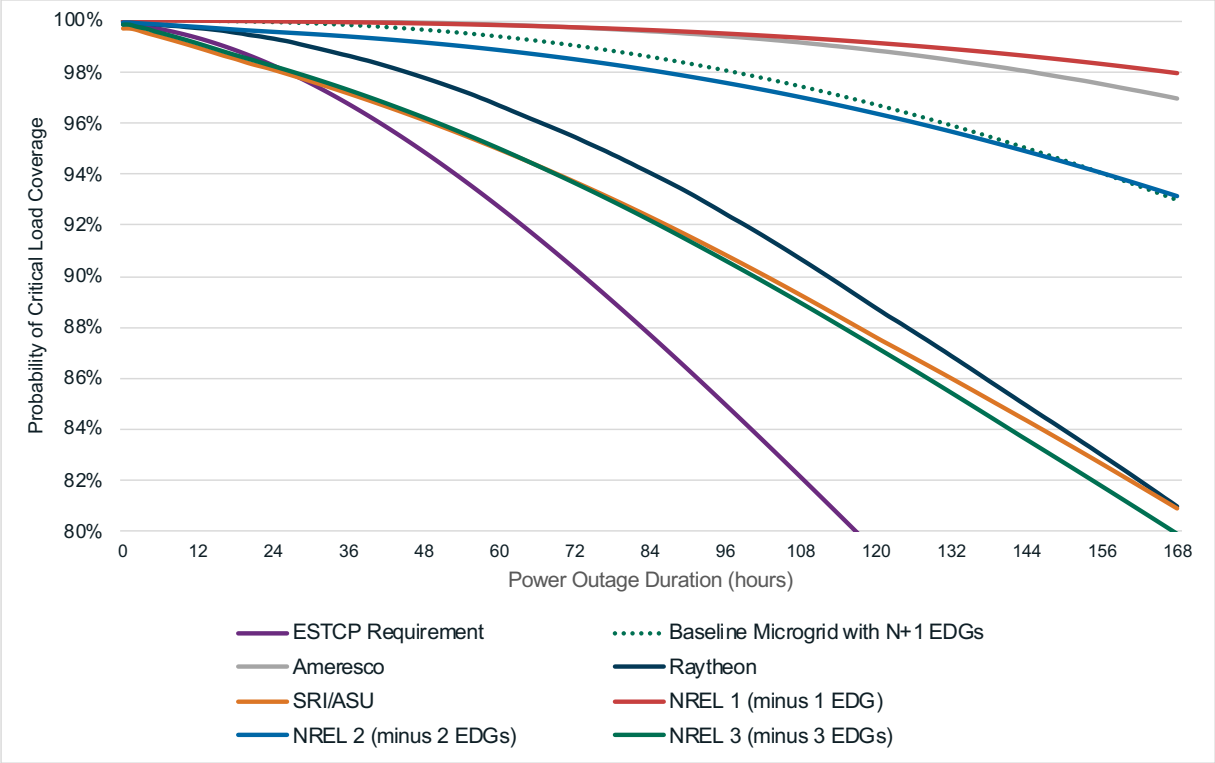


**Figure E-4. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at NAS Patuxent River**

## E3. NAS Corpus Christi

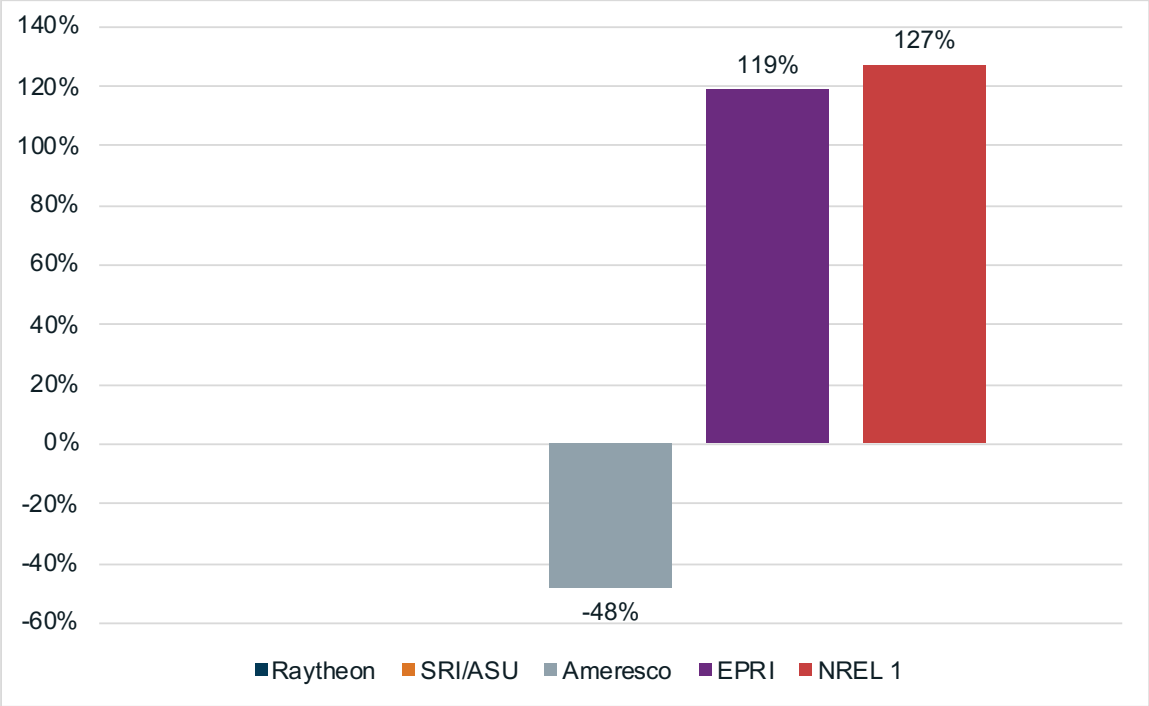


**Figure E-5. Battery Storage-Enabled Microgrid Savings for NAS Corpus Christi % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-4. Microgrid Net Cost and Asset Sizing Data for NAS Corpus Christi**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| **ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW)** | $89.00 | | | | |
| **PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW)** | Not Modeled | Not Modeled | $132.00 | -$17.30 | NREL 1: -$24.00 |
| **PI BESS Power (kW)** | | | 1,217 | 4,600 | 1,200 |
| **PI BESS Energy (kWh)** | | | 7,300 | 18,400 | 2,400 |
| **PI BESS Duration (Hours)** | | | 6 | 4 | 2 |
| **PI Number of EDGs Removed in Storage-Enabled Microgrid** | | | 1 | 1 | 1 & 2 |

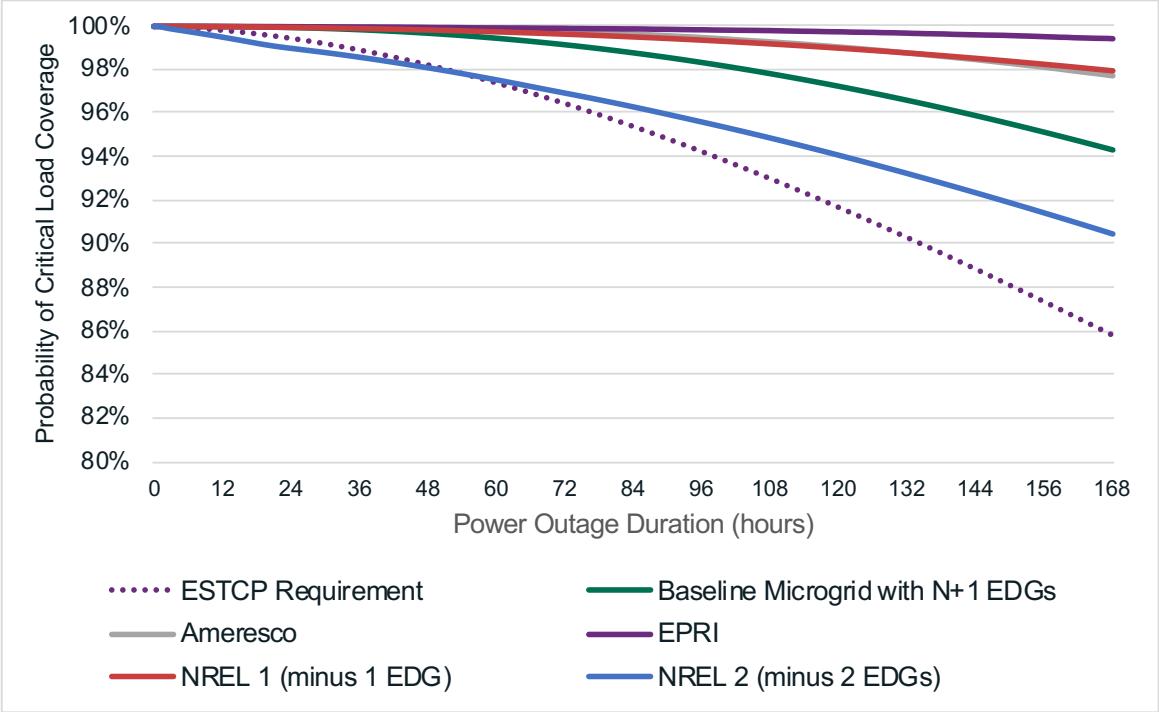


**Figure E-6. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at NAS Corpus Christi**

## E4. Fort Bliss

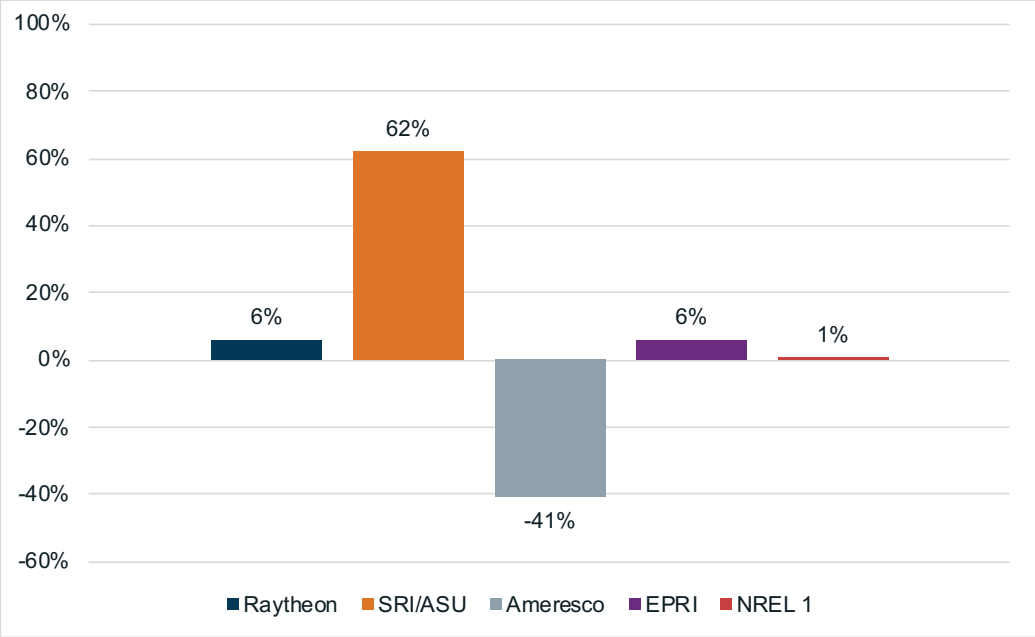


**Figure E-7. Battery Storage-Enabled Microgrid Savings for Fort Bliss: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-5. Microgrid Net Cost and Asset Sizing Data for Fort Bliss**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW) | $83.00 | | | | |
| PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW) | $78.00 | $31.49 | $117.00 | $77.80 | NREL 1: $82.00 NREL 2: $76.00 |
| PI BESS Power (kW) | 1,700 | 2,700 | 2,000 | 1,225 to 1,255 | 600 |
| PI BESS Energy (kWh) | 2,210 | 2,700 | 12,000 | 1,225 to 1,255 | 1,800 |
| PI BESS Duration (Hours) | 1.3 | 1 | 6 | 1 | 3 |
| PI Number of EDGs Removed in Storage-Enabled Microgrid | 1 | 2 | 1 | 2 | 1 & 2 |

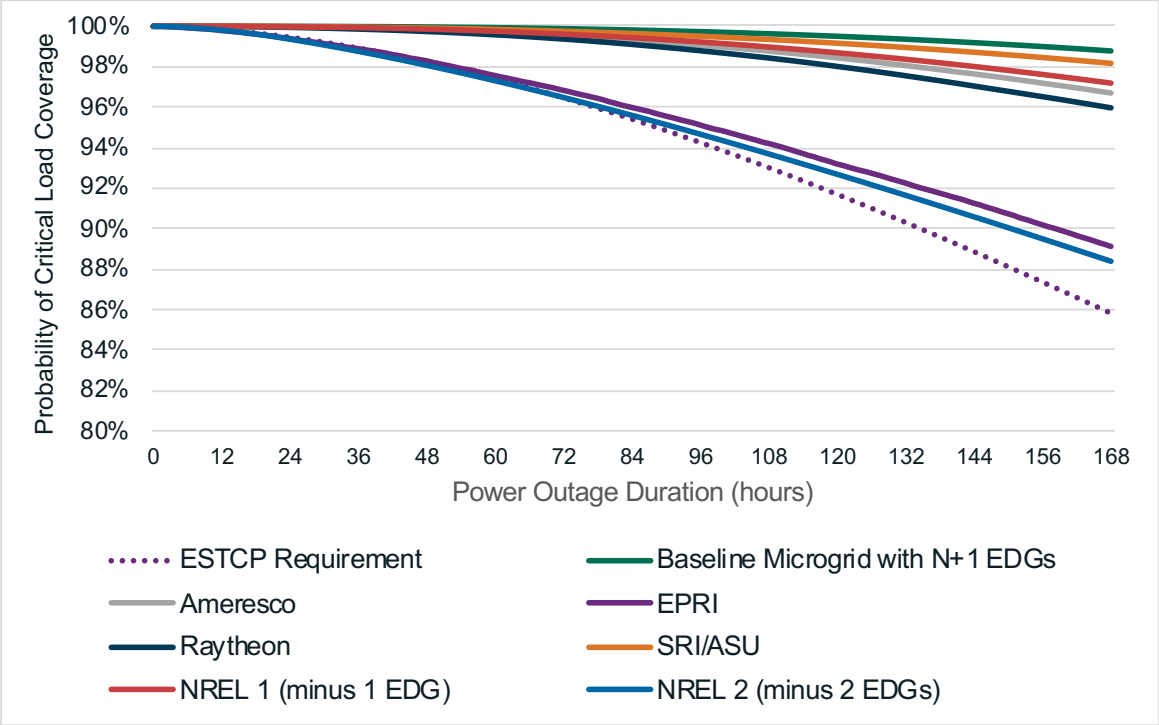


**Figure E-8. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at Fort Bliss**

## E5. Holloman AFB

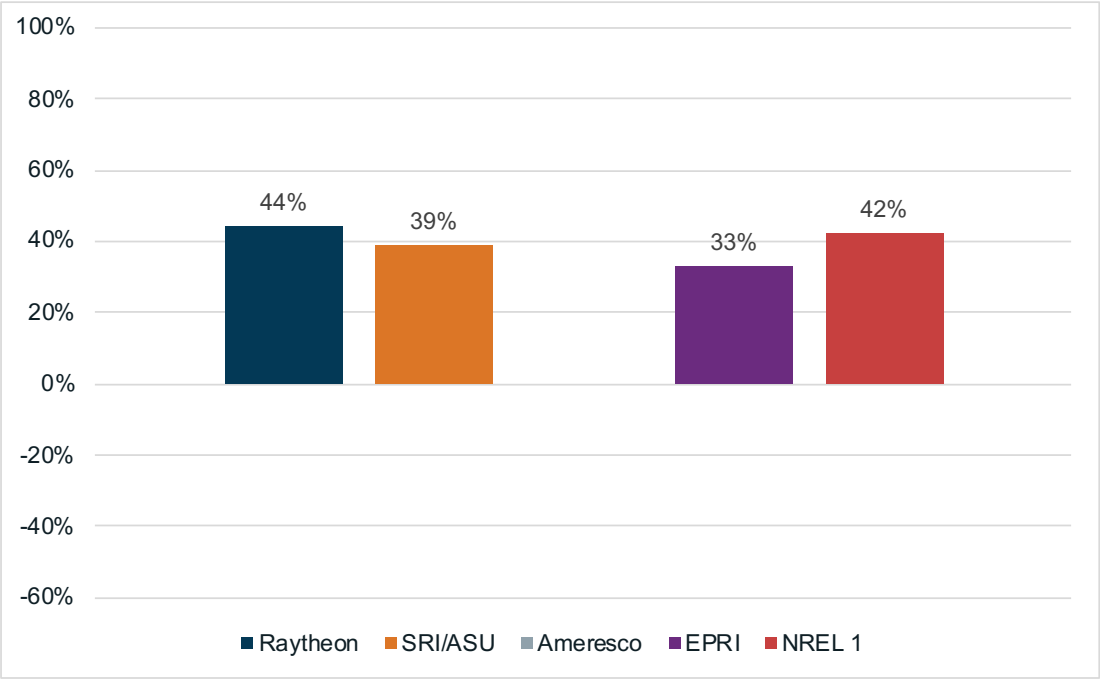


**Figure E-9. Battery Storage-Enabled Microgrid Savings for Holloman AFB: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-6. Microgrid Net Cost and Asset Sizing Data for Holloman AFB**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| **ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW)** | $98.00 | | | | |
| **PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW)** | $55.00 | $59.40 | Not Modeled | $65.53 | NREL 1: $57.00 NREL 2: $53.00 NREL 3: $49.00 |
| **PI BESS Power (kW)** | 2,400 | 1,800 | | 3,600 to 3,800 | 800 |
| **PI BESS Energy (kWh)** | 6,480 | 1,800 | | 14,400 to 15,200 | 3,600 |
| **PI BESS Duration (Hours)** | 2.7 | 1 | | 4 | 4.5 |
| **PI Number of EDGs Removed in Storage-Enabled Microgrid** | 2 | 3 | | 2 | 1, 2 & 3 |

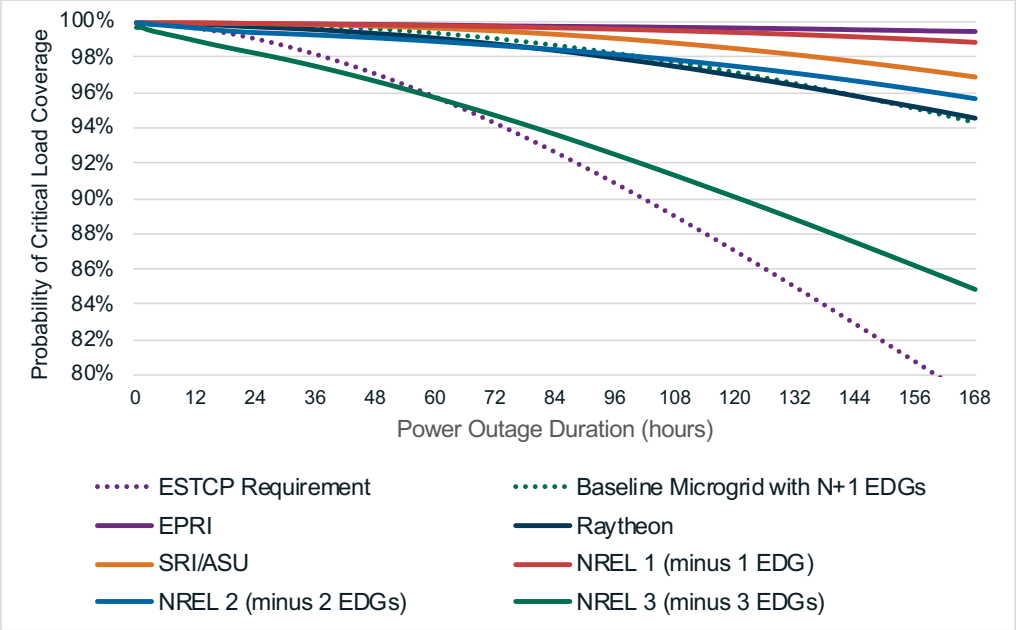


**Figure E-10. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at Holloman AFB**

## E6. March ARB

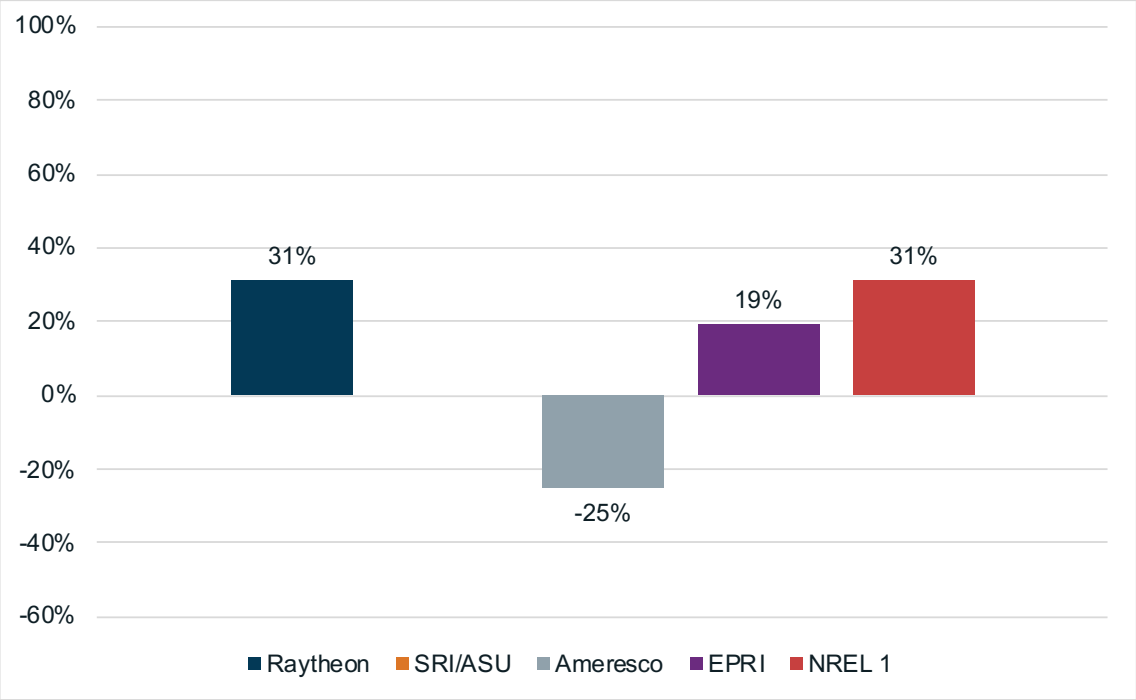


**Figure E-11. Battery Storage-Enabled Microgrid Savings for March ARB: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-7. Microgrid Net Cost and Asset Sizing Data for March ARB**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW) | $416.00 | | | | |
| PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW) | $286.00 | Not Modeled | $519.00 | $337.20 | NREL 1: $286.00 |
| PI BESS Power (kW) | 2,400 | | 875 | 1,000 | 500 |
| PI BESS Energy (kWh) | 3,120 | | 7,000 | 4,000 | 1,750 |
| PI BESS Duration (Hours) | 1.3 | | 8 | 4 | 3.5 |
| PI Number of EDGs Removed in Storage-Enabled Microgrid | 1 | | 1 | 1 | 1 |

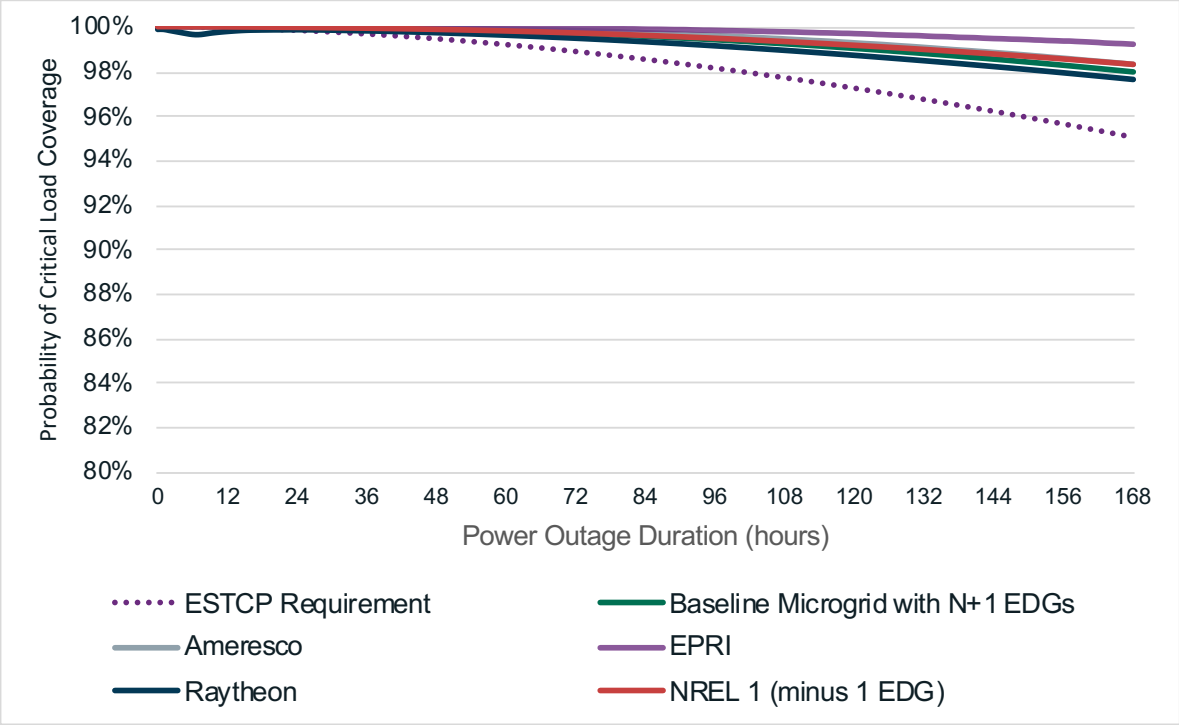


**Figure E-12. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at March ARB**

## E7. Naval Base Ventura County

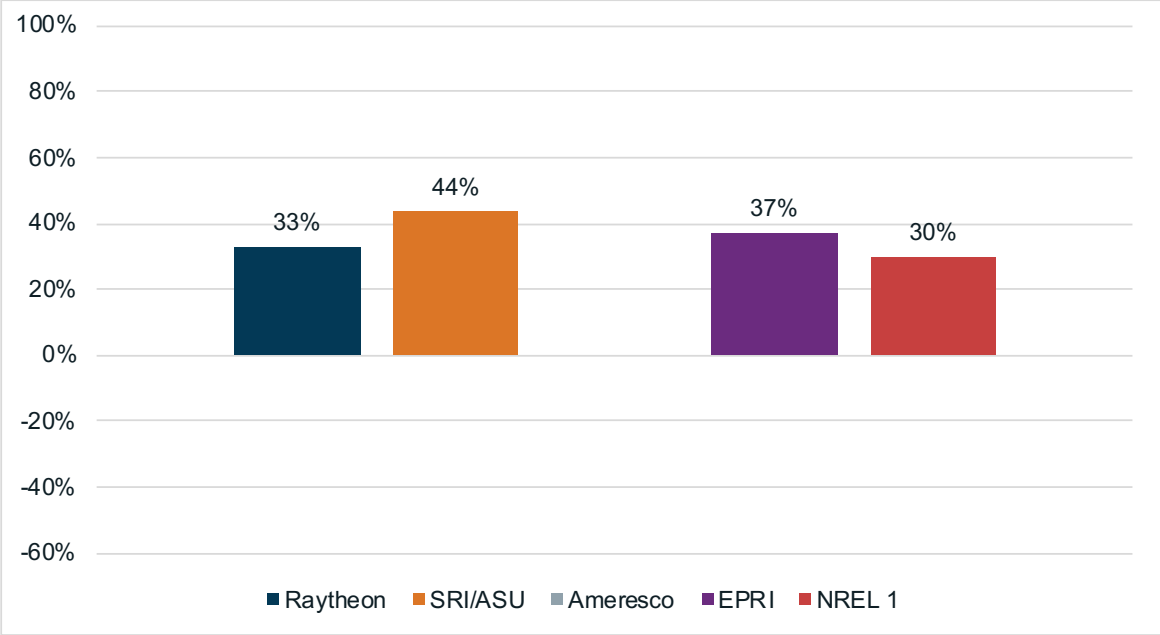


**Figure E-13. Battery Storage-Enabled Microgrid Savings for Naval Base Ventura County: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

**Table E-8. Microgrid Net Cost and Asset Sizing Data for Naval Base Ventura County**

| Attribute | Raytheon | SRI/ASU | Ameresco | EPRI | NREL |
|---|---|---|---|---|---|
| ESTCP Baseline Net Annual Cost of Protecting Critical Load ($/kW) | $135.00 | | | | |
| PI Storage-Enabled Net Annual Cost of Protecting Critical Load ($/kW) | $91.00 | $75.38 | Not Modeled | $85.20 | NREL 1: $94.00 |
| PI BESS Power (kW) | 2,500 | 450 | | 4,375 | 1,000 |
| PI BESS Energy (kWh) | 3,250 | 450 | | 17,500 | 2,000 |
| PI BESS Duration (Hours) | 1.3 | 1 | | 4 | 2 |
| PI Number of EDGs Removed in Storage-Enabled Microgrid | 1 | 2 | | 2 | 1 & 2 |

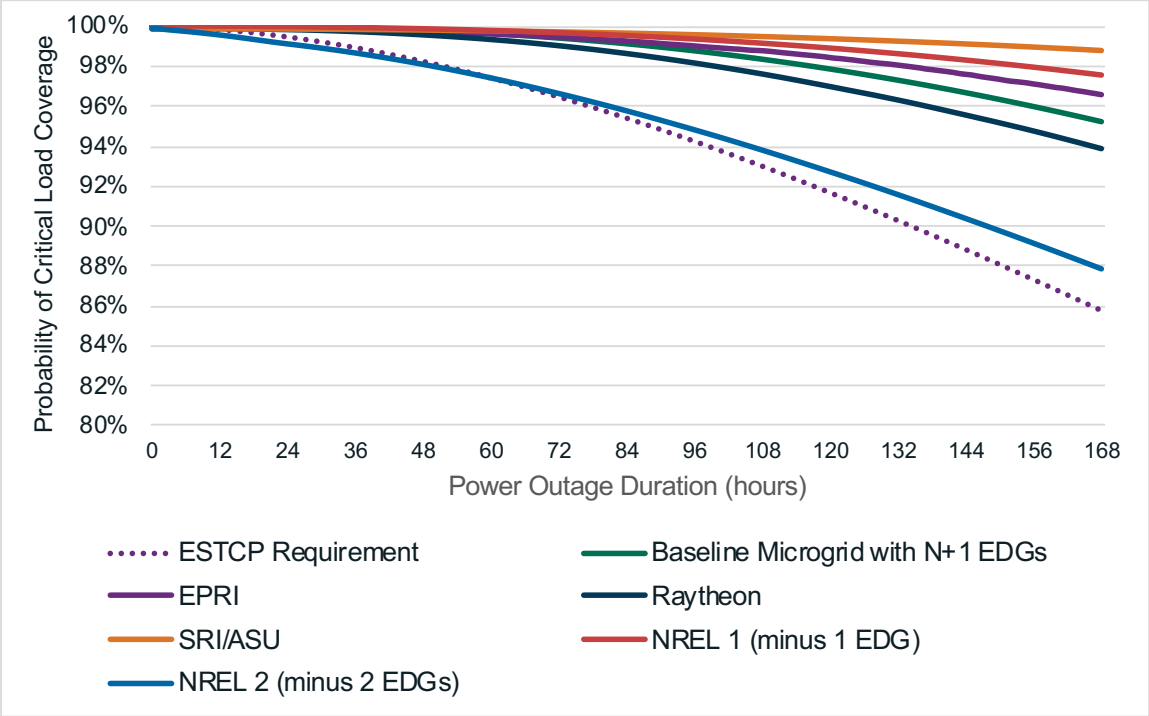


**Figure E-14. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week at Naval Base Ventura County[7]**

7 The results from the SRI/ASU team displayed in this chart are from a scenario with an optimized and larger amount of PV capacity on-installation than in the ESTCP-provided baseline, and the reliability performance of SRI/ASU's storage-enabled microgrid in that scenario is 98.8% at 168 hours. The SRI/ASU team also computed reliability performance using the ESTCP-provided PV capacity; in that case, reliability performance at 168 hours was 89.1%.

# Appendix F: Additional Economic Results Comparison

To supplement **Figure 5** in the body of the report showing percentage savings in microgrid costs for Fort Bliss, NAS Patuxent River, and Holloman AFB, **Figure F-1** provides results on the same metric for the other four installations studied. These net cost results are in comparison to the baseline microgrid, without storage. The results indicate the savings per annual kW of peak critical load brought by the inclusion of BESS in the microgrids. Positive percentages in the chart represent improved economics.

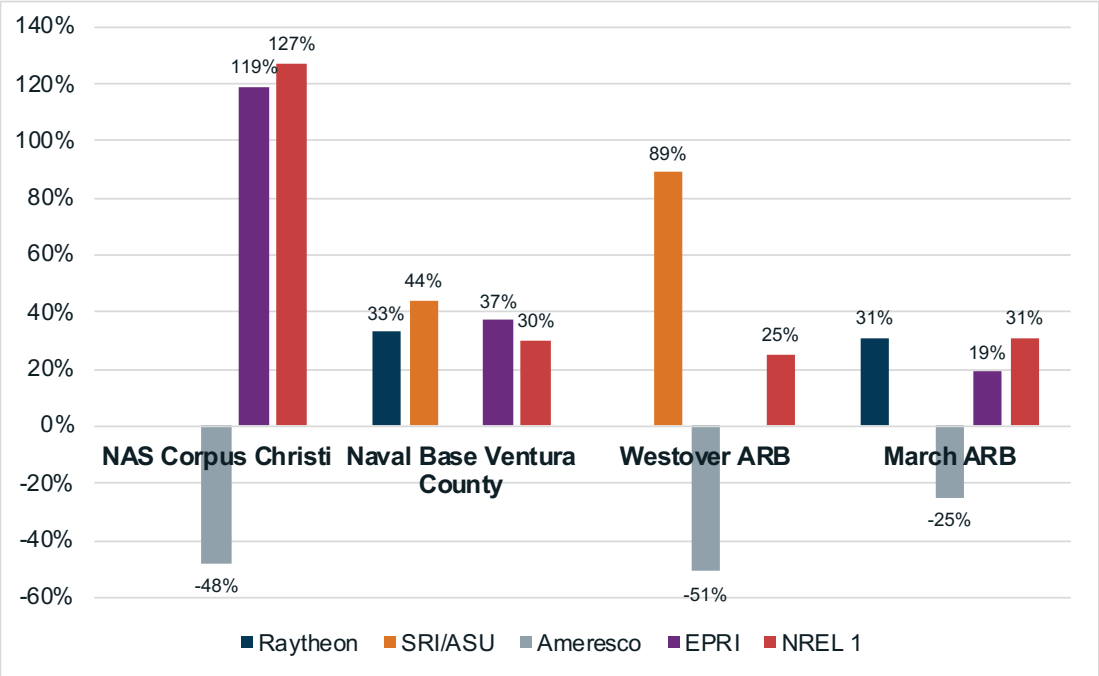


**Figure F-1. Battery Storage-Enabled Microgrid Savings at Four Installations: % Improvement in Net Cost of Protecting Critical Load vs. Baseline**

The results in **Figure F-1** reflect modeling of Li-ion BESS by Raytheon, SRI/ASU, EPRI, and NREL, and a vanadium redox flow BESS (an emerging technology) by Ameresco.[1,2] Li-ion BESS brought savings of 19% (EPRI at March ARB) to 127% (NREL at NAS Corpus Christi), depending on the installation and modeler. Among Li-ion BESS microgrids, each modeler obtained roughly similar results at a given installation, except for Westover ARB. At that installation, differing approaches to wholesale electricity market participation between the SRI/ASU and NREL teams led to very different economic results. Baseline microgrid costs for these four installations are provided in **Table F-1** and **Table F-2.** [3]

1 NREL's reliability analysis determined that two EDGs could be removed at NAS Corpus Christi and Naval Base Ventura County, while still surpassing the reliability requirement. NREL-calculated economic results would likely improve at those installations with removal of an additional EDG, but its results are only shown for removal of one EDG.

2 Where a modeler's results are not shown for an installation, that is because it did not select the installation for analysis.

3 The formulae underlying these tables are described in Section 3.2 of the report.

**Table F-1. Aggregate Baseline (No Storage) Microgrid Costs at Four Installations**

| Military Installation | Baseline Microgrid 20-Year NPV of Energy Security Assets + Electricity Costs for Installation (a) | Pre-Microgrid 20-Year Present Value of Electricity Costs for Installation (b) | Peak Critical Load (c) | Baseline Microgrid Net Annual Cost of Protecting Critical Load ($/kW) (d) |
|---|---|---|---|---|
| **Westover ARB** | $26.2 MM | $20.5 MM | 1,707 kW | $166 |
| **NAS Corpus Christi** | $106.8 MM | $98.9 MM | 4,410 kW | $89 |
| **March ARB** | $65.8 MM | $60.8 MM | 600 kW | $416 |
| **Naval Base Ventura County** | $110.7 MM | $99.9 MM | 4,003 kW | $135 |

**Table F-2. Individual Components of Baseline (No Storage) Microgrid Net Costs at Four Installations (all data in annual $/kW of peak critical load)**

| Military Installation | EDGs (A) | UPSs (B) | Microgrid Hardware, Software, & Support (C) | Demand Response & Peak Shaving Savings (D)[4] | Annual Net Cost of Protecting each Kilowatt of Peak Critical Load (E)[5] |
|---|---|---|---|---|---|
| **Westover ARB** | $77 | $31 | $85 | ($27) | $166 |
| **NAS Corpus Christi** | $52 | $21 | $49 | ($34) | $89 |
| **March ARB** | $121 | $52 | $243 | ($0) | $416 |
| **Naval Base Ventura County** | $57 | $23 | $54 | ($0) | $135 |

4 There are no DR savings at the two California installations (March ARB and Naval Base Ventura County) in the baseline microgrid because fossil-fuel generators are not allowed to operate in DR programs effective January 1, 2019, per California Public Utilities Commission Decision 16-09-056. There are no assumed peak shaving savings at these two installations in the baseline due to the potentially high complexity and cost of using fossil-fuel generators for such purposes under local or regional environmental regulations.

5 Rounding causes $1/kW differences in totals in some cases.

# Appendix G: NREL REopt Modeling

## G1. Purpose

To complement the PIs' Phase I analysis, ESTCP commissioned NREL to perform independent economic and reliability analyses of storage-enabled microgrids at the seven military installations studied. NREL used a standard Li-ion BESS for both its economic and reliability analysis. NREL's REopt modeling tool was utilized for the economic calculations. Including NREL in this manner brought four benefits to the ESTCP R&D effort:

- Side-by-side assessment of all seven installations by a single entity (each PI only modeled five installations);
- Ability to compare PI results, which often involved combinations of battery types and emerging technologies, to a standard Li-ion BESS configuration;[1]
- Display of economic results obtained from a single, federal government modeling tool;[2] and
- Analytic inclusion of NREL in Phase I to facilitate transition to Phase II hardware-in-the-loop modeling that will occur with three of the PI teams at NREL's ESIF.

NREL's economic and reliability methodology and results are briefly summarized below.

## G2. Economic Methodology

The NREL team relied on the same starting assumptions, data, retail electricity cost savings and demand response opportunities, wholesale market participation opportunities, and constraints as the PIs. NREL also used the same outcome metrics as the PIs. To inform its work, NREL researched and applied evolving market participation rules for behind-the-meter and front-of-the-meter battery storage in the electricity markets serving the seven Phase I military installations.

NREL then applied the technology and market expertise of its staff to create economic results through use of its REopt tool. A schematic of REopt operation for this ESTCP project is in **Figure G-1**.[3]

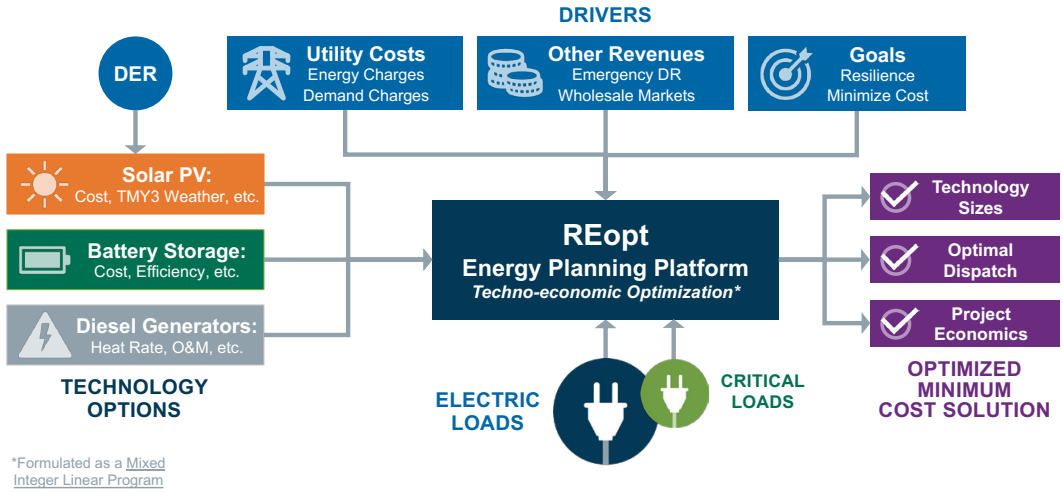


**Figure G-1. Summary of NREL REopt Modeling Inputs and Outputs**

1 NREL also assessed a flow BESS in microgrids for Westover ARB and NAS Patuxent River using the same methodology. NREL's flow BESS results are not detailed in this report, but they showed that flow systems did not achieve economic results as positive as Li-ion systems, largely due to the higher capital costs and lower roundtrip efficiency assumed for the flow systems.

2 A simplified version of this tool (REopt Lite) is publicly-available at: https://reopt.nrel.gov/tool.

3 REopt has additional capabilities that were not used for this ESTCP project and are not displayed in the figure.

REopt functioned to minimize ESTCP's key economic metric (the annual net cost of protecting each kW of peak critical load) at each installation by optimizing the combination of (i) BESS size[4] and cost and (ii) net cost savings from hourly dispatch of EDGs and BESS over a 20-year investment period.

For the REopt analysis, NREL also removed at least one EDG at each installation to contribute to cost savings, while still meeting ESTCP's reliability requirements for covering critical loads during power outages.

## G3. Economic Results

Like the PIs, NREL first analyzed a baseline (without battery storage) microgrid at each military installation and, then, analyzed a microgrid with a BESS at the installation. NREL's economic results from each type of microgrid are briefly summarized below.

### G3.1. Baseline Microgrids

Because REopt's methodologies led to more frequent dispatch of EDGs for peak shaving and other activities than in ESTCP's more conservative baseline approach, NREL calculated lower baseline net costs of protection for several installations. The NREL-calculated values are shown next to ESTCP-calculated values in **Table G-1**.[5,6]

**Table G-1. ESTCP and NREL REopt Baseline (No Storage) Microgrid Net Costs**

| Military Installation | ESTCP Baseline Microgrid Net Annual Cost of Protecting Critical Load ($/kW) | NREL REopt Baseline Microgrid Net Annual Cost of Protecting Critical Load ($/kW) |
|---|---|---|
| **Westover ARB** | $166 | $158 |
| **NAS Patuxent River** | $98 | $60 |
| **NAS Corpus Christi** | $89 | $69 |
| **Fort Bliss** | $83 | $83 |
| **Holloman AFB** | $98 | $57 |
| **March ARB** | $416 | $419 |
| **Naval Base Ventura County** | $135 | $136 |

It is important to reiterate that these differences are not due to data nor formula differences between the ESTCP and NREL baselines. Instead, they are almost exclusively due to the REopt optimization algorithm leading to more frequent dispatch of EDGs for certain installations. In **Appendix E**, the *baseline values* reported are from ESTCP's analyses that were provided to PIs near the outset of their contracts, not from NREL's REopt analyses that were conducted in parallel with the PIs' analyses.

4 NREL constrained maximum battery sizes for installations in the PJM (NAS Patuxent River) and CAISO (March ARB and Naval Base Ventura County) markets to prevent enormous BESS from being selected to capture ancillary service revenues. This is due to great price uncertainties in future ancillary service prices.

5 NREL did not remove UPSs at any installation as part of its REopt analysis.

6 While REopt does not explicitly consider reliability in its optimization calculations, NREL did have BESS peak shave excess critical load so that the remaining EDGs maintained the N+1 reliability capacity of the baseline microgrid in cases when only one EDG was removed at an installation. Doing so helps assure that the REopt tool does not short-cut reliability to achieve better economic results.

### G3.2. Storage-Enabled Microgrids

NREL's BESS assumptions and economic and reliability results are shown alongside those of the PIs in **Appendices B** and **E**, respectively. Findings from the REopt analysis are also described in **Section 3** of this report. In **Figure G-2**, NREL's economic results for storage-enabled microgrids at all seven installations where one EDG has been removed using Li-ion BESS are consolidated.[7]

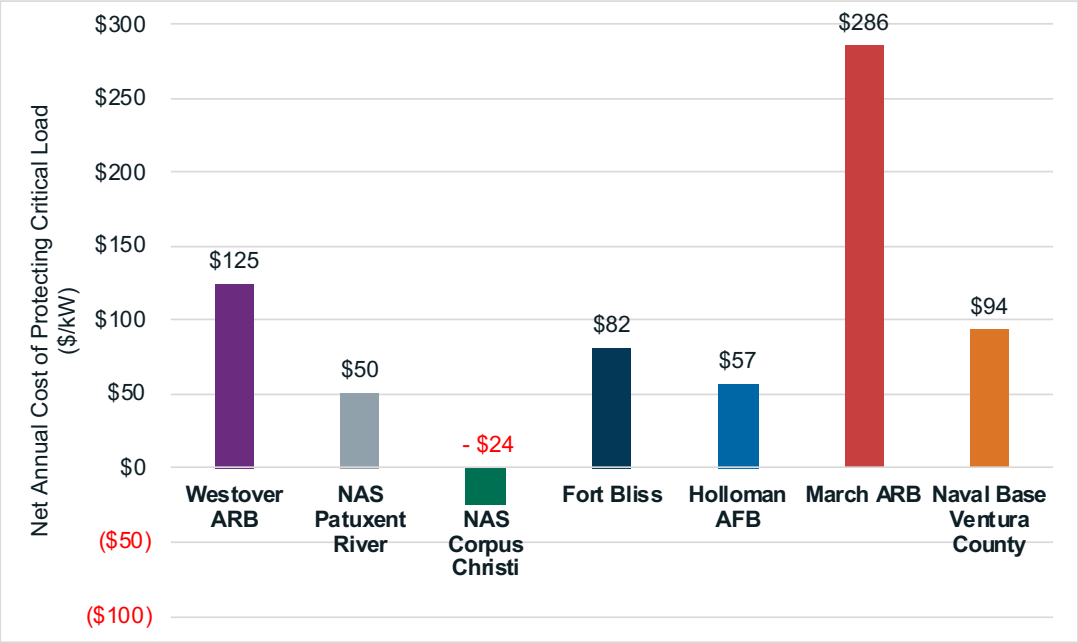


**Figure G-2. Storage-Enabled Microgrid Net Costs from NREL's REopt Analysis (case where one EDG is removed from each installation's baseline microgrid)**

## G4. Reliability Methodology and Results

Results from NREL's reliability analysis of storage-enabled microgrids for each of the seven military installations studied are in **Appendix E**. In **Figure G-3**, NREL's reliability results are provided for cases when one EDG is removed from each microgrid.

7 Removing a second EDG at Fort Bliss yields about $6/kW in additional annual savings for the storage-enabled microgrid. At NAS Patuxent River, removing two and three EDGs save an additional $5.50/kW and $11/kW annually, respectively. For Holloman AFB, the respective additional annual savings from removing two and three EDGs are about $4/kW and $8/kW.

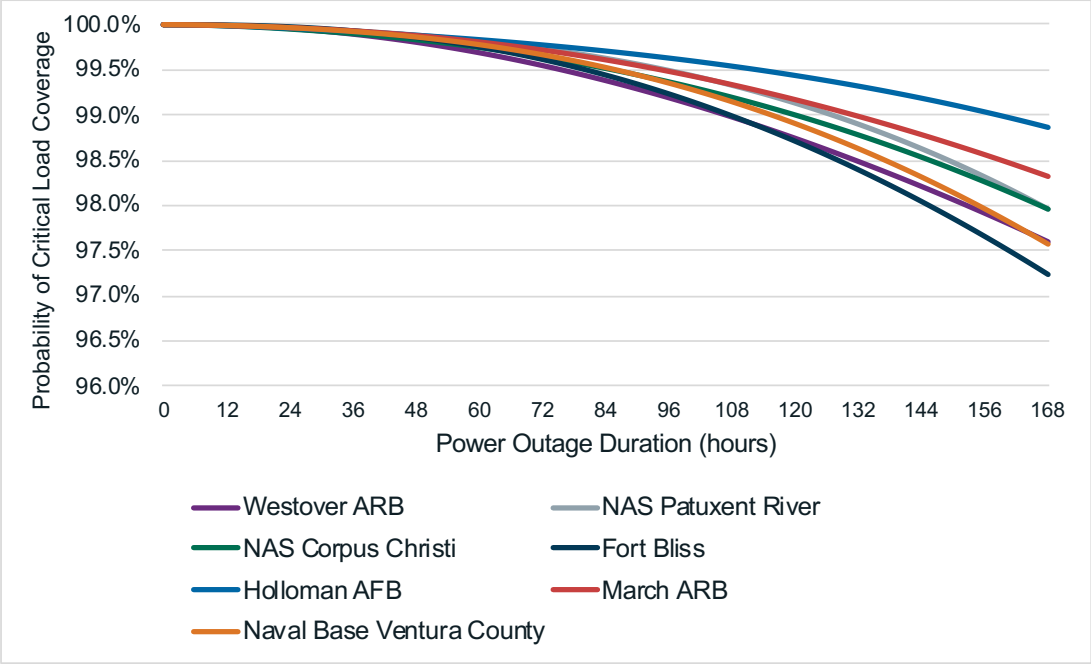


**Figure G-3. Probability of Battery Storage-Enabled Microgrids Fully Meeting Critical Load for Power Outages of up to One Week/NREL Modeling when One EDG is Removed from the Microgrid**