EXECUTIVE SUMMARY

Design, Modeling, and Control of Hybrid Energy Storage System for Defense Installation Microgrids

ESTCP Project EW19-5277

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ARB	Air Reserve Base
AS	Ancillary services
ASU	Arizona State University
DoD	United States Department of Defense
ESM	Energy security model
ES	Energy storage
ESS	Energy storage system
ESTCP	U.S. Department of Defense Environmental Security Technology Certification Program
HESS	Hybrid energy storage system
ITC	Investment tax credit
kW	Kilowatt
kWh	kilowatt-hour
LCOE	Levelized Cost of Energy or Electricity
MACRS	Modified accelerated cost-recovery system
MWh	Megawatt-hour
NAS	Naval air station
PV	Photovoltaic
UPS	Uninterruptible Power Supply

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1.0 INTRODUCTION

This document describes design, modeling, and control of a hybrid energy storage system (HESS) for Department of Defense (DoD) microgrids.

Southern Research, with 350Solutions, has managed a program to optimize energy storage (ES) implementation in DoD microgrids, with collaborators Arizona State University (ASU) and XENDEE Corporation developing a microgrid and energy storage design, modeling, and controls platform. The integrated methods from ASU and XENDEE optimize a microgrid that can contain multiple different energy storage types—a HESS approach—in conjunction with diesel, renewable, and other generation platforms. Microgrid designs with optimized asset selection, sizing, and configuration are coupled with model predictive controls and dispatch algorithms to optimize real-time performance and economics.

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2.0 OBJECTIVES

The primary objectives of this project were to:

- Demonstrate the value of integrating optimized energy storage solutions, including the potential for multiple technology types and multi-asset HESSs within DoD microgrids.
- Improve energy security performance as a function of cost compared to a similar microgrid without storage at DoD installations.
- Develop an integrated, microgrid design tool that rapidly produces performance- and cost-optimized, storage-technology-agnostic, customized microgrid designs and specifications.
- Demonstrate controls techniques to improve revenue from energy market participation.
- Perform co-simulation of design and controls methodologies to maximize performance and financial objectives for the project lifetime.

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3.0 ENERGY STORAGE TECHNOLOGIES

The project team selected six energy storage technologies as summarized in Table 1. Storage technologies evaluated broadly covered current commercially available storage approaches and chemistries. This allowed modeling of storage integration considering a range of key technology attributes, such as C-rate, efficiency, and life. Each of these core technology types was selected based on ability to excel in one or more of the six key performance attributes: coverage, availability, reliability, duration, ride-through capability, and stacked-value.

Table 1. Summary of Modeled Energy Storage TechnologyS

Manufacture	Technology/ Chemistry	Expected Life (Cycles)	C-rate	Round Trip Efficiency (%)	Storage Cost ($/kWh)
Maxwell	Ultra-capacitor	1,000,000	Balance of system limited	85-95	
All Cell	Li-ion	2,200	3C/2	90	350
Blue Planet	$LiFePO_4$	8,000	1C	98	650
Eos	Aqueous zinc	5,000+	C/4	75	240
NGK	Sodium sulfur	4,500+	C/6	75	317
Avalon (lower cost for >20MWh)	Flow	20,000+	C/4	80	563/398

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4.0 DOD INSTALLATIONS MODELED

Five DoD installations with varying microgrid capacities were evaluated for design and incorporation of an optimized HESS approach, as summarized in Table 2.

Table 2. Installation Characteristics and Potential Microgrid Benefits

Installation	Selection Rationale & Characteristics of Interest
Westover Air Reserve Base (ARB)	Smallest facility with lowest annual electricity cost. High cost structure. High projected comparative solar capacity. Potential for microgrid to cover significant peak and critical load.
Naval Base (NB) Ventura County	Mid-sized facility. California market (high electricity cost). Low PV capacity (but significant potential). Low critical load as percentage of peak demand. Small ESS investment with potential resiliency impacts.
Holloman Air Force Base (AFB)	Significant PV resource as percentage of peak (33%) and critical (83%) loads. Large utility with demand and time of use charges. High potential for utilizing solar PV plus energy storage.
Naval Air Station (NAS) Patuxent River	Large energy consumer. Regionally unique (mid-Atlantic). Electric Cooperative supplier. Unique use case. PJM Interconnection regional transmission organization market access.
Fort Bliss	Largest energy consumer of group. Small critical load as percentage of peak demand, but largest critical load of all sites. Large, vertically integrated utility with multiple price structures. Potential for significant quantity of energy storage to mitigate time of use and demand charges.

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5.0 MODELING METHODOLOGY

An optimized microgrid and energy storage platform with integrated analytics and controls was utilized to evaluate potential HESS solutions at each of the five select DoD installations. This approach rapidly provides tailored energy storage enabled microgrid designs for any installation by considering climate zone, local energy market, and location specific use cases. The approach combines economic optimization through the XENDEE platform and ASU's energy security model (ESM) to evaluate energy asset portfolios. This method ensures energy security metrics are achieved while providing the lowest cost energy. Figure 1 shows the general process used to select the optimal energy asset portfolio for each of the considered bases.

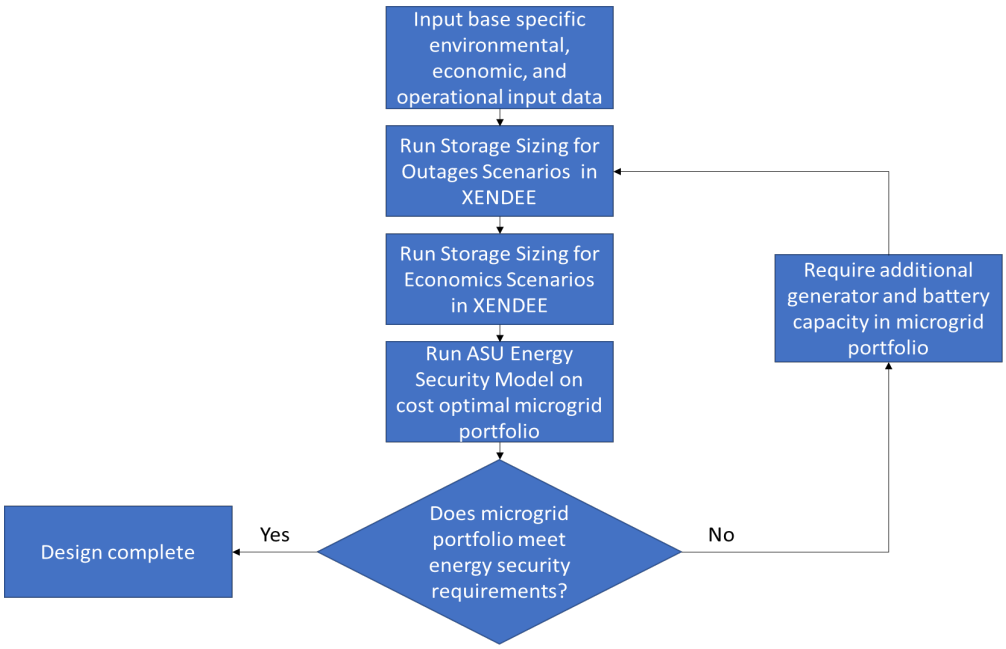

Figure 1. Process Flow Diagram Detailing the Steps Used to Calculate the Cost-optimal Microgrid Portfolio for Energy Security Operations of Each Base Considered

The models utilized the following tools:

- XENDEE: XENDEE secure cloud computing microgrid platform (XENDEE, 2017) provides economic system optimization via distributed energy resource-customer adoption model technology—a state-of-the-art decision support tool for decentralized energy systems, including buildings and microgrids—and also implements critical electrical design analysis (power flow, short circuit, reliability, arc-flash).
- ASU ESM: ASU's ESM is a Python-based standalone model that, for our purposes, calculates a critical load coverage probability curve and provides an optimized dispatch methodology to maximize coverage probability. The model can be used for real-time microgrid controls.

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6.0 PERFORMANCE ASSESSMENT

A summary of the primary performance metrics and the performance of the optimized ESS-enabled microgrid design is provided in Table 3. Key findings are:

Energy Storage Technology Selection:

- For the core case with only potential energy storage addition and no market participation or incentives, energy storage is not specified in the optimal microgrid for three locations – Westover ARB, Holloman AFB, and NB Ventura County. For Ft. Bliss and NAS Patuxent, small quantities of energy storage are specified. When incentives and wholesale market participation are included, energy storage is selected for all sites, with significant impacts on net protection cost and levelized cost of electricity.
- The overall difference in performance and economic impacts between different storage options in the optimized microgrid is quite small, and depends highly on the system costs. For these cases, any of four identified technologies could be selected with <1% impact on economics, including net protection cost and levelized cost of electricity.
- A $LiFePO_4$ battery was identified as the optimal storage technology to use in four military bases' optimal portfolio due to its high lifetime and low self-discharge rate. A flow battery was identified as the optimal storage technology for Westover for the same reasons. However, other technologies also show promise with nearly equivalent economic performance.
- The combination of an ultracapacitor with battery storage typically provides the best performance, with potential for significant reductions in uninterruptible power supply (UPS) and generator costs.

Energy Security Performance:

- Performance objectives related to critical load coverage (24- and 168-hour) were met by the economically optimized microgrid design and dispatch scenario at Holloman (no ES), Ventura (no ES), and Fort Bliss (with ES), but not at Westover and Patuxent (24 hr).
- When access to incentives results in energy storage specification at all sites, the critical load coverage performance objectives are readily met. The optimized ESS enabled microgrid designs provide significant improvements in reliability to meet critical loads, especially for long outage duration (168-hour), and greater than 50% probability to meet 130% of critical load for 24-hour outages.
- Significant capability is provided to support portions of critical loads when no fuel was available are demonstrated for the optimized ESS microgrid when incentives are enabled.
- Fuel use was reduced for all sites with the optimized ESS microgrid (with incentives) compared to the baseline microgrid, when covering 100% critical load.

Table 3. Summary of Performance for Optimized Storage-enabled Microgrid

Performance Objective	Reliability to Meet 100% of Critical Load	Reliability to Meet 130% of Critical Load	Reliability to Meet 10% and 30% of Critical Load with no Fuel	Net Life-cycle Costs of Deployment and Operation	Fuel Use Reduction to Meet 100% Critical Load
Success Criteria	**Meets or exceeds reliability probability curve for baseline microgrid for 24-hour, 168-hour outages**	**Probability to serve critical load 24-hour and 168-hour outages**	**Probability to serve critical and ride-through load. No minimum standard**	**Net cost is at or below level of baseline microgrid in current and future volatile scenarios**	**Fuel use is at or below the level of the baseline microgrid**
Objective Met?	Yes, for all installations, when incentives are considered	No Min. Standard. Results Below	No Min. Standard. Results Below	Met for Westover, Holloman, Ft. Bliss.	Yes, for all installations, with optimized ES-microgrid
Metric	**Probability to meet load (%) for 24 hr/168 hr outage**	**Probability to meet load (%) for 24 hr/168 hr outage**	**Probability to meet load (%) for 24 hr and 10%/30% of critical load**	**Net cost of protecting each kilowatt of peak critical load ($/kW)**	**Average fuel saved compared to the baseline microgrid (gal/outage)**
Westover ARB Requirement	99.84/95.08	NA/NA	0/0	165.94 (baseline microgrid)	NA
Westover ARB Results - No Inc	96.87/81.77	56.48/18.53	0/0	129.77	0
Westover ARB Results - With Inc	100.00/100.00	94.74/85.89	100.00/59.45	18.67	-25
Westover ARB Results - Sized Solar	100.00/100.00	99.93/89.21	89.04/43.53	Not calculated	672
Holloman AFB Requirement	99.04/78.58	NA/NA	0/0	98.35 (baseline microgrid)	NA
Holloman ARB Results - No Inc	99.28/86.47	73.51/38.40	0/0	64.12	0
Holloman AFB Results - With Inc	99.96/96.93	99.5/61.07	97.53/0.00	59.40	16,500
NAS Patuxent Requirement	98.30/67.37	NA/NA	0/0	97.63 (baseline microgrid)	NA
NAS Patuxent River Results - No Inc	98.12/80.88	49.62/5.65	0.16/0.00	66.37	5,949
NAS Patuxent River Results - With Inc	98.12/80.88	49.62/5.65	0.16/0.00	64.12	5,949
NAS Patuxent Results - Sized Solar	98.90/86.26	33.42/1.89	7.19/0.00	Not calculated	20,155
NB Ventura Co. Requirement	99.43/85.81	NA/NA	0/0	135.45 (baseline microgrid)	NA
NB Ventura Co. Results - No Inc	97.03/67.88	32.59/0.00	0/0	76.89	0
NB Ventura Co. Results - With Inc	99.63/89.10	66.80/3.64	96.39/0.00	75.38	2,937
NB Ventura Co. Results - Sized Solar	99.91/98.82	42.98/4.34	99.99/0.00	Not Calculated	17,899
Fort Bliss Requirement	99.25/82.25	NA/NA	0/0	82.70 (baseline microgrid)	NA
Fort Bliss Results - No Inc	99.48/90.76	72.50/51.20	0.00/0.00	31.17	20,807
Fort Bliss Results - With Inc	99.97/98.10	79.03/63.77	0.15/0.00	31.49	20,716

Optimal storage capacity for each technology type and installation, as well as projected levelized cost of energy (LCOE)[1] for each system design are provided in Figures 2a and 2b (design with incentives).

[1]*Levelized Cost of Energy (LCOE)—measures lifetime costs divided by energy production for a specific site or project via calculation of net present value of the total cost of building and operating a power plant (microgrid) over an assumed lifetime.*

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7.0 COST ASSESSMENT

Estimated energy storage system costs are summarized in Table 4.

Table 4. Optimized Storage-enabled Microgrid Systems for All Locations

	Holloman AFB	Westover ARB	NB Ventura Co.	Fort Bliss	NAS Patuxent River
Best Choice Scenario	Blue Planet-Cap;	Avalon-Cap;	Blue Planet-Cap;	Blue Planet-Cap;	Blue Planet-Cap;
Microgrid Total Cost [k$]	**6509**	**5763**	**5876**	**12504**	**8545**
Energy Storage [k$]	503	2391	881	755	252
ES-Balance of System [k$]	266	1263	465	398	133
Microgrid infrastructure [k$]	262	174	262	262	349
UPS [k$]	2103	809	1456	3888	2750
Diesel Generators [k$]	3375	1125	2813	7200	5063
Original Diesel Gen	9	4	7	8	12
HESS Diesel Gen	6	2	5	6	9

Note: All best choice scenarios were found modeling ITC/MACRS incentives applied to storage, and include market participation, where available. Cost-optimal solutions for bases when designed without applying incentives selected no storage for four of the bases.

Overall, for the optimized ES-enabled microgrid (with investment tax credits (ITC) and modified accelerated cost-recovery system (MACRS) incentives), net lifecycle costs were below those of the baseline microgrid for all sites. Important findings are:

- On each base, the greatest ancillary service (AS) potential is provided by installing the largest optimal ESS possible, providing the most capacity for participation.
- Westover ARB provided the greatest potential for AS revenue and significant differences in LCOE for different technologies due to large solar photovoltaic (PV) generation combined with ES.
- LCOE is directly correlated with AS revenue, where larger shares of AS revenue produce the solutions with the lowest overall LCOE.
- For the Wholesale Market cases, low real-time pricing rates drive down storage sizing and AS revenue.

Example revenues for the optimized ES-enabled microgrid for Westover ARB are summarized in Figure 3.

PV system size relative to total load is a primary driver in storage sizing and operation. For NB Ventura County, if all three technologies—energy storage, PV generation, and generators—are optimally sized, rather than restricting the PV array capacity to the pre-planned 830 kW, the optimal technology portfolio includes a much greater amount of PV and storage (Figure 4). The increase in PV and storage capacity improves microgrid ability to meet critical loads through renewable generation and storage, and fewer diesel generators are needed for backup power. A significant reduction in both LCOE (~17%) and total annual energy cost (~15%) can be achieved with additional PV and storage, with more potential opportunities for demand charge reduction and price arbitrage during normal operation. Both utility energy purchases and demand charges are significantly reduced when the microgrid is sized without the 830 kW array capacity restriction.

Figure 2a. Optimal Microgrid Portfolio and Levelized Cost of Electricity of Each Base Modeled for Each Battery Technology Paired with a Ultracapacitor/UPS System That Can Extend the Expected Life with No ITC or MACRS Incentives

Figure 2b. Optimal Microgrid Portfolio and Levelized Cost of Electricity of Each Base Modeled for Each Battery Technology Paired with a Ultracapacitor/UPS System that Can Extend the Expected Life Including ITC and MACRS Incentives

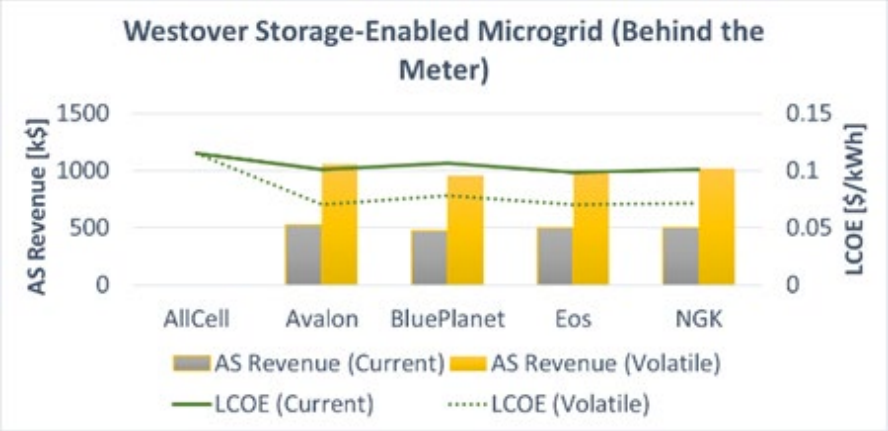

Figure 3. Potential Revenues from Ancillary Services at Westover ARB with Storage-Enabled Microgrid.

Each battery Technology is paired with a ultracapacitor/UPS system that can extend the expected life including ITC and MACRS incentives

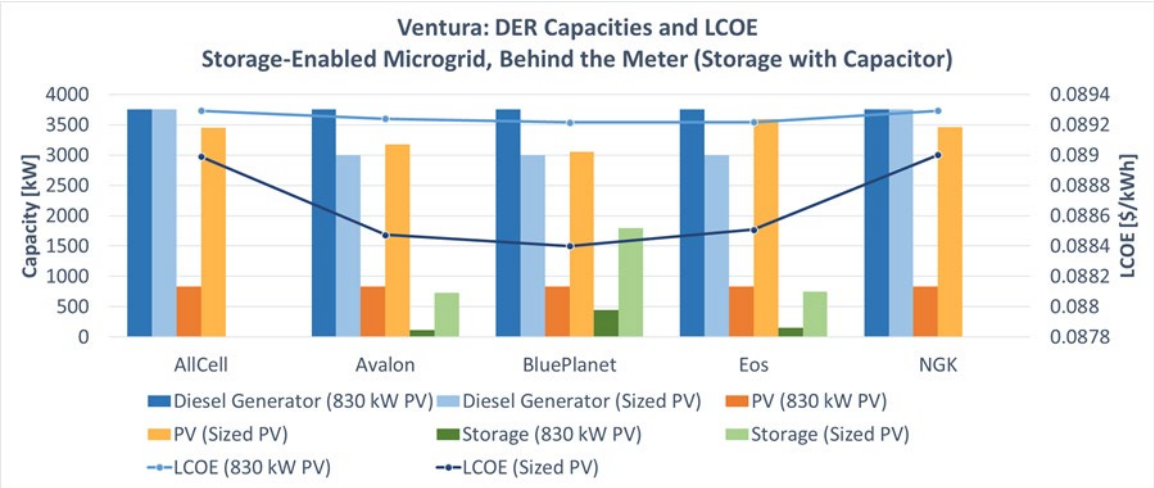

Figure 4. Optimal Sizing of All Assets (PV, Generators, Storage) for Ventura.

Each battery technology is paired with a ultracapacitor/UPS system that can extend the expected life including ITC and MACRS incentives.

8.0 STUDY CONCLUSIONS

Primary conclusions of the study are that an optimized storage-enabled microgrid can:

- Improve energy security over 24-hour and 168-hour time horizons as measured by the critical load coverage probability (CLCP).
- Provide increased ability to meet greater than 130% critical load without resizing the system.
- Reduce fuel use by up to 22% during 7-day outages, thereby increasing mission autonomy in case of fuel supply shortage.
- Integrate on-grid economic optimization with off-grid reliability to provide resilience with potential return on investment at sites with significant market participation potential.
- Lower net protection cost via optimization of assets, including diesel generators, by adding storage and reducing generator units as compared to the baseline generator-only case, while meeting required critical load coverages.

In addition, important factors to consider include:

- Implementation of a hybrid system with ultracapacitors can improve the lifetime of long-duration storage, with additional potential benefits to be evaluated in Phase II.
- Hybrid battery-battery energy storage systems have potential to provide benefits in certain applications, but the economics of such systems are not typically better than single technology systems for the cases evaluated.
- Optimizing the entire microgrid, with a focus on the sizing and integration of PV generation with ESS can provide significantly improved economics, e.g. reducing LCOE by an added 15% and increasing no-fuel critical load coverage by 70+% for NB Ventura County.
- Microgrids that participate in wholesale markets could increase revenue at three of the five modeled installations, with potential for nearly $0.5M/year in additional revenue for a facility such as Westover ARB.