EXECUTIVE SUMMARY

Real-Time Itemized Electricity Consumption Intelligence for DoD Bases

ESTCP Project EW-201335

SEPTEMBER 2019

Distribution Statement A
This document has been cleared for public release

Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

EXECUTIVE SUMMARY

Project: EW-201335

TABLE OF CONTENTS

Page

1.0 INTRODUCTION AND OBJECTIVES 1
2.0 TECHNOLOGY DESCRIPTION 3
3.0 PERFORMANCE ASSESSMENT 5
4.0 COST ASSESSMENT 9
5.0 IMPLEMENTATION ISSUES 11
6.0 CONCLUSIONS AND RECOMMENDATIONS 13

LIST OF FIGURES

Page

Figure ES-1. Belkin Echo System 3
Figure ES-2. Disaggregation Algorithm 4
Figure ES-3. The Prototype Residential Echo Module, Designed to Fit Under the Electric Service Meter 4
Figure ES-4. Building 1 - IT Activities 5
Figure ES-5. Building 2 - Barracks 5
Figure ES-6. Building 3 - Motor Pool Maintenance Facility 6

LIST OF TABLES

Page

Table ES-1. Objectives, Metrics, Data, and Success Criteria 1
Table ES-2. Performance Objectives, Criteria, and Results..... 6

Page Intentionally Left Blank

ACRONYMS AND ABBREVIATIONS

AC	alternating current
AFV	armored fighting vehicle
AHU	air handling unit
API	application programming interface
BEMS	building energy management systems
CT	current transformer
DDC	direct digital control
DoD	U.S. Department of Defense
DPW	Department of Public Works
FFT	Fast Fourier Transform
GB	gigabyte
HF	high frequency
HVAC	heating, ventilating, and air conditioning
IT	information technology
JBLM	Joint Base Lewis-McChord
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt-hour
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
MB	megabyte
NILM	Non-Intrusive Load Monitoring
NILMS	Non-Intrusive Load Monitoring System
SMPS	switch-mode power supply
TB	terabyte
UPS	uninterruptible power supply
VAC	volt-ampere reactive

LIST OF TABLES

Page

W	watt

Page Intentionally Left Blank

ACKNOWLEDGEMENTS

This project would not have been possible without the assistance from Joint Base Lewis-McChord's Department of Public Works; specifically, Mr. Sakhawat Amin and Mr. Patrick McLaughlin. Two building managers hosted our operations, namely, Mr. Bruce Parent and SSG Blaine Walters.

Adam Christensen of Three Seas contributed to the analyses and provided key data processing and graphics support. Mark Wilson and Gari Kloss provided life-saving editing.

Page Intentionally Left Blank

1.0 INTRODUCTION AND OBJECTIVES

Energy consumption in U.S. Department of Defense (DoD) buildings represents a major cost and has both security and environmental impacts. For these reasons, the DoD continuously seeks to reduce energy consumption in its building stock. The starting point must be a good understanding of how much energy is consumed and which devices are consuming it. The Belkin Echo is a novel technology that enables non-intrusive electricity monitoring of individual devices inside a building. Non-intrusive monitoring is attractive because it can substantially decrease the cost of acquiring detailed energy consumption data and permit rapid identification of energy waste or mechanical breakdown. One approach to non-intrusive load identification is to install a single, highly sensitive meter and apply cloud-based algorithms to identify unique high-frequency signatures of each energy-using device in the building.

The project's primary goal was to demonstrate the technology and its ability to guide retrofits in DoD buildings. Success would be demonstrated by meeting four quantitative objectives:

- Low-cost installation
- Accurate measurement of energy consumption
- Identification of energy consumption by individual devices
- Identification of energy-saving measures and their impact

These objectives were translated into the metrics, data requirements, and success criteria shown in Table ES-1.

Table ES-1. Objectives, Metrics, Data, and Success Criteria

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Simple, quick, and low-cost installation	Cost to install Belkin technology compared to submeters, measured in dollars	Track costs per device in each installation	Net savings of ~$1,500 in each building where the Belkin Echo technology is deployed compared to an estimated submetered cost of $5,000/building
Accurate measurement of total energy consumption	The difference between total consumption as measured by the Belkin Echo and ground truth equipment (or the utility meter when applicable) over a fixed period of time, in kilowatt-hours	Collect total measured energy by the technology Collect total measured energy from utility ground truth instrumentation Collect total energy reported by the utility meter (when available)	Total energy consumption to be +/- 2% of total energy reported by ground truth system (or utility meter) over said period of time

Table ES-1. Objectives, Metrics, Data, and Success Criteria (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria
Accurate disaggregation of energy consumed by individual loads	Energy Error metric and Event Detection metric.	Compare disaggregated data vs. actual data collected from ground truth instruments Aggregate consumption vs. aggregate ground truth vs. utility meter (if available)	Minimum 85% accuracy in energy reported and events detected/ classified Total energy consumption is +/-2% of actual total energy
Energy saving informed by the Belkin Echo technology	Reduction in energy consumption measured in kilowatt-hours	Establish an energy consumption baseline and compare to results after the technology is deployed	10% reduction compared to the baseline

A fifth qualitative objective was to provide clear, actionable data to the building's energy manager. The success of this objective was to be evaluated through interviews with key staff.

2.0 TECHNOLOGY DESCRIPTION

Belkin's Echo technology is comprised of three parts: (1) the physical sensor hardware, (2) the disaggregation algorithms, and (3) the user interface for presenting actionable energy intelligence (see Figure ES-1). The sensor collects real-time voltage and current measurements at one sampling rate, and broadband high frequency (HF) noise measurements at a second, much higher, sampling rate. The HF noise is created by devices as they switch on or off, or otherwise by switch-mode power supplies which are used in many modern appliances. The combination of power characteristics and the HF noise from each type of device has a unique "signature" that results from the device's internal electrical circuit design. Echo captures this signature and uses proprietary machine-learning algorithms to analyze it.

Echo technology further uses the amount of power drawn, length of use, time of day, concurrent events, and ambient temperatures (among others) to identify the energy consumed by category or device type. The system can generate reports, such as a consumption report similar to a credit card or telephone bill, and/or make data available to other systems for analysis or control.

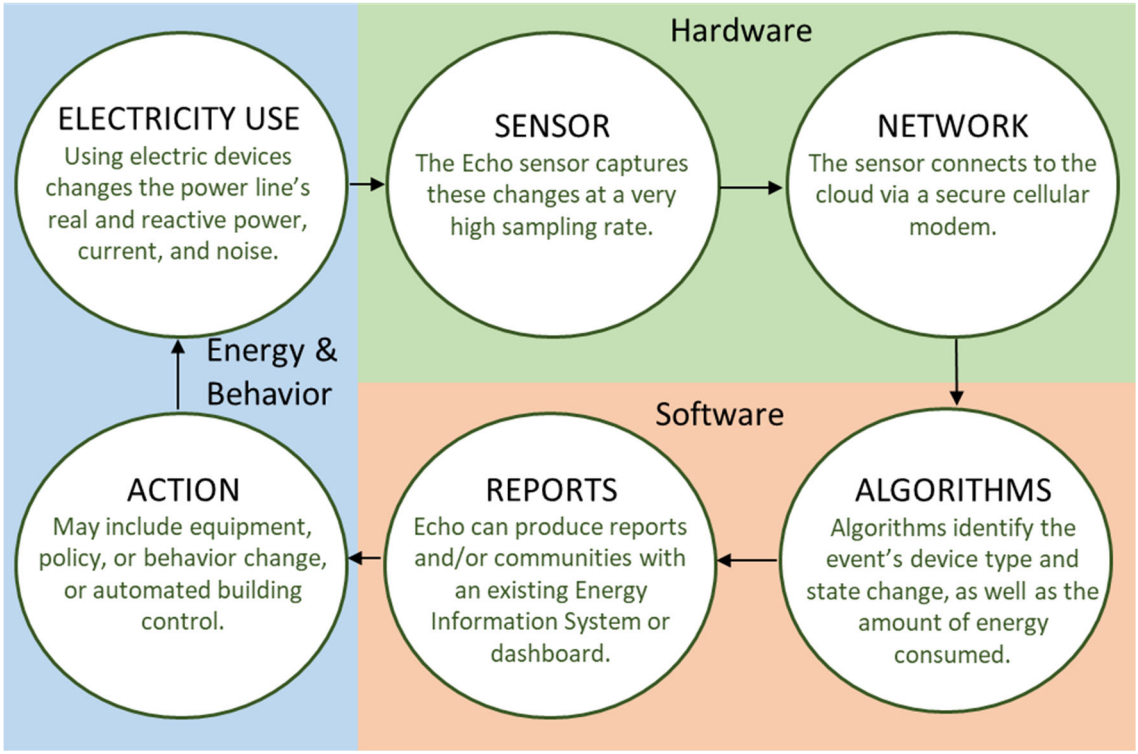

Figure ES-1. Belkin Echo System

Figure ES-2 illustrates, in part, the procedure in which Echo sensor data are translated into information about a device's energy consumption. The algorithm exploits knowledge about the presence of a device with "edges" (associated with a load turning on or off) in power use to calculate energy consumption.

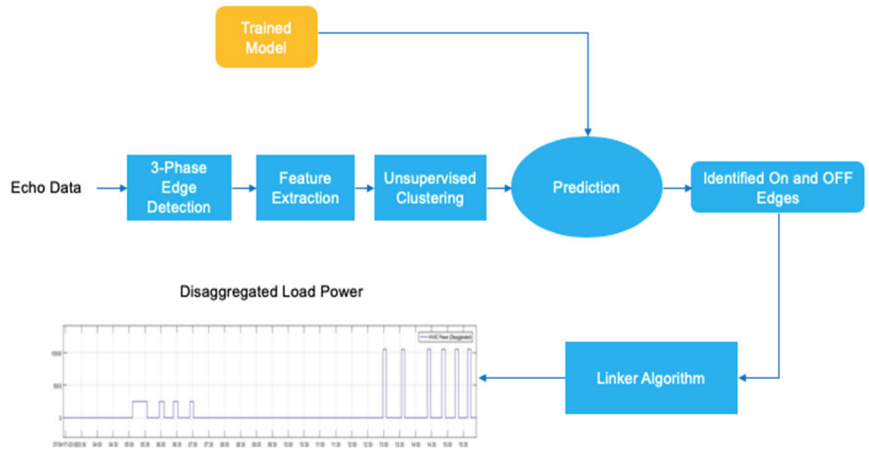

Figure ES-2. Disaggregation Algorithm

A residential version of the Echo had been created (Figure ES-3). One of the innovative features in this design was its easy installation: it could be inserted as a kind of ring behind a standard building kilowatt-hour meter. It was hoped that a similar design would be possible for smaller DoD buildings.

Figure ES-3. The Prototype Residential Echo Module, Designed to Fit Under the Electric Service Meter

3.0 PERFORMANCE ASSESSMENT

Echo's ability to generate accurate and actionable information was compared to the ground truth; that is, data collected through a parallel monitoring technology measuring electricity use at each building circuit. Joint Base Lewis-McChord (JBLM) was selected for the demonstration because the base has buildings that are excellent candidates, based on several criteria, including geographical location and logistical efficiency. Equally important, JBLM's Department of Public Works (DPW) was eager to test the Echo technology and collaborate.

The Echo was installed in three buildings at JBLM: a building housing information technology (IT) activities, a barracks, and a motor pool maintenance facility (figures ES-4, ES-5, and ES-6). The installations were undertaken sequentially so experience could be applied to subsequent buildings.

Figure ES-4. Building 1 - IT Activities

Figure ES-5. Building 2 - Barracks

Figure ES-6. Building 3 - Motor Pool Maintenance Facility

The project had varying success in achieving its initial objectives. All three buildings had three-phase power, rather than the split-phase power typically found in residences. The Echo system was customized for three-phase power, was installed in every building, and was simple, quick, and relatively inexpensive. The Echo was not able to generate an accurate itemization of electricity consumption, but it was able to identify some major loads and estimate their energy consumption. Data security issues prevented construction of a web-based dashboard to convey results and recommendations to the building energy manager. Instead, the recommendations were delivered in person to the relevant building manager with supporting documentation. Finally, it was possible to identify energy savings resulting from information delivered to the building energy managers in two buildings. The results are summarized in Table ES-2.

Table ES-2. Performance Objectives, Criteria, and Results

Performance Objective	Success Criteria	Results
Simple, quick, and low-cost installation	Net savings of ~$1,500 in each building where the Belkin Echo technology is deployed compared to an estimated submetered cost of $5,000/building	The total costs for a deployment of an Echo and circuit-level metering system in a single building were estimated to be $75,000 and $56,000, respectively. An Echo deployment in a single building costs about $19,000 more than a circuit-level monitoring technology. In this scenario, the project objective was not met. The higher costs of Echo data analysis are responsible for the largest difference, though they are offset by the lower costs of installation and removal. The Echo metering system would most likely be cheaper than circuit-level monitoring for basewide deployment because the Echo's costs decline sharply with scale. At least 10 buildings would need to be metered before the Echo technology would become competitive.

Table ES-2. Performance Objectives, Criteria, and Results (Continued)

Performance Objective	Success Criteria	Results
Accurate measurement of total energy consumption	Total energy consumption to be +/- 2% of total energy reported by the ground truth system (or utility meter) over said period of time	Echo achieved this performance objective based on comparisons with circuit-level metering.
Accurate disaggregation of energy consumed by individual loads	Minimum 85% accuracy in energy reported and events detected/ classified Total energy consumption is +/-2% of actual total energy	Echo was able to disaggregate large individual loads but was unable to disaggregate a large fraction of power consumption in the test buildings. Once a load was detected, however, Echo was able to reliably estimate monthly energy consumption within 11%–14% of ground truth in the devices examined. The algorithms designed to identify devices based on their high-frequency signatures were confused by the many simultaneous device events occurring in a commercial building. In addition, random high-frequency background noise caused by external sources complicated interpretation of the signal.
Energy saving informed by Echo technology	10% reduction compared to the baseline	Energy-saving opportunities exceeding 10% in the test buildings were identified with a combination of Echo and circuit-level data and building audits. However, Echo technology alone was unable to identify the devices causing the high consumption when the loads were individually small or continuously drawing a constant amount of power—two features that frustrated Echo's ability to detect them.
Provide clear, actionable data to the buildings energy manager(s)	Increase in satisfaction over the baseline	Data security issues prevented construction of a web-based dashboard. Instead, the recommendations were delivered in person to the relevant building manager with supporting documentation. Building managers appeared satisfied with this process and results.

Echo's most novel feature, extracting performance behavior from high-frequency power data, had difficulty identifying device signatures for three reasons. First, non-specific high frequency noise obscured many device signatures. Second, the high number of simultaneous device signatures greatly complicated identification. Finally, many devices had power consumption (or changes in power) of about 100 watts (W), which was below the measurement threshold when the building's total power demand was over 10 kilowatts (kW). The Echo was able to reliably identify only one load: the air handler fan. This load was larger than most and had distinct on/off edges.

Page Intentionally Left Blank

4.0 COST ASSESSMENT

The cost of obtaining itemized energy data from Echo was compared to that of obtaining the data from circuit-level measurements (such as those obtained through eGauge). The model draws upon cost elements that were tracked at JBLM or were estimated. Neither measurement system delivers true itemized consumption data,[1] but both systems often can identify and quantify major loads with post-metering analysis.[2] Note that this cost model does not include benefits, such as energy savings, but the benefits of the two options are discussed below and elsewhere in the report.

The total costs for a deployment of an Echo and circuit-level metering system in a single building were estimated to be $75,000 and $56,000, respectively. An Echo deployment in a single building costs about $19,000 more than a circuit-level monitoring technology. In this scenario, the project objective was not met. The higher costs of Echo data analysis are responsible for the largest difference, though they are offset by the lower costs of installation and removal.

The Echo metering system would most likely be cheaper than circuit-level monitoring for basewide deployment. Echo's costs decline sharply with scale, while circuit-level metering costs decline less so. In particular, the costs for analysis of Echo data will fall when many buildings at a base are concurrently metered. We did not estimate the number of buildings required for the Echo to be cheaper than circuit-level metering because there are too many uncertainties. Nevertheless, at least 10 buildings would need to be metered before the Echo technology would become competitive.

[1] Circuit-level monitoring provides itemized consumption for major loads on dedicated circuits, but not for circuits with multiple or diverse loads, such as plug-load and lighting circuits.

[2] An alternative cost model would use a system that acquired true itemized data. This system would resemble the Belkin WeMos used in this project to collect device-level data. However, this project demonstrated that it was impractical to attach them to all devices, and that the occupants quickly disconnected or disabled a significant fraction of them. Most important, the WeMos are highly intrusive and were therefore not a reasonable comparison system.

Page Intentionally Left Blank

5.0 IMPLEMENTATION ISSUES

Both technical and institutional barriers prevented full implementation and achievement of the project's goals. Belkin's Echo was designed for residential applications and required extensive modification to accommodate three-phase service at JBLM buildings. It also required time-consuming post-processing.

Power measurements typically had 1 percent resolution, which made a large fraction of the building loads indistinguishable from noise. This limitation is faced by all non-intrusive metering technologies in commercial buildings.

About 70 plug load power measurement devices were installed to directly (and intrusively) measure electricity consumption of specific loads as a means of validating the Echo's itemization estimates. However, occupants often unplugged them and some failed; as a result, little useful data were obtained.

The most important institutional barrier was restrictions on communications inside the bases. Robust broadband connections were essential because of the high data requirements for both the Echo and circuit-level metering systems. On-site storage was not practical because it required frequent visits for data transfer. For security reasons, we were not permitted to use base communications networks and were forced to develop a unique communications strategy for each building. This added costs and time to each installation.

Page Intentionally Left Blank

6.0 CONCLUSIONS AND RECOMMENDATIONS

This project's primary goal was to demonstrate the technology and its ability to guide retrofits in DoD buildings. The performance objectives were only partially achieved. The project was a success, however, in that it pushed the limits of a promising new monitoring technology and exposed its weaknesses when placed into real-world conditions. It showed where further research and development will be required to make the technology viable. The project also collected detailed energy consumption information about three, very different, categories of DoD buildings and untapped opportunities for energy savings. Unexpectedly, the project also showed the interplay between monitoring strategies and the identification of energy-saving opportunities. These are discussed below, along with some recommendations for further work.

High Continuous Use of Energy in Buildings. High continuous energy use by diverse equipment (e.g., fans, pumps, transformers, office equipment) was a feature in all three test buildings and in many commercial buildings. In Building 3, for example, almost half of the total electricity use was in the continuous category. All three conservation measures proposed in this project targeted these continuous loads (and the two measures that were implemented successfully reduced them). DoD should consider a program to specifically target and reduce continuous loads in buildings.

Large Energy-Saving Opportunities Still Exist in DoD Buildings. While not the primary goal of this project, several energy-saving measures were identified, implemented, and verified. In one building, ventilation fan energy consumption was cut 97 percent with only a four-month payback time.

Measurements of Higher Harmonics of Current. Activity in the fifth harmonic appeared to correlate with operation of some electronic loads. Current harmonic measurements require installation of current sensing devices such as those used in this project, so system installation would not simplify, but might add functionality. A modest research project (in the laboratory and the field) could confirm the existence and applicability of these signals for non-intrusive metering.

Non-Specific Sources of HF Voltage Noise. This project hoped to employ HF voltage noise as a means to identify devices and their operating behavior. HF device signatures were often obscured by other, seemingly random, HF noise. The sources of those noises could not be identified; indeed, it was not clear if they originated inside or outside the buildings. Further research is needed to identify the sources of this random noise and, if possible, filter them. The ability of the Echo system to perform as expected relies on finding a solution to this issue.

The Data/Information Dilemma. So much data and so little information. The Echo generated roughly 1 terabyte (TB) of data per day! In the end, however, relatively little actionable information was derived from it. Very high rates of data generation and transmission have direct and indirect costs. DoD should review the incremental value of building energy (and other operations) data and develop general guidelines for collection and storage. For example, analysis (and reduction) should take place locally as much as possible.

Optimal Combinations of Metering Strategies. The original premise of this project was that an Echo could collect data cheaper and more conveniently than through submetering or circuit-specific metering. Edge detection—the foundation of non-intrusive load monitoring systems (NILMS)—is still not sufficiently robust for application to commercial buildings, even when supplemented with clues from HF noise. There are just too many simultaneous events, many of which are caused by small devices whose power signatures are smaller than the measurement error of the sensors. Additionally, engineering and operations knowledge of facilities under study is a critical part of energy-related decision making, and, along with data collection, must be an explicit part of the information-gathering and analysis process.

Combinations of metering strategies may be more effective and cheaper. Ultimately, we are looking for a metering "sweet spot" involving a combination of the technologies described above. However, every building has unique technical and institutional characteristics which, if not taken into account, will result in unrealistic recommendations and reduced energy savings. Automated techniques for identifying and recommending energy-saving measures still need to be paired with audits and personal attention to the needs of the occupants and building managers.