FINAL REPORT

Real-Time Itemized Electricity Consumption Intelligence for DoD Bases

ESTCP Project EW-201335

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Alan Meier
Lawrence Berkeley National Laboratory

Omid Jahromi
Belkin International

Dan Cautley
Slipstream

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This project aimed to demonstrate and evaluate a novel technology that non-intrusively monitors the electricity consumption of individual devices inside a building. Belkin's Echo technology consists of a sensor and disaggregation algorithms. 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 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," which enables it to "itemize" electricity use of devices in the building. The performance objectives were only partially achieved. 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.

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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
JBLM	Joint Base Lewis-McChord
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt-hour
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
NILM	Non-Intrusive Load Monitoring
NILMS	Non-Intrusive Load Monitoring System
MB	megabyte
SMPS	switch-mode power supply
TB	terabyte
UPS	uninterruptible power supply
VAC	volt-ampere reactive
W	watt

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ABSTRACT

INTRODUCTION AND OBJECTIVES

This project aimed to demonstrate and evaluate a novel technology that non-intrusively monitors the electricity consumption of individual devices inside a building.

TECHNOLOGY DESCRIPTION

Belkin's Echo technology consists of a sensor and disaggregation algorithms. 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 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," which enables it to "itemize" electricity use of devices in the building.

PERFORMANCE AND COST ASSESSMENT

The performance objectives were only partially achieved. 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. Echo's most novel feature, extracting performance behavior from high-frequency power data, had difficulty identifying device signatures because: non-specific high frequency noise obscured many device signatures; the high number of simultaneous device signatures greatly complicated identification; and many devices had power consumption (or changes in power) around 100 watts, which was below the measurement threshold. More than 30 percent of all electricity consumption in the buildings was continuous, and that consumption was invisible to the Echo technology. An Echo deployment in a single building costs about $19,000 more than a circuit-level monitoring technology. The higher costs of Echo data analysis are largely responsible for the 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 Echo's costs decline sharply with scale, while circuit-level metering costs decline less so.

IMPLEMENTATION ISSUES

Belkin's Echo was designed for residential applications and required extensive modification to accommodate three-phase service at Joint Base Lewis-McChord (JBLM) buildings. It also required time-consuming post-processing. The most important institutional barrier was restrictions on communications inside the military bases. Security regulations prevented the use of base communications networks and forced development of a unique communications strategy for each building.

PUBLICATIONS

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EXECUTIVE SUMMARY

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)

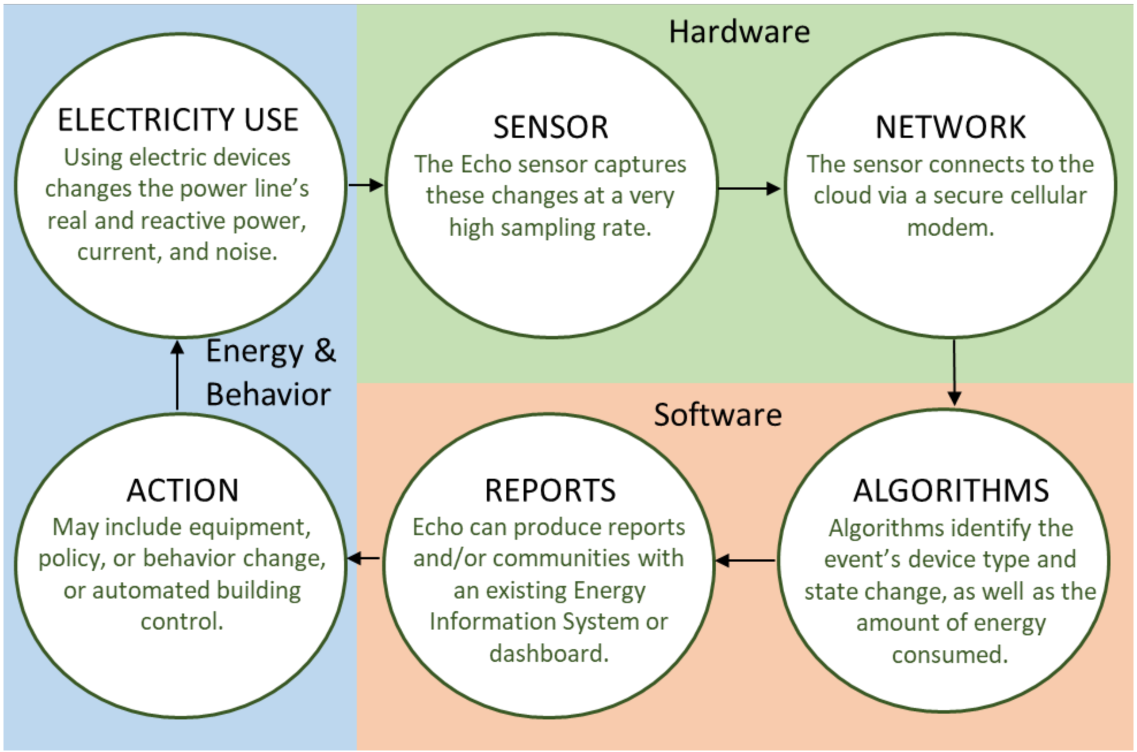
Performance Objective	Metric	Data Requirements	Success Criteria
Accurate disaggregation of energy consumed by individual loads	Energy Error metric and Event Detection metric.	Compare disaggregated data vs. actual data collected from ground truth instruments Aggregate consumption vs. aggregate ground 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.

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.



ELECTRICITY USE
Using electric devices changes the power line’s real and reactive power, current, and noise.

SENSOR
The Echo sensor captures these changes at a very high sampling rate.

NETWORK
The sensor connects to the cloud via a secure cellular modem.

ALGORITHMS
Algorithms identify the event’s device type and state change, as well as the amount of energy consumed.

REPORTS
Echo can produce reports and/or communities with an existing Energy Information System or dashboard.

ACTION
May include equipment, policy, or behavior change, or automated building 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.

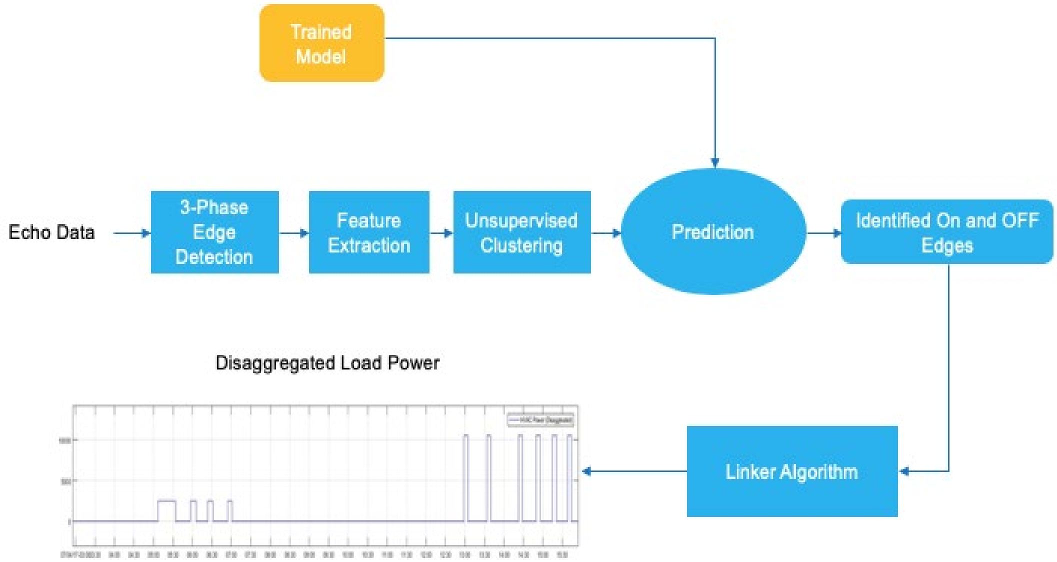


Figure ES-2. Disaggregation Algorithm

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

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 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.
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.

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,[2] but both systems often can identify and quantify major loads with post-metering analysis.[3] 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.

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.

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[2] 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.

[3] 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.

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.

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 would not simplify system installation, 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.

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1.0 INTRODUCTION

1.1 BACKGROUND

Many DoD buildings lack electricity meters or a means to regularly evaluate each building's energy consumption. Even when monthly electricity data are collected for a building, it is almost impossible to identify which equipment is using the most electricity and if the systems are functioning efficiently. Attaching meters to every energy-using device is very expensive and impractical. This situation makes it difficult to undertake cost-effective retrofits and equally difficult to evaluate the success of the retrofits. Non-intrusive monitoring of individual devices inside a building could provide a cost-effective alternative to attaching a power meter to every device of interest.

1.2 OBJECTIVE OF THE DEMONSTRATION

The Belkin Echo is a novel technology that enables non-intrusive monitoring of individual devices inside a building. This is accomplished by installing a single, highly sensitive meter and applying cloud-based algorithms to identify unique signatures of each energy-using device in the building. The primary goal of the project was to demonstrate the technology and its ability to guide retrofits in DoD buildings.

A secondary, qualitative, goal was to deliver the detailed—or "itemized"—energy consumption information to the building managers and document energy savings from installation of retrofits, repairs, and changes in operating practices.

1.3 REGULATORY DRIVERS

Belkin's technology addresses at least four existing and anticipated regulations, Executive Orders, DoD directives, and other drivers. Executive Order 13693 requires federal agencies to reduce energy intensity of operations by 2.5 percent annually. The Belkin Echo enables DoD to measure progress towards this goal at a more granular scale, evaluate savings from efforts to date, and identify new opportunities. The same Executive Order establishes a minimum renewable energy requirement for federal buildings by 2025. While Belkin's Technology does not directly reduce energy use, it enables building managers to identify underperforming equipment and waste, and observe reductions as a result of their actions, ultimately moving towards net zero energy goals.

The Energy Policy Act of 2005 is a significant driver for DoD energy efficiency. From the perspective of a building manager, its most important requirements are achieving a percentage reduction in buildings energy use (Section 102), mandatory energy use measurement (Section 103), and procurement of energy efficient products (Section 104). In each case, Belkin's technology helps the building manager realize these goals.

The Federal Leadership in High Performance and Sustainable Buildings (DOE 2019) commits federal agencies to implement a common set of sustainable guiding principles for integrated design, energy performance, water conservation, indoor environmental quality, and materials—and also requires establishment of energy performance goals. The commitment also includes measurement and verification in accordance with US. Department of Energy (DOE) guidelines.

The Belkin Technology provides the data to establish these goals and, ultimately, to demonstrate compliance.

DoD's overall goals for its facilities are codified in the Unified Facilities Criteria (UFC 3-400-01). The UFC calls for energy-saving measures and design standards in new buildings and existing buildings undergoing refurbishment. The relevant part of the UFC applying to this project and the Belkin Technology is the requirement for retrofits during the second phase. In this project, however, personalized information will be substituted for new efficiency improvements. These goals are echoed in the Army Energy Security Implementation Strategy of 2009. Among its five strategic objectives is increased energy efficiency across platforms and facilities. This project seeks to reduce energy use in an Army facility in a way that can be widely replicated in other facilities at low costs.

Belkin Echo offers the equivalent of submetering, but at lower costs and simpler data handling. ASHRAE and other groups are recommending increased levels of submetering. For example, submetering requirements were added to ASHRAE 90.1-2010. These requirements will ensure that the building operators receive information about all of the energy being used by building equipment.

DoD facilities are increasingly required to comply with LEED building requirements (or criteria similar to them). A key requirement of LEED is submetering, energy measurement, and verification in sufficient detail to enable usage analyses. These criteria can be achieved or exceeded, in part, with the use of the Belkin technology.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

"You can't manage what you don't measure." This adage is especially relevant to saving energy in buildings. Measuring the energy use of a building and the equipment inside it is the first step in saving energy. And, later, measurements are needed to confirm that the predicted savings were actually achieved. Unfortunately, measuring energy use is expensive, time-consuming, and intrusive. For these reasons, researchers have sought new techniques to measure energy consumption—especially electricity consumption—that are cheaper, faster, and less intrusive.

The traditional method to measure a building's or appliance's electricity consumption requires connecting the load to a kilowatt-hour meter (kWh-meter) and observing the cumulative consumption over a specified time, such as day, week, or year. Direct metering of loads (or sometimes circuits) is widely accepted as "ground truth" because it is highly reliable: the meters are accurate and there are few opportunities for errors to be introduced. Direct metering is attractive for a single device but less so when several devices in a home or building need to be measured, and especially if the building is occupied and the appliances are actually being used by people. The occupants trip over wires, disconnect meters, and often resent the intrusion. For these reasons, large-scale submetering of appliances in buildings is impractical.

Non-intrusive load monitoring (NILM) is generally defined as the identification and quantification of electric loads using measurements at a single location (e.g., meter or service entrance). A NILM system (NILMS) was first proposed and tested in the 1980s (Hart 1992). When a load—a refrigerator, for example—is switched on and off, it creates a characteristic transient electrical signature in the voltage and current domains of the incoming power. These transients can be identified by comparing the signals to the operation of a known appliance. When the time between switching on and off is measured, the appliance's electricity consumption can be estimated. The identification procedure becomes increasingly difficult as more loads are measured with a single meter because the combined signals become increasingly complex, masking the signature of individual loads. Hart's contribution was the automated application of Fourier transforms and other procedures to disentangle the signals. The procedure involved searching for changes in voltage and current waveforms—"edges"—that signal an appliance changing its power state. In general, full identification of loads (i.e., the pairing of an identified electrical signature with a known appliance or device) requires training—active identification of the loads being measured. Development of a library of waveforms corresponding to recognized loads is one concept that can contribute to accurate identification with little or no on-site training.

Early systems could typically resolve as much as 90 percent of a home's energy use, but only under controlled conditions and with extensive training (Lin et al. 2016). Researchers have continued to refine the approach by increasing the frequency resolution of the meter and improving the disaggregation algorithms. At the same, computation power has increased. These improvements have led to faster, more sensitive non-intrusive metering systems. Recently, several services have emerged to provide load disaggregation to residential customers. These systems typically sample loads at five-minute intervals. Most of the research and development has been directed towards residential buildings (Butner et al. 2013). NILMs have been applied to only a few commercial buildings under controlled conditions (Norford and Leeb 1996).

2.2 TECHNOLOGY DEVELOPMENT

Researchers at the Georgia Institute of Technology (Georgia Tech) significantly improved NILM technology in 2006 to include the ability to detect modern day consumer electronic loads, and published results in 2007 (Gupta et al. 2010). This initial work was sponsored in part by the National Science Foundation and the Intel Research Council. In 2009 Georgia Tech granted an exclusive license to Zensi, Inc., a corporation founded by the inventors. Zensi developed the system until it was acquired by Belkin in 2010. All rights were transferred to Belkin. Belkin has invested substantially and has deployed its monitoring devices in various pilot testing locations in California, Georgia, Illinois, North Carolina, and Washington.

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 2-1). The sensor collects real-time voltage and current measurements at one sampling rate, and broadband high frequency 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. Flowcharts for two key Echo procedures are displayed in Figures 2-2 and 2-3.

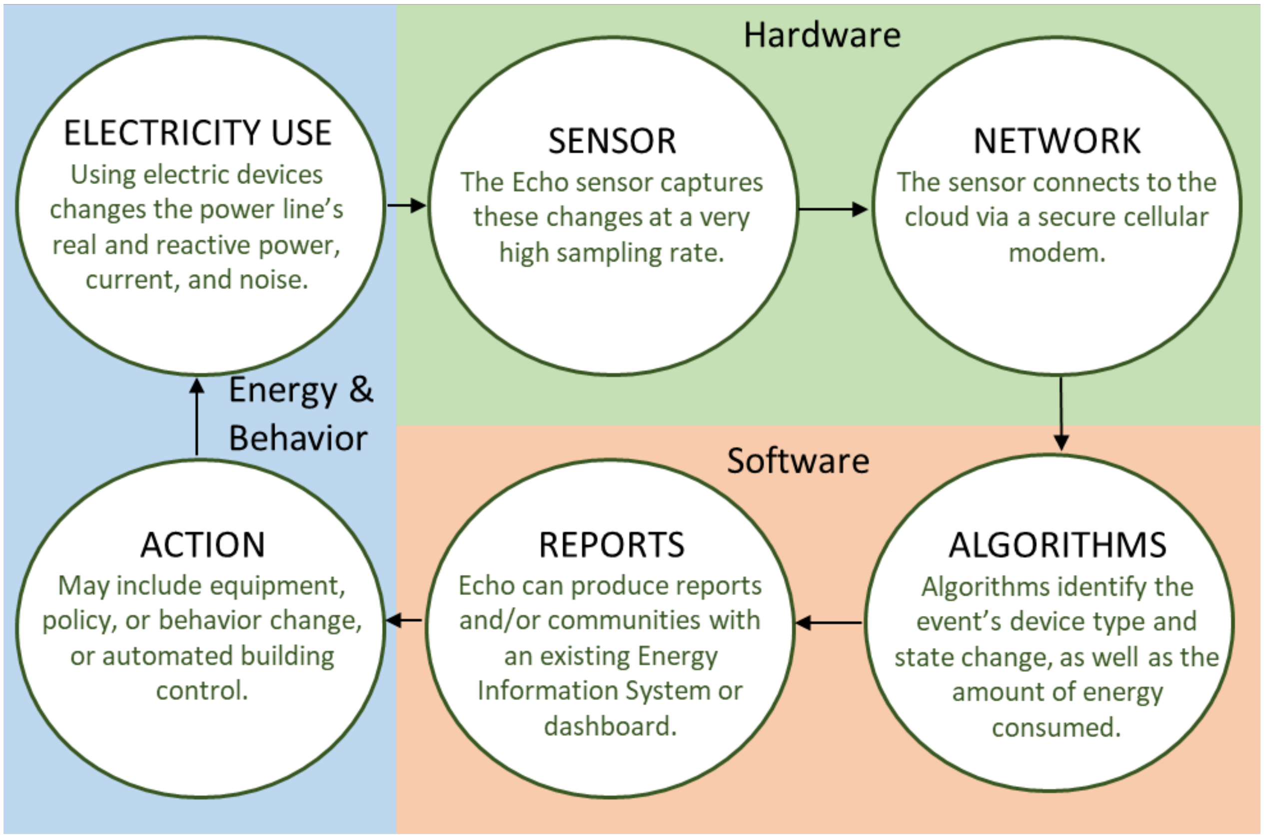

Figure 2-1. Belkin Echo System

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 (see Figure 2-2). 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.

The Echo Technology is well-suited to obtain itemized energy consumption information in smaller DoD buildings. This information is valuable because small buildings represent the majority of DoD's building stock—and a significant fraction of DoD's total building energy use. An important obstacle to reducing the energy use has been the absence of accurate data on an individual device's energy consumption and appliance-specific energy-saving opportunities, so improved data collection could support significant energy reductions in those buildings.

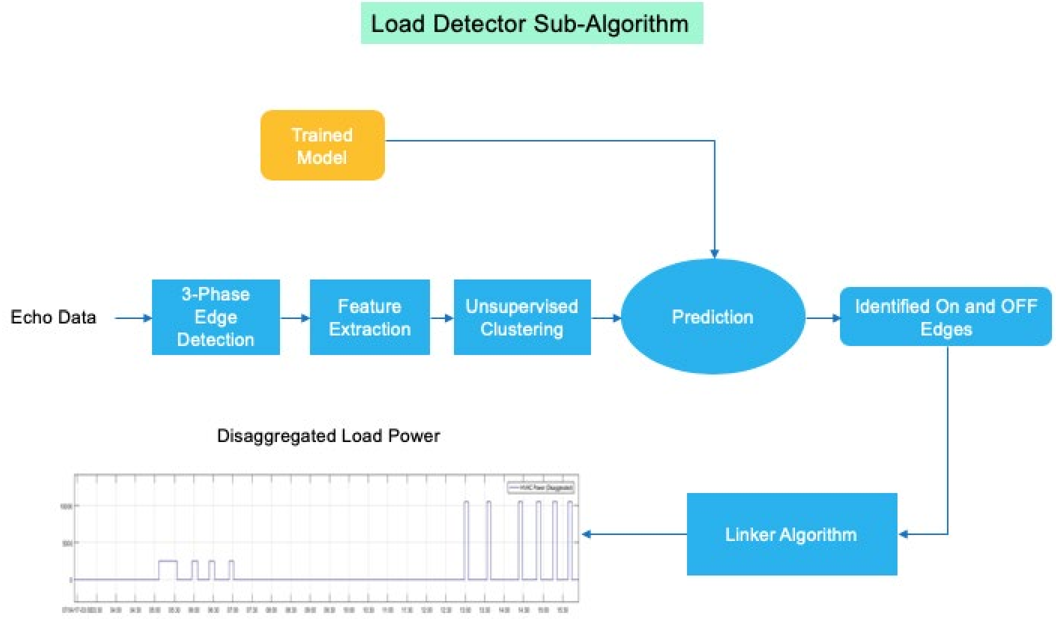

Figure 2-2. Flowchart of Echo Load Detector Sub-algorithm

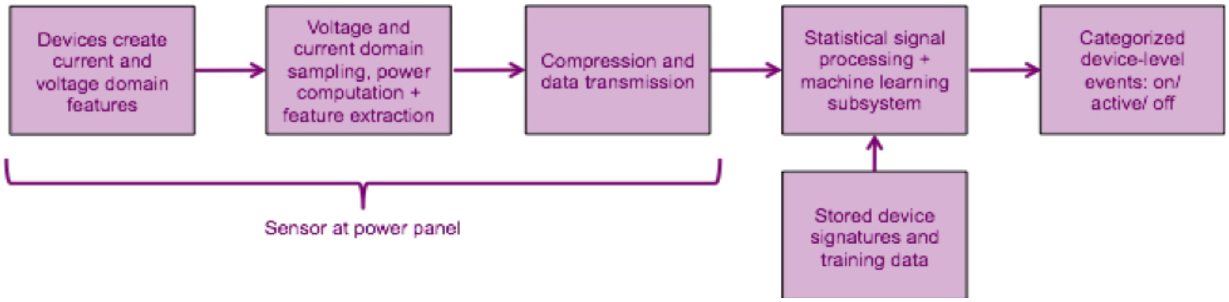

Figure 2-3. Technology Workflow

One of the innovative features of the Echo technology is the design of the sensor package. Belkin designed a prototype residential package that could be inserted as a kind of ring between the residential electrical panel and the standard building kilowatt-hour meter (Figure 2-4).

Figure 2-4. Prototype Residential Echo Module Designed to Fit in the Kilowatt-hour Meter's Form Factor

However, the residential Echo was designed for split-phase residential electrical service and could not be used for three-phase service commonly found in larger buildings. Rather than fabricate an entirely new Echo for three-phase service, Belkin chose to create a "virtual" three-phase meter, consisting of three split-phase meters. A laboratory version is shown in Figure 2-5, with current transformers (CTs) for current measurement.

Figure 2-5. Echo Hardware in Three-phase Box Form Factor (using CTs for Current Measurement)

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Based on Belkin's experience with the residential meter and additional research and development, it appeared that the Echo offered many advantages compared to conventional technologies for obtaining device-level energy consumption data. The anticipated advantages and risk prior to the initiation of the project are summarized below:

- **Performance Advantages:** The principal benefit to the DOD of a non-intrusive monitoring technology is exponentially increased information about energy use, which is especially valuable when presented in a clear and actionable way that directly translates to energy savings. Studies repeatedly show that giving energy users detailed, device-level information about how they use energy can reduce a typical building's electricity use by more than 10 percent. Some case studies have shown building electricity savings of 20 to 30 percent (Ehrhard-Martinez et al. 2010). Itemized or disaggregated energy information combined with analytical tools can be used to drive behavior change, inform equipment purchase decisions, help maintain building performance, and provide measurement and verification for other efficiency programs.

- **Cost Advantages:** There are no commercially available systems for non-residential buildings that itemize electricity information at this granular scale. The closest device is an electric submeter that costs several thousand dollars and is either read manually or requires added investment in data management. The cost of submetering is at least $5,000 per building, with few immediate savings. Meters are designed for ease of billing, not saving. Alternatively, metering at the circuit level is complex, expensive, and does not provide the device-level information expected from Echo. Belkin expected that its commercial Echo system (when in commercial production) would cost less than circuit-level monitoring and generate more actionable savings information.

- **Performance Limitations:** Echo exploits novel technologies and systems that naturally create new risks. To rapidly and efficiently identify electrical loads within a commercial building, Echo requires a database of electrical load signatures for commercial buildings. Unfortunately, this database has not yet been developed or validated. Creating this database—even a modest one—will require active training (against ground truth data or by other means). There is a risk that making such a database will be more difficult than expected. Another risk is that commercial-style military buildings have a higher background noise level than most residences, making current techniques to identify device signatures inadequate. It has already been determined that certain lights and smaller miscellaneous electrical devices have less intense signatures than high powered devices; indeed, accurate detection and identification of those loads was difficult. Finally, there are uncertainties regarding the delivery of information to the energy managers and occupants. Simply informing them of energy-saving opportunities does not guarantee that they will implement those measures.

- **Cost Limitations:** While hardware costs are minimal, a single Echo sensor collects about 1 TB of data every two days, so data storage costs need to be considered as deployments increase beyond the scope of the demonstration and into mainstream adoption.

- **Need for Additional Information:** Successful itemization of electric loads is just one element of an energy savings strategy; knowledge of building systems and operations, decision making authority, and (for all but the smallest improvements) funding are also necessary.

- **Potential Barriers to Acceptance:** There are both technical and institutional barriers to acceptance of the Echo. Technical barriers can occur where non-standard electrical connections prevent easy installation of the Echo. The original Echo device was designed to fit standard residential electric meters, and we developed a standardized installation approach for three-phase power systems. Inadequate, or unreliable, broadband access can be an even greater obstacle to installation and use of the Echo. Management and operators are unfamiliar with working with and maintaining a data-intense system.

- **Institutional Barriers that May Occur at Several Levels:** First, management and operators may be skeptical about the value of information in guiding efficient operation. Second, management may be unable to identify a logical recipient of the data. This person needs to be both in a position to receive the information supplied by the Echo and to act on it.

3.0 PERFORMANCE OBJECTIVES

This project's primary goal was to demonstrate the technology and its ability to guide retrofits in DoD buildings. Success was measured by four quantitative objectives:

1. Simple, quick, and low-cost installation
2. Accurate itemization of electricity consumption
3. Clear presentation to the building energy manager(s)
4. Identification of actual savings

The metrics, data requirements, and success criteria for these performance objectives are listed in Table 3-1 below.

Table 3-1. 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 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 Belkin Echo and ground truth equipment (or the utility meter when applicable) over a fixed period of time, in kWh	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 the total energy reported by ground truth system (or utility meter) over said period of time
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 Echo technology	Reduction in energy consumption measured in kWh.	Establish energy consumption baseline and compare to results after technology is deployed	10% reduction compared to baseline

Table 3-1. Objectives, Metrics, Data, and Success Criteria (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria
Qualitative Performance Objectives			
Provide clear, actionable data to the buildings energy manager(s)	Buildings energy manager(s) report a high level of satisfaction with the presentation and quality of the data	Perform two interviews to collect feedback from the energy manager(s): (1) The first interview prior to installation to create a baseline; (2) The second interview post installation to capture a satisfaction level.	Increase in satisfaction over the baseline

Figure 3-1 presents an overall timeline for the project. It lists the key milestones from project initiation to completion. More detailed timelines are presented for individual buildings in the narratives.

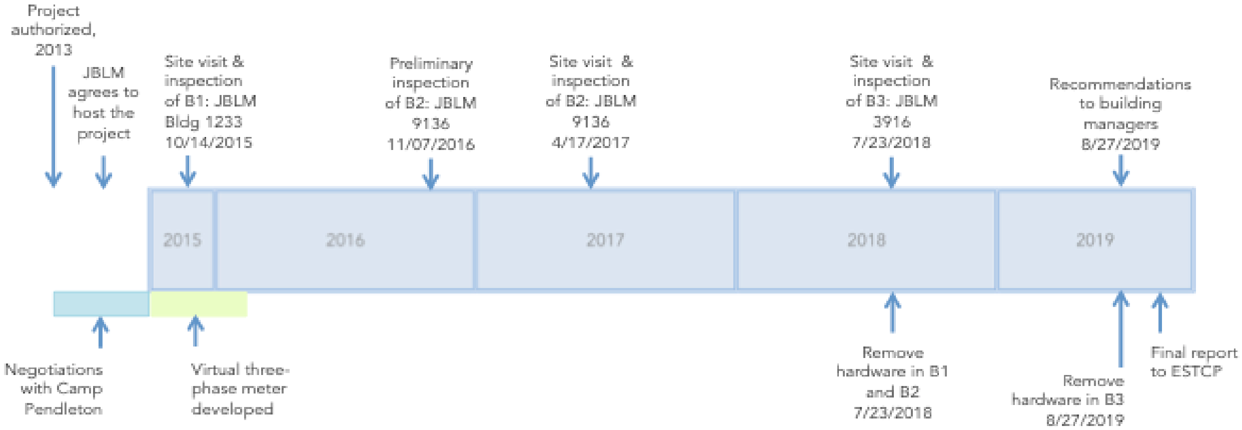

Figure 3-1. Project Timeline

The results of this project are summarized in the Table 3-2 below. However, each result has been greatly simplified, and many aspects are omitted. Detailed explanations of the results are presented in subsequent sections of this report.

Table 3-2. Summary of Project Results

Performance Objective	Success Criteria	Results
Simple, quick, and low-cost installation	Net savings of ~$1,500 in each building where 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 Echo's costs decline sharply with scale. At least 10 buildings would need to be metered before the Echo technology would become competitive.
Accurate measurement of total energy consumption	Total energy consumption to be +/-2% of total energy reported by 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 the 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 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 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.

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4.0 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

We had considerable difficulty identifying a suitable facility for the test. The major barriers were lack of suitable buildings, restrictions on communications/data transfer, and base staff that were unwilling to assist us. Negotiations with several bases fell through for one or more of the above reasons. Ultimately, Joint Base Lewis-McChord (JBLM) met our criteria, and it was selected. Appendix A lists the Points of Contact at JBLM and key personnel in the project.

Joint Base Lewis-McChord is a strategically vital, joint force power projection platform. Located 18 minutes south of Tacoma, Washington, and 25 minutes north of Olympia, the state capitol, JBLM is situated in a key location along Interstate 5, allowing easy access to Sea-Tac Airport and to the deepwater ports of Tacoma and Seattle. JBLM supports more than 40,000 active duty, National Guard and reserve service members in 2,119 buildings, which have a floor area of almost 24 million square feet.

JBLM was selected because the site has buildings that are excellent candidates for the demonstration 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. JBLM was also logically attractive because it was within driving distance of Belkin's Seattle facilities, which simplified the logistics of project management. Geographic and climate information for the selected location are described in Table 4-1 below.

Table 4-1. Climate Information for JBLM

Geographic Region	Pacific Northwest
Average Temperature	52°F
Average Annual Precipitation	37.13 inch
Days/Year with Precipitation	147 days
Annual Hours of Sunshine	2,163 hours

4.2 FACILITY/SITE CONDITIONS

Access to the buildings was generally easy thanks to the assistance of JBLM staff. However, two site conditions affected the project. First, no historical energy data were available for the buildings. In addition, the buildings lacked whole-building kilowatt-hour meters. Absence of historical consumption data prevented us from gaining a deeper understanding of the buildings' long-term performance. Lack of whole-building meters prevented easy calibration of the ground truth data. These problems are typical for bases and were not entirely unexpected.

The second site problem was difficulty in establishing broadband communications. Base security policies prevented us from piggybacking on existing communications systems. In Building 3, a cellular system was installed to transmit data.

5.0 TEST DESIGN

This section describes the framework for testing the Echo technology. The testing framework evolved significantly between the initial (proposed) approach and the approach actually employed. The principal reasons for the changes were constraints imposed by the tested building and limitations of the Echo technology. Both approaches are described, and the reasons for changes have been explained below.

Note also that testing a metering technology is inherently different from testing a new device, retrofit, or piece of equipment. The Echo does not save energy directly; instead, it collects information that enables a building manager or base utilities department to more effectively identify energy-saving opportunities. Evaluating the technology's effectiveness is therefore inherently different, too.

5.1 CONCEPTUAL TEST DESIGN

The measurements were designed to evaluate the performance objectives under uncertain conditions. The test plan needed to be flexible enough to accommodate changing conditions in the buildings being monitored. At the same time, the tests needed to accommodate the inevitable glitches associated with a prototype technology undergoing its first full-scale field test.

5.2 BASELINE CHARACTERIZATION

Two phases of evaluation were originally envisioned in this project. The first phase compared the Echo outputs to ground truth. In this case, "ground truth" was the electricity consumption measured by a custom-installed data-logging system (eGauge). This system consisted of meters on all major building circuits. In addition, selected devices and equipment were metered with specially modified versions of Belkin's wireless WeMo "smart plug" measurement and control devices.

The project's second phase sought to deliver itemized information to the building managers and occupants, along with recommendations for energy-saving actions. It was anticipated that the building manager would implement these recommendations and achieve a reduction in energy use. Thus the second evaluation focused on understanding the delivery of information and actions taken by the building managers and occupants. The building's energy use prior to the retrofits was expected to serve as the baseline. (Pre-retrofit energy consumption was assumed to be obtained from the Echo or submetered data. If the building was equipped with a utility meter, then longer-term pre-retrofit consumption would be available, too.) Continued measurement after the implementation of energy efficiency measures allows determination of energy savings.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The principal technology components in Echo are the sensor and the software algorithms to evaluate the data. Ideally, the sensor is configured into a ring that can be inserted easily into a conventional kilowatt-hour meter at the building service entrance (Figure 2-4). This design was successfully fabricated and used for residential, two-phase Echo sensors. The original design could not be used in this project because all the JBLM test buildings (and most military buildings) are serviced with higher voltage, three-phase power. Instead, a "virtual meter," consisting of three residential meters, were used, one on each phase. This virtual meter was installed where the power entered the building (Figure 2-5).

The second major technology component was the collection of algorithms used to "itemize" the building's energy consumption. These algorithms resided either on the cloud or in Belkin's own computers. Flow charts describing the energy disaggregation algorithm were introduced earlier (Figures 2-2 and 2-3).

5.4 OPERATIONAL TESTING

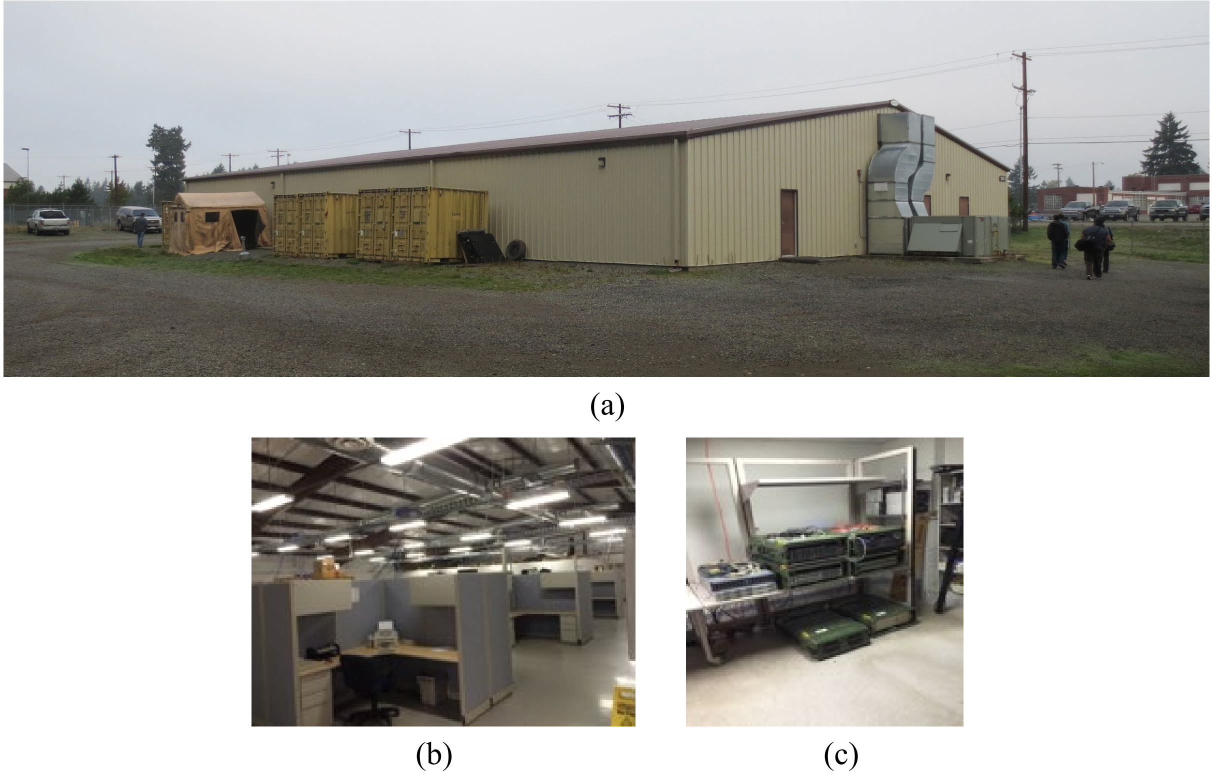
The operation of the Echo was tested in three buildings; these tests are described separately, in a narrative for each building. Separate descriptions are necessary because of differences in the buildings, the testing strategies, the analyses, and other circumstances.

Each narrative includes a description of the building and our reasons for selecting it. Then we discuss issues related to the installation of the Echo (and the ground truth metering), the period of testing, and the evaluation. Finally, we discuss some of the building-specific results.

5.4.1 Building 1

Building Description

Building 1 is a 10,000 square foot (ft^2) single-story, slab-on-grade office building (Figure 5-1). The building's primary function is IT and computer support. A large fraction of the floor area is open for cubicles, with enclosed offices along much of the perimeter. About 20 people work in the building. It has no windows. It contains toilets, showers, a small kitchen, and a utility room. One room is dedicated to repairing and testing servers.


(a)

(b) (c)

Figure 5-1. Building 1 (a) Exterior, (b) Interior Cubicles, (c) Server Room

The building is heated with a single packaged, forced-air heating, ventilating, and air conditioning (HVAC) system that includes natural gas heating and compressor-driven cooling. A networked thermostat controlled building temperatures and heating schedules—it could be (and was occasionally) adjusted by the building manager to meet comfort needs. An additional air conditioner was installed during the measurement period to cool the server room. An electric heater provides hot water for rest rooms (with showers) and a kitchenette.

The principal activity in the building is providing IT and logistical support to various missions. As such, the number of occupants varied widely as staff were moved to forward bases. Staff typically worked weekdays, except for surges when preparing for a mission.

The building contained many computers, servers, and ancillary equipment.

The building was selected because its systems appeared to be relatively simple and it had no unusual loads. It contained many computers and a variety of office equipment, which would be typical of many DoD buildings. A timeline for Building 1 is shown in Figure 5-2.

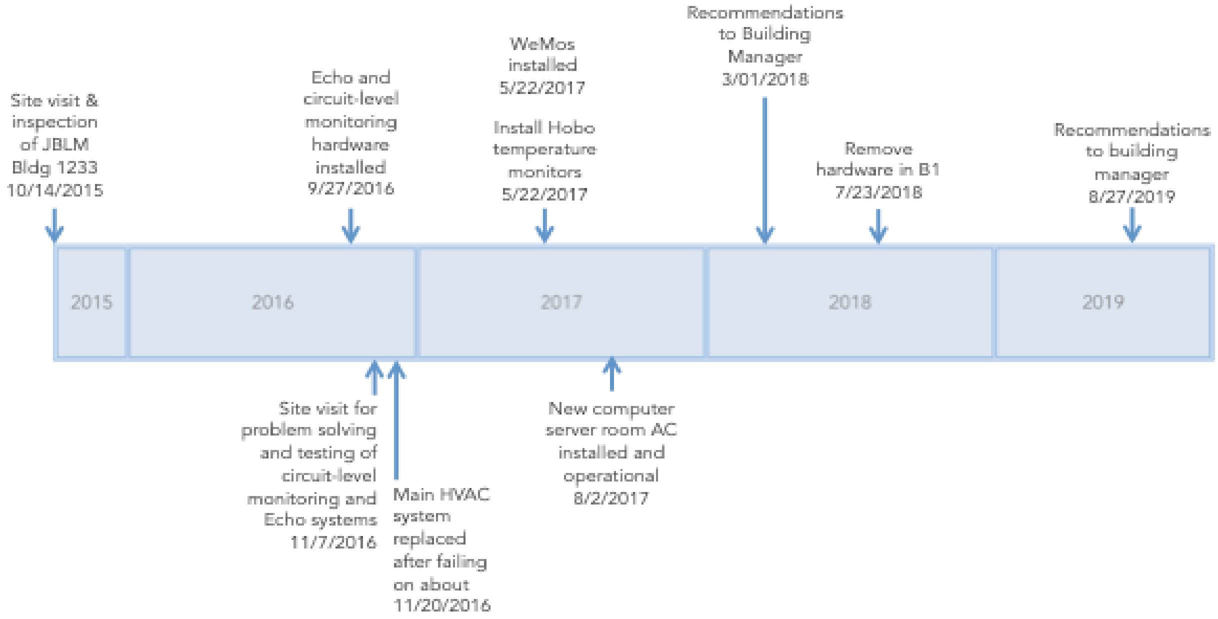


Figure 5-2. Timeline for Activities in Building 1

Equipment Installation Issues

The Echo was designed for residential, dual-phase[4] service, so it had to be adapted for three-phase service in Building 1 (and all subsequent buildings). Rather than fabricating a new, native, three-phase sensor, Belkin installed a dual-phase unit on each line and created a "virtual" three-phase sensor by digitally combining and synchronizing the data. This is shown schematically in Figure 5-3.

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[4] We use the term "dual-phase" to describe typical U.S. residential electric service in which power is delivered on two 120-volt lines that are 180 degrees out of phase with one another. Other terms for this system (e.g., "split-phase") exist.

This procedure was unexpectedly complex. In addition, the team opted to install Echo devices at each subpanel rather than at the main electric service entrance, and with three separate panels, this required nine Echos.

The initial installation did not capture the HVAC system, which was served through a disconnect in the main service panel and would have required an additional set of three Echo devices. (The circuit-level monitoring system was wired to pick up HVAC power, however.)

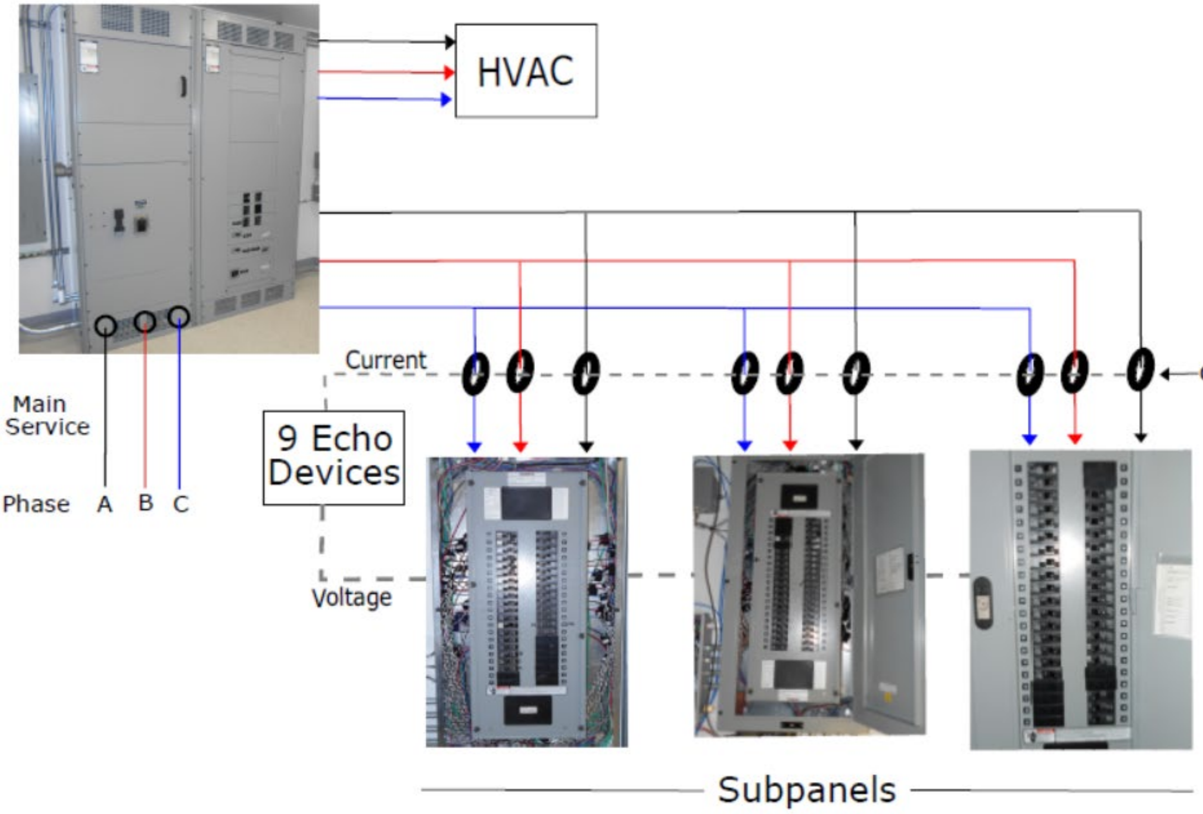

Figure 5-3. Schematic of Nine Echo Devices Acting as Virtual Three-phase Sensors, Connected to Three Subpanels

Ultimately, on further discussion with the local electrical contractor, the team determined it would be practical to install Echo devices at the main electrical service entrance to Building 1, consistent with the original intent of the project. The service wiring used three parallel conductors on each of the three voltage phases—a typical arrangement in commercial facilities with significant loads. Rather than attempt to measure the total current through all the parallel conductors, the team installed a single CT on one of the three conductors on each phase. Assuming the current in parallel conductors is self-balancing and very nearly equal, the total current on each phase is then simply three times the measured current (with power following the same rule). This approach, when practical, greatly simplifies installation and reduces the number of Echo devices required. Two Echos were used (each Echo is capable of measuring power on two phases). In this case, it also meant that HVAC power would be included in the Echo data. The updated installation schematic is shown in Figure 5-4.

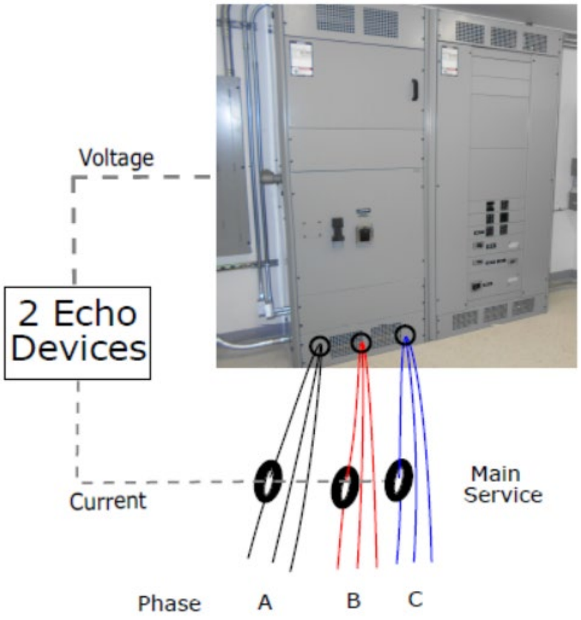

Figure 5-4. Echo Devices Using a CT on One of Three Parallel Conductors on Each Phase of Power at the Service Entrance

The circuit-level meters for acquiring ground truth (eGauge devices) on each of the 92 circuits in the building were installed without major problems. This was a substantial installation based on number of subpanels and separate eGauge devices required.

A second level of measurement was undertaken to monitor electricity consumption of individual pieces of equipment. These measurements were collected to verify Echo's itemization procedures. A smart plug capable of measuring electricity use and transmitting the results via Wi-Fi was used to collect electricity use from any 120 volt plug-in device, including PCs, displays, printers, a drinking fountain, a refrigerator, and other types of office equipment. These smart plugs were specially modified Belkin WeMos. About 70 WeMos were installed. To our knowledge, this was the largest single installation of WeMos ever attempted. This installation required unusual arrangements; for example, Wi-Fi routers were specially modified to capture location-specific WeMo data.

For operational and security reasons, the servers and computers could not be submetered. Gas consumption was not metered.

Operational Issues

Conditions in the building changed over time. The number of occupants fluctuated as staff prepared for missions, departed, and returned. Servers—each drawing a few hundred watts— were also sent on missions, while others were brought back.

The building HVAC unit failed in late November 2016, and was replaced in early December. An additional ductless air conditioner was installed in August 2017 to cool the primary server room. During the winter, occupants in some perimeter offices used supplemental resistance heaters; their usage depended on outside temperature and deployments. This consumption appeared on appliance circuits.

Evaluation Issues

Capturing ground truth energy consumption with the WeMos for a large number of individual devices in an actual working environment proved much more difficult than expected. There were frequent interruptions, discontinuities, and terminations in the WeMo data, in part because the occupants disconnected the WeMos. WeMos were sometimes unplugged briefly, while at other times they were moved to different devices, or removed entirely, creating difficulty in matching Wemo data to both Echo and circuit-level data. Ultimately, the WeMo measurements were not of value for verification of the Echo's itemization because the Echo was generally not able to identify these small loads.[5] This experience illustrates the difficulty of collecting true device-level consumption data for extended periods in a commercial building.

Building-Specific Results

Some findings for Building 1 are presented in Figure 5-5, below. These results cover both the building's energy consumption patterns and the performance of the Echo. More general discussion of the Echo's performance is discussed later.

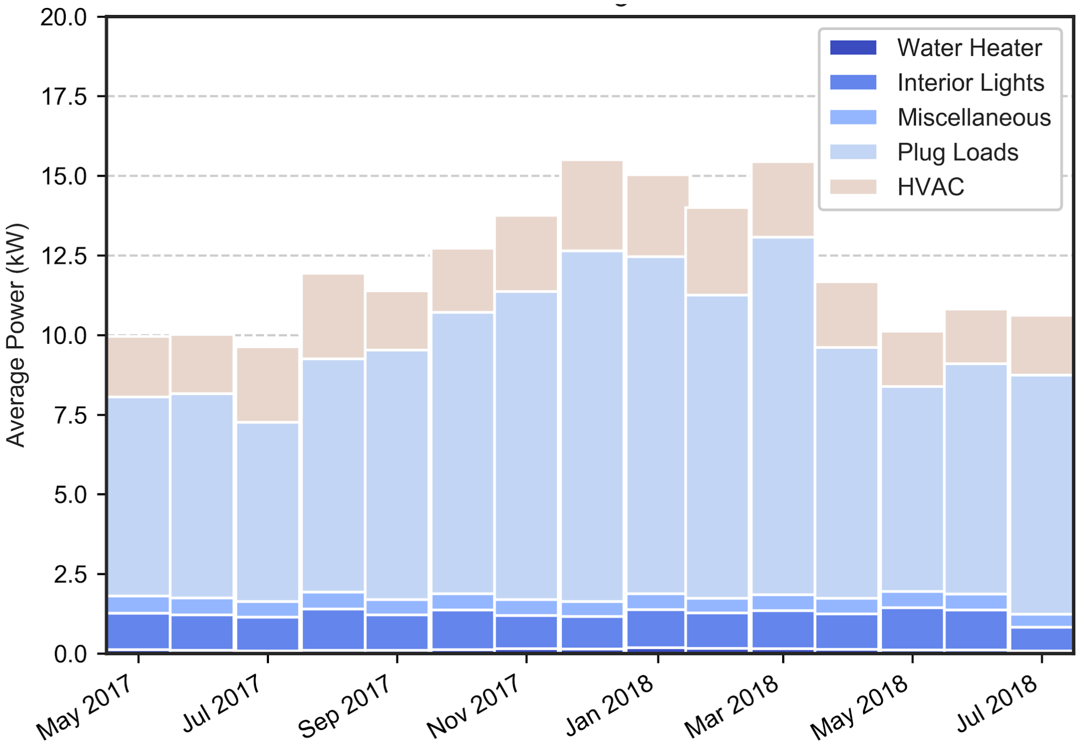

Figure 5-5. Building 1 Monthly Average Power

Power aggregated by major end load categories.

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[5] The WeMos were not used in subsequent buildings after it became clear that the Echo system could not detect most plug loads.

A monthly electricity consumption profile (expressed in terms of average power) is shown in Figure 5-5, broken down by major end uses. (Note that these data were obtained through circuit-level measurements rather than from Echo.)

Figure 5-6 shows a more detailed profile; a time series plot of electricity consumption over a typical week. The building is generally completely unoccupied outside normal work hours, and the baseline energy consumption appears to be made up primarily of plug loads with near-continuous power use (probably IT servers) and HVAC continuous fan operation.

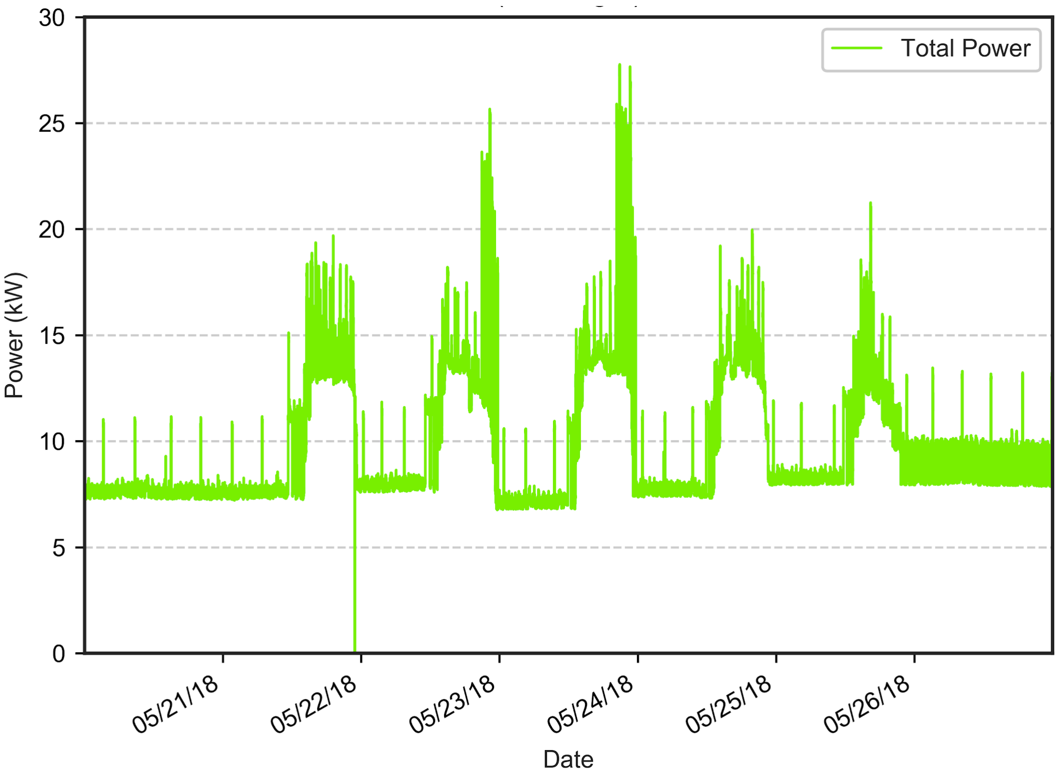


Figure 5-6. Building 1 Total Power Consumption Profile Over a One-week Period

Two trends are evident in this building. First, electric power consumption does not fluctuate much with season; this is not a surprise because, while the building has air conditioning, it was not used very often, and heat is provided by gas. Lighting does not vary by season because there are no windows. Second, plug loads are responsible for roughly half of Building 1's electricity. This consumption includes a high fraction of continuous or standby power use.

Some load-specific plots, based on circuit-level data, demonstrate patterns of energy consumption over time (see Figures 5-7 through 5-9). See Appendices B, C, D, and E for details of accuracy and sensitivity.

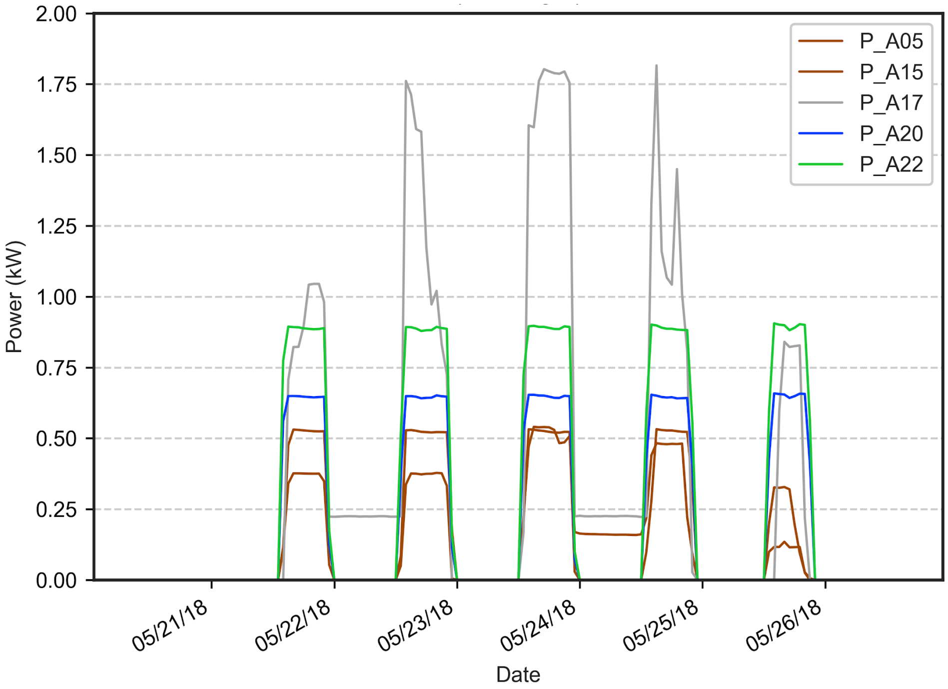


Figure 5-7. Building 1 Lighting Energy Use by Individual Circuit Shows Consistent Operation During Occupied Hours and Good Discipline in Turning Lights Off When the Building is Unoccupied

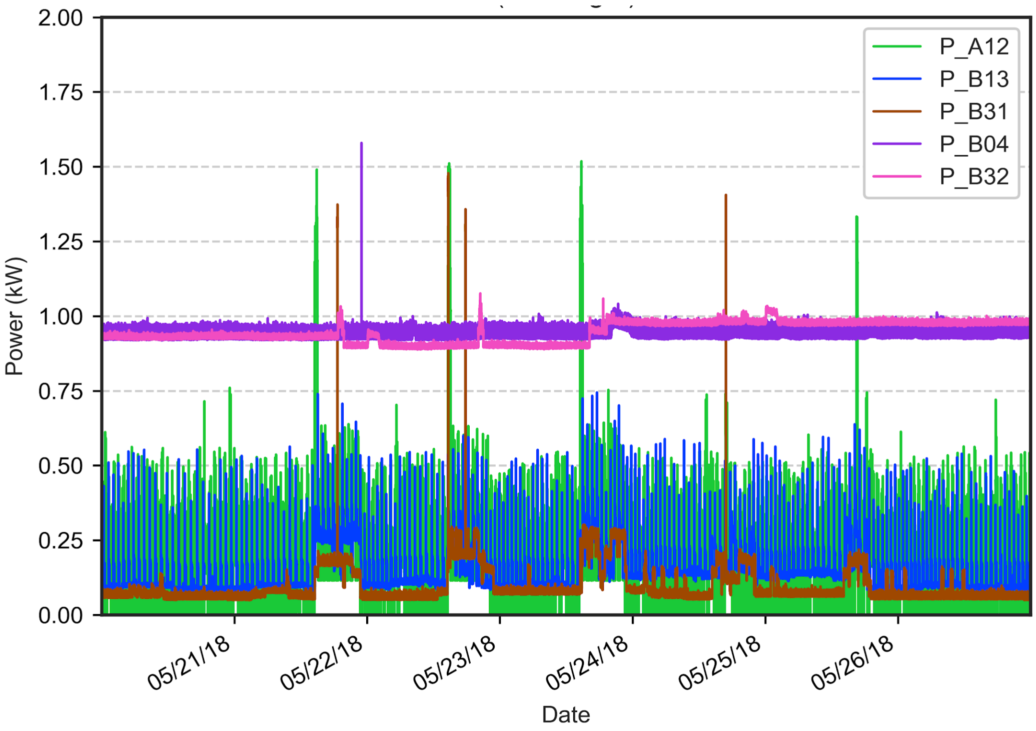


Figure 5-8. Building 1 Plug Loads for Selected Circuits, with Some Circuits Showing Near-constant Use Over Time (e.g., for Server Operation), with Others Showing Fluctuation or Cyclical Operation

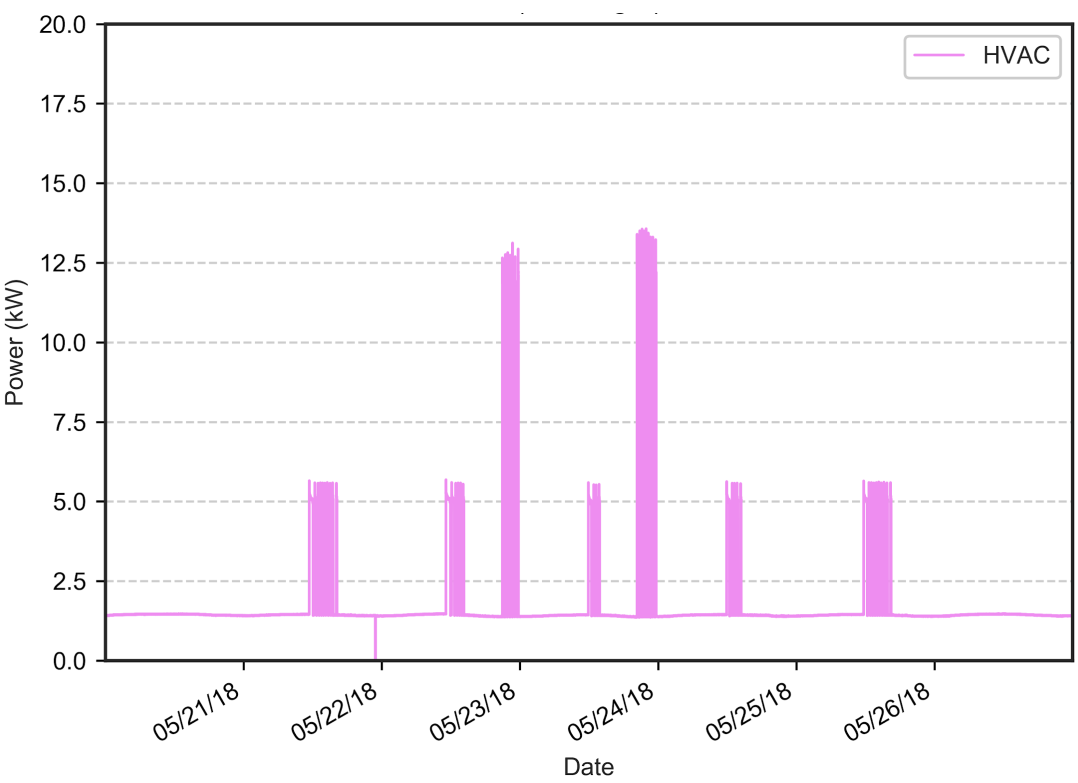


Figure 5-9. Building 1 HVAC Energy Use Shows Evidence of Normal System Cycling

The system runs regularly for heating in winter months, but inspection of the data revealed that cooling is used sporadically (and this was confirmed in discussion with the building manager). The baseline energy use of about 1.6 kW indicates continuous fan operation, which probably can be reduced.

The Echo algorithms were able to reliably identify only one load: the air handler fan. This load was larger than most and had clear on/off edges. Roughly 30 percent of Building 1's loads were invisible to Echo because they were continuous loads and did not provide the necessary edges for identification with its algorithms. Other loads were undetectable; their relatively small on/off signals were obscured by other equipment (discussed in detail later).

Analyses of high frequency voltage spectra were performed but found to be unreliable as an element in the itemization process (see Appendix D). Random, ambient high-frequency electrical noise obscured device events and confused the Echo algorithms. The sources of the noise could not be identified but appeared to have come from both outside and inside the building, and may have included devices and systems as diverse as IT components, transformers, and motors. One specific source of interference was identified, the switching power supply in an uninterruptible power supply (UPS) for lighting. It exhibited a high-frequency signal and pattern of power use. These spikes obscured many device transitions (edges) and confused the Echo algorithms. For this reason, no further analyses of high frequency voltage patterns were undertaken.

Supplying Itemized Consumption Data to the Building Manager

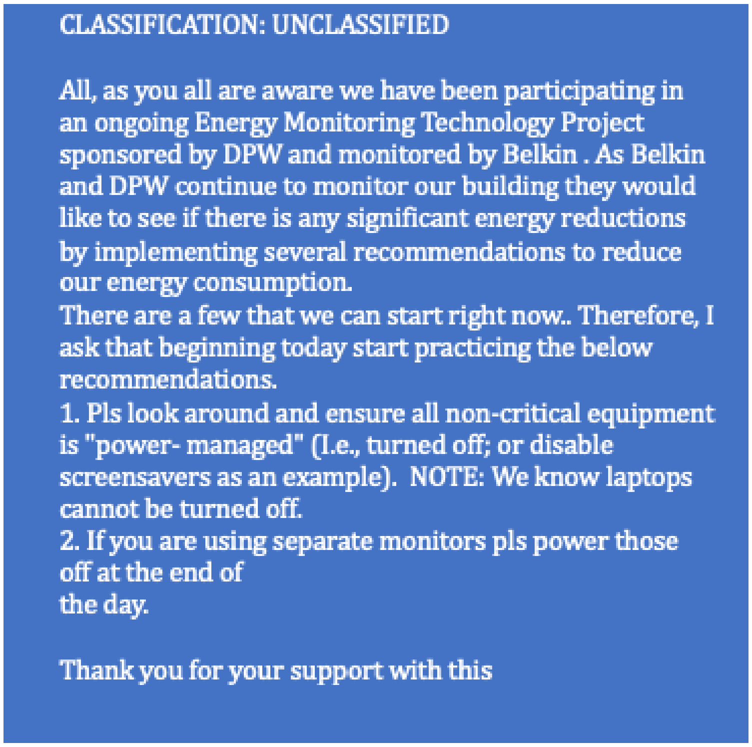
We had insufficient electric power itemization from the Echo system to test the proposal that providing itemized energy consumption information to the building manager could save energy.

As a substitute, we used circuit-level measurements to provide this information and as a basis for recommendations to reduce energy consumption. We presented our analysis to the building manager and the Department of Public Works and made the recommendations shown in Table 5-1.

Table 5-1. Energy-saving Recommendations for Building 1

Energy-Saving Recommendations	Estimated Energy Savings in End Use
Install carbon dioxide sensor to control ventilation	40% of ventilation
Install light-emitting diode (LED) lighting and local motion sensors	20% of installed lighting
Operations: Ensure that all non-critical equipment is power-managed (disable screensavers on displays, etc.)	0%–20% of Office Equipment
Install skylights or light tubes	5% of lighting
Re-paint roof with “cool” surface to reduce AC energy	5% of cooling

Most of these measures required considerable investment in new equipment and staff time to install; as a result, they were deemed not immediately feasible. A behavior change program to address plug loads did appear feasible, and with office equipment representing a large fraction of total energy consumption, it was an attractive option. At his own initiative, the building manager requested occupants to switch off office equipment when they left the building or were not otherwise using it. His message is duplicated in Figure 5-10.



CLASSIFICATION: UNCLASSIFIED

All, as you all are aware we have been participating in an ongoing Energy Monitoring Technology Project sponsored by DPW and monitored by Belkin . As Belkin and DPW continue to monitor our building they would like to see if there is any significant energy reductions by implementing several recommendations to reduce our energy consumption.
There are a few that we can start right now.. Therefore, I ask that beginning today start practicing the below recommendations.
1. Pls look around and ensure all non-critical equipment is "power- managed" (I.e., turned off; or disable screensavers as an example). NOTE: We know laptops cannot be turned off.
2. If you are using separate monitors pls power those off at the end of
the day.

Thank you for your support with this

Figure 5-10. Message Distributed by the Building Manager of Building 1

The building occupants responded by:

- Turning off nearly all computer monitors
- Turning off all printers
- Turning off a paper shredder
- Unplugging microwaves and coffee pots
- Unplugging CD and DVD duplicator machines

The impact of his request and the occupants' actions are shown in Figure 5-11. The period covers 17 days prior to and 17 days after the announcement.

Reductions in electric consumption started immediately after the building manager's request to staff, but usage further decreased over a period of at least two weeks after the request. Comparison of the 17-day pre- and post-announcement periods shows about a 25 percent reduction in office equipment electricity use (and a 17 percent reduction in total building electricity use). The persistence of behavioral energy use changes is always difficult to measure, and is complicated in this case by mission-related staffing changes, transfers of occupants, and installation of new equipment. The building manager was interviewed 16 months later to gauge the persistence of these behaviors. He stated that the behaviors described above had become fully adopted and routinized by staff and, if anything, expanded since initiation. Thus, energy savings probably persisted, if not rose.

This small experiment confirms the large potential savings available through more careful control of office equipment, and the importance of occupant behavior.

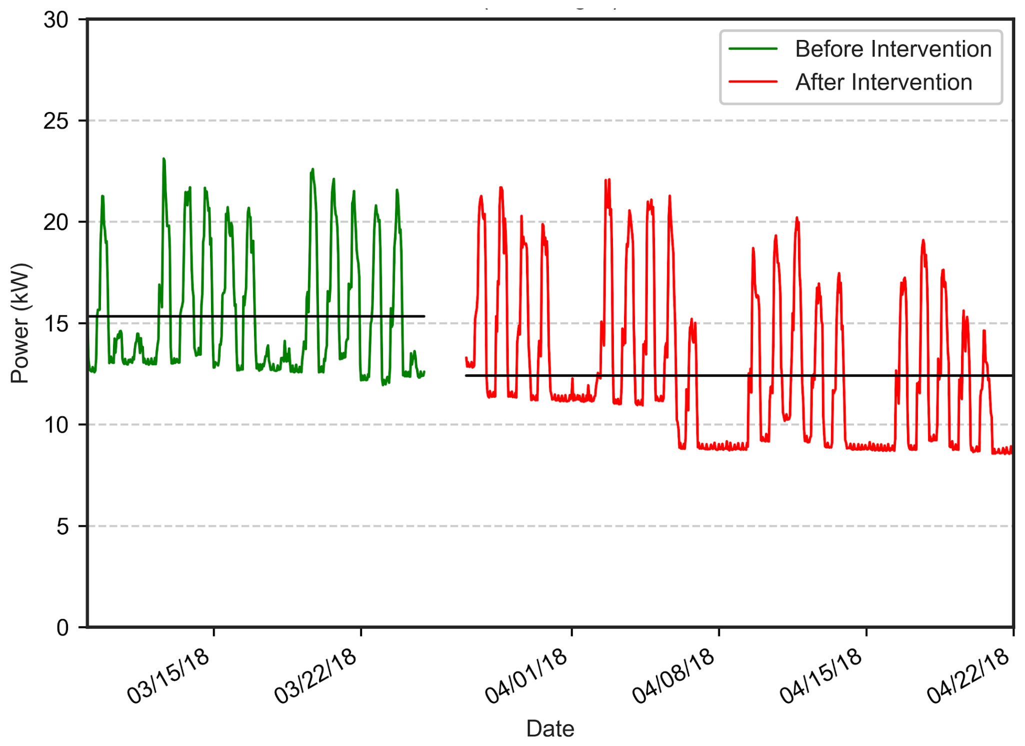


Figure 5-11. Power Draw Decrease Driven by Behavior Changes, Specifically a Building Manager's Instructions to Staff to Exercise More Active Control of IT Hardware

5.4.2 Building 2

Building Description

Building 2 is a recently constructed multi-story barracks, consisting of 18 three-bedroom apartment suites, administrative offices, and common areas (Figure 5-12). At the time of construction it earned an LEED Silver accreditation. Heating is delivered from a central gas boiler on the ground floor, with hot water distributed to fan coil units in individual suites. There is no air conditioning. Each suite contains a small kitchen and laundry (with especially efficient appliances). Larger, commercial-grade washing machines and dryers on the ground floor are available to clean bulky gear after exercises and missions. Building 2 has master electricity and gas meters, but historical consumption data were not collected.

Figure 5-12. Building 2 - Barracks

The building was selected because barracks and residences represent a large fraction of DoD building stock. It was, however, recognized that finding energy savings would be challenging because an LEED building should already be energy-efficient.

Figure 5-13 shows a timeline for Building 2.

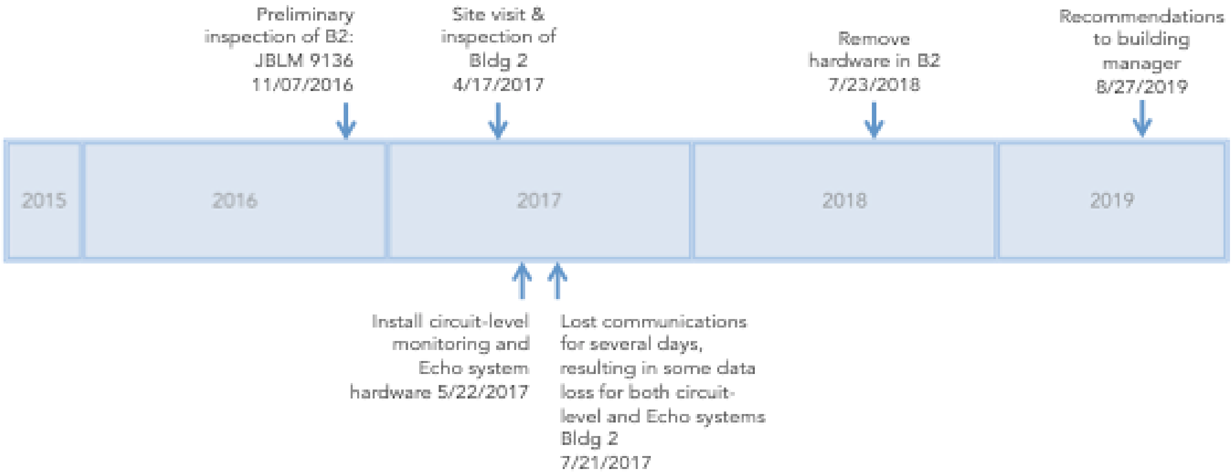


Figure 5-13. Timeline for Activities in Building 2

Equipment Installation Issues

Equipment installation was relatively straightforward. Circuit-level monitoring was installed to measure power on 91 of 196 individual circuits. In addition, total power was monitored at the supply conductors to each of five subpanels such that the circuit-level monitoring captures all electric loads in the facility with the exception of three residential suites. Commercial Internet service was installed for data transmission.

Operational Issues

The building's boiler failed prior the measurement period. The Department of Public Works installed a temporary, mobile heating system placed on a trailer outside the building. While making this emergency repair, contractors modified controls settings and bypassed some circulation pumps and circuits. These interventions rendered the electricity consumption measurements related to space and water heating suspect and probably unusable. The failure of the building's heating system appeared to leave some occupants cold, so they installed personal heating devices, increasing energy use in living quarters.

Evaluation Issues

The use of in-apartment space heaters by some occupants may have distorted energy use patterns at the level of individual living units.

Occupancy levels fluctuated as soldiers went on missions and exercises. We were unable to obtain information on the number of occupants over time.

Building-Specific Results

Some findings for Building 2 are presented below. These results cover both the building's energy consumption patterns and the performance of the Echo. More general discussion of the Echo's performance is discussed later.

Monthly electricity use for Building 2, broken down by major end uses, is shown in Figure 5-14. About half of the electricity was consumed in living space (i.e., the appliances, lighting, and plug loads in the residence suites). Loads in living spaces were higher in the winter; not surprising given fewer daylight hours and the likelihood that occupants spent more time indoors, with electric space heaters also a probable contributor. Pumps, used to circulate hot water to fan coils for space heating, showed higher energy consumption in the winter months. The fan coil units ran continuously, suggesting a controls problem.

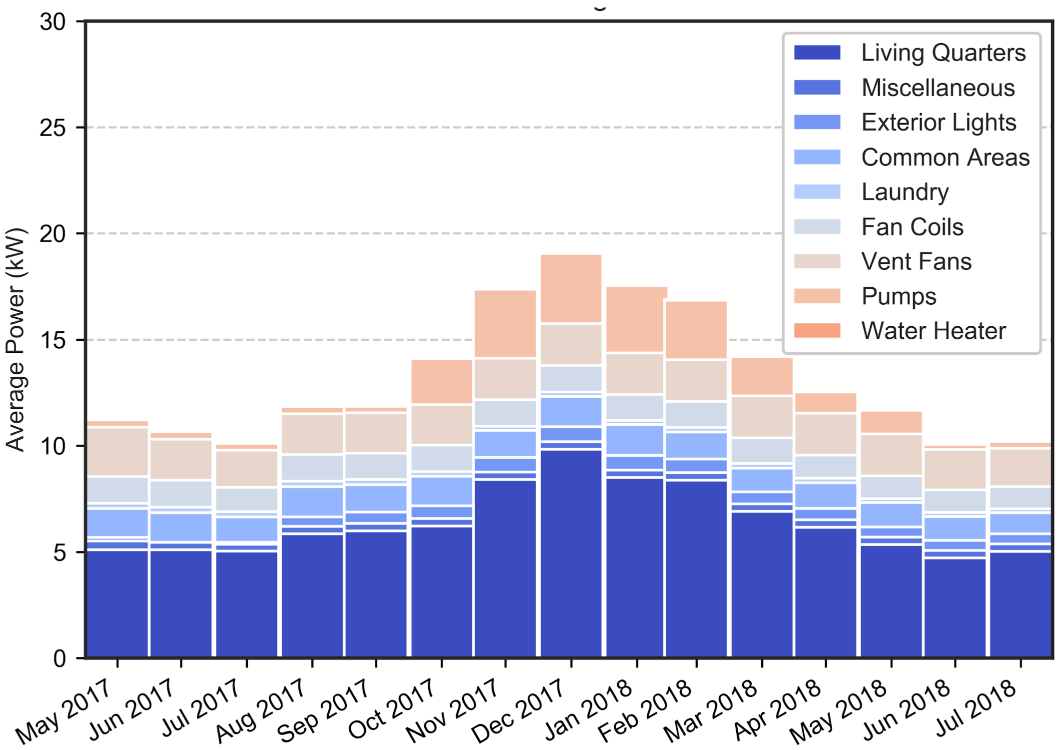


Figure 5-14. Building 2 Monthly Average Aggregate Power

A time series plot of electricity consumption over one week is shown in Figure 5-15. The building has very high baseline energy use, much of which is caused by continuous operation of building ventilation and fan coil units.

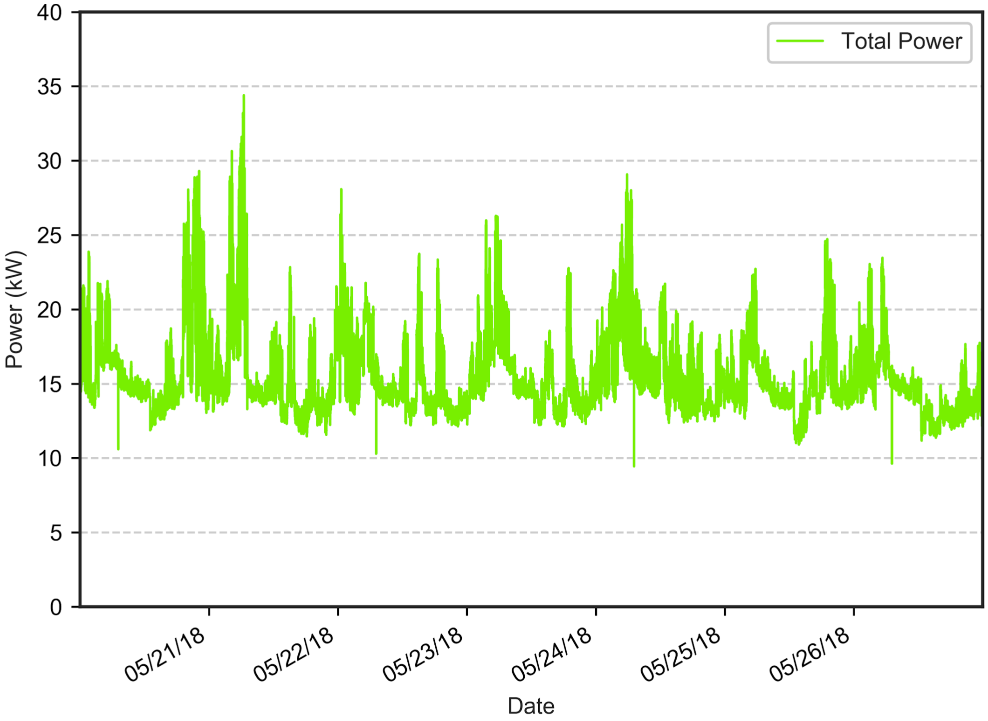


Figure 5-15. Building 2 Total Power Consumption Profile Over a One-week Period

Some load-specific plots, based on circuit-level data, demonstrate patterns of energy consumption over time (Figures 5-16 through 5-18).

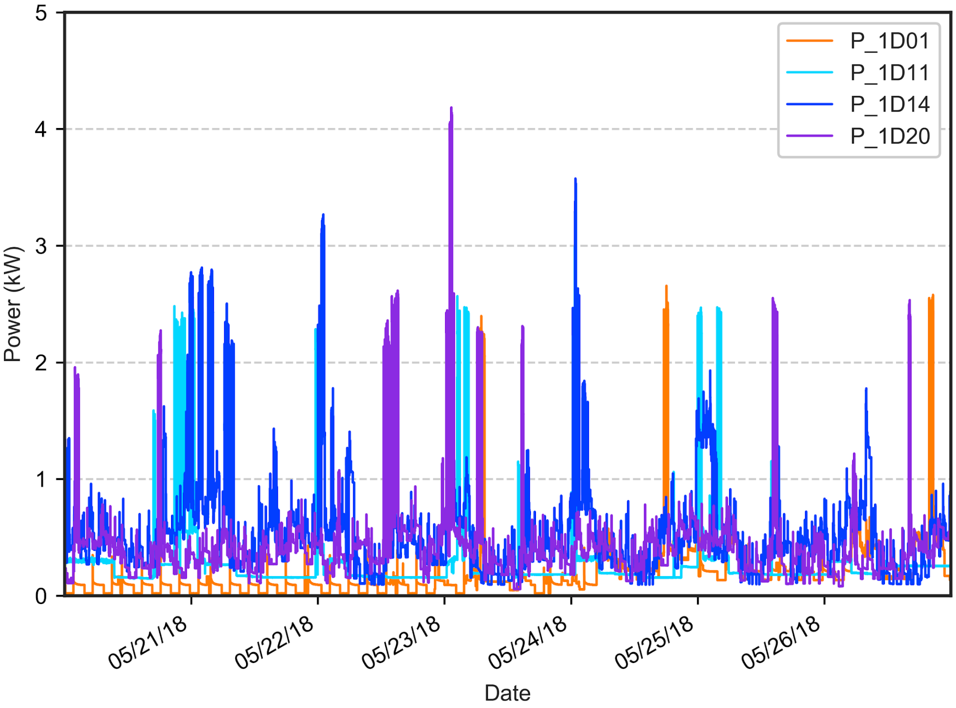


Figure 5-16. Building 2 Energy Use in a Sample of Four Living Suites, Showing Large Variation Between Suites and Over Time

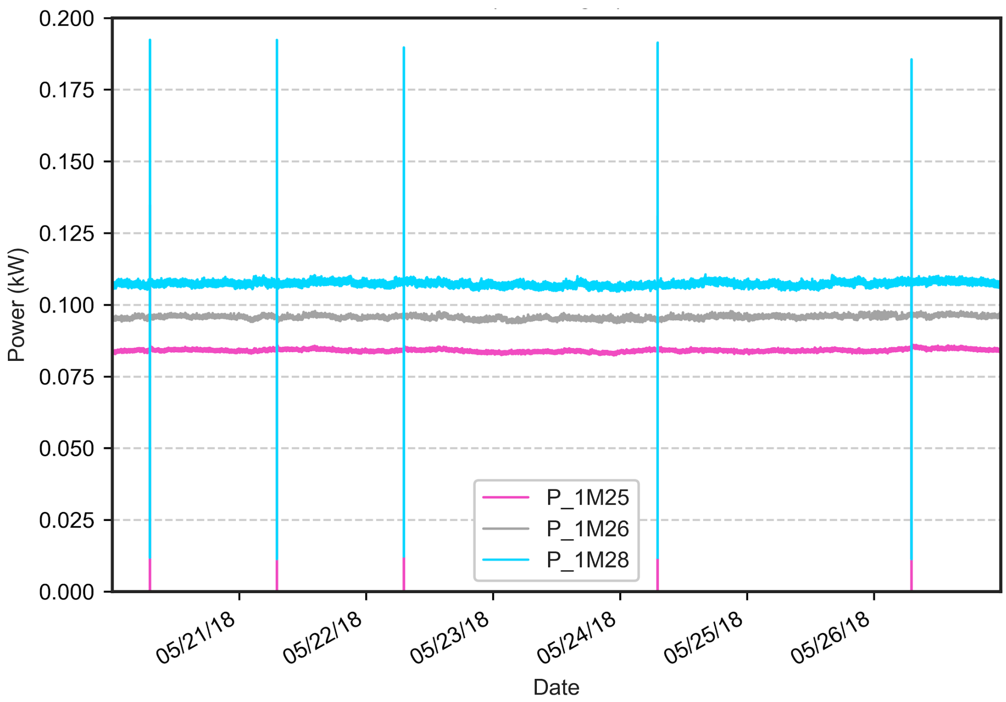


Figure 5-17. Building 2 Energy Use by a Sample of Fan Coil Units, Showing Constant Operation.

The cycling in which power use drops to zero and then shows a spike on restart is likely part of an automated controls calibration process.

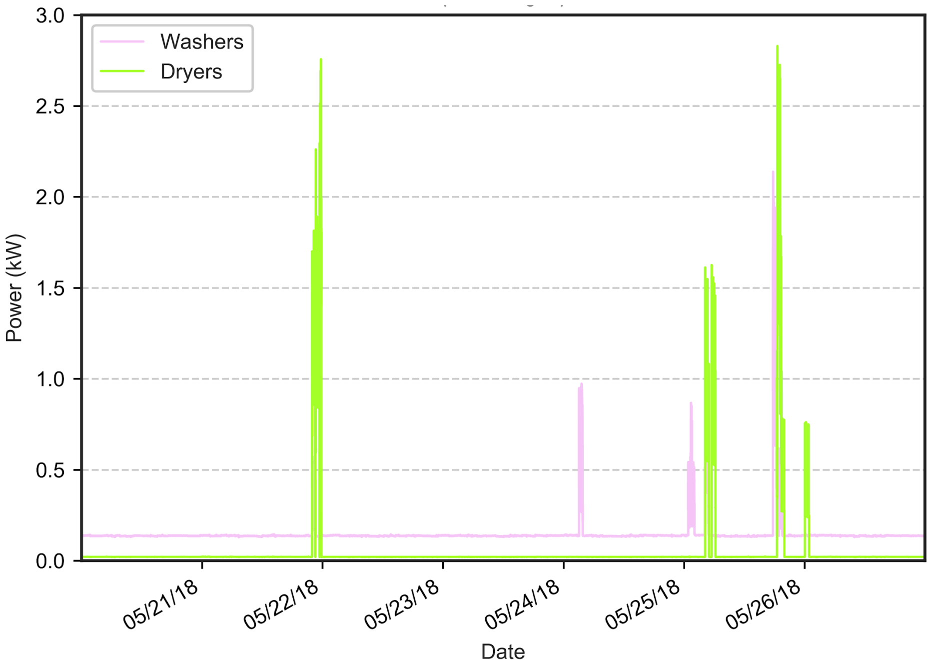


Figure 5-18. Energy Use of the Common-area Clothes Washers and Dryers Shows They Are Used Only Occasionally.

In-suite laundry equipment is probably used for the bulk of laundry needs.

Based on our evaluation of the circuit-level data, we recommended that DPW reset the controls on the fan-coil units and circulation pumps. This measure could not be immediately implemented because of the ongoing repairs to the building's HVAC system.

Echo algorithms were unable to itemize any loads in Building 2. The electric loads consisted of many similar refrigerators, ranges, clothes dryers, etc. which could not be successfully disaggregated. For example, at any given moment, at least 10 refrigerators could be operating, each generating essentially identical signals, making it impossible to create the matched pairs of on/off power edges needed to itemize energy use. Building 2 had no large, unique loads. One unique load category (though not so large), the commercial washing machines and dryers, were metered and compared to Echo data. Echo algorithms were unable to identify any characteristic signal by the washing machines.

Building 2 proved to be a poor application of the Echo technology. The individual loads were relatively small and too similar and coincident for the algorithms to successfully identify them.

5.4.3 Building 3

Building Description

Building 3 is used for repair and maintenance of Stryker armored fighting vehicles (AFVs). It has two large work bays (shown on the left in Figure 5-19) and an office area (right side). Figure 5-20 shows one view of the work bay. Floor area of the shops is about 21,000 square feet, and the office wing totals about 11,800 square feet. Two smaller structures outside the main building are also fed from the electrical service in this building. Fourteen overhead doors enable vehicles to drive in. A vehicle exhaust ventilation system is available to capture tailpipe emissions, allowing vehicles to safely operate inside. The building has a packaged air handler providing heating to the office wing, a ceiling-mounted HVAC unit in each of the two shop areas, and gas radiant heaters installed over each overhead door. The office wing air handler includes cooling capability.

Building 3 was selected because it had a few large loads, including two compressors, a vehicle exhaust extraction fan, and two overhead cranes. This building should in principle be a good candidate for Echo. A timeline for activities in Building 3 is shown in Figure 5-21.

Figure 5-19. Building 3, with Sliding Doors on Left Opening into the Repair Bays, and an Office Area to the Right Side

Figure 5-20. One of Two Repair Bays in Building 3

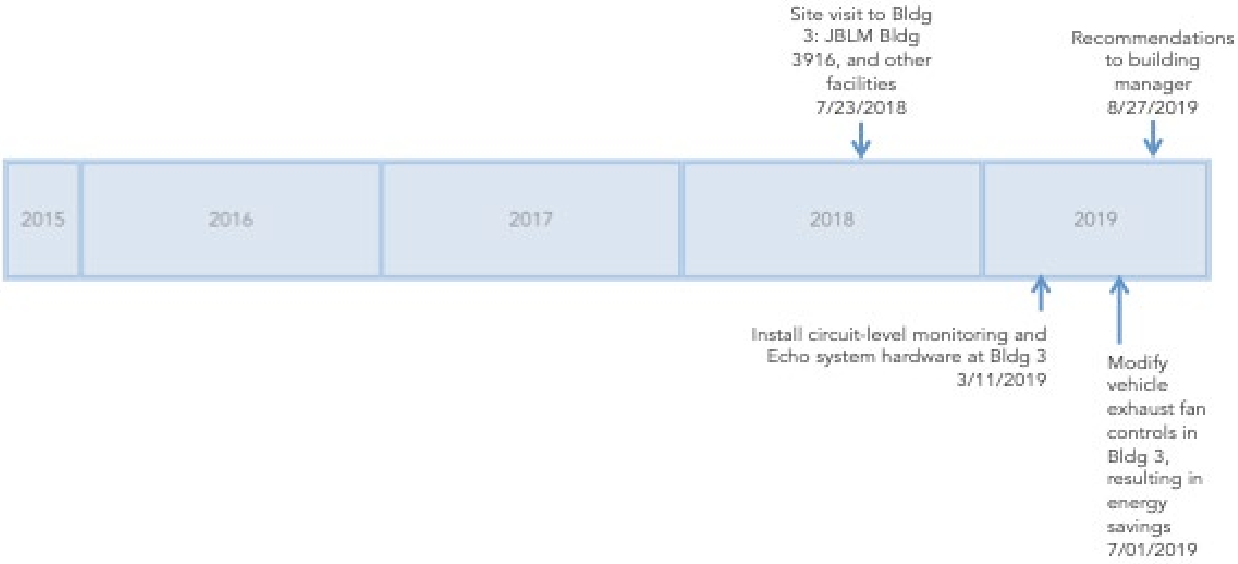


Figure 5-21. Timeline for Activities in Building 3

Equipment Installation Issues

Building 3 posed several significant installation challenges. First, the electric service is 480 volt-ampere reactive (VAC), three-phase power, whereas the Echos are (after earlier modifications) only capable of metering 240 VAC. An adapter, consisting of a 2:1 voltage transformer and high frequency voltage noise by-pass capacitors, was fabricated to allow the Echo system to be connected to the 480 V supply.

Building 3 has about 199 individual electric circuits serving end loads; it was impractical to install circuit-level monitoring on every individual circuit, but we did monitor 63 of these circuits, based on a selection of loads that could test the itemization ability of the Echo and might offer energy efficiency opportunities. In addition, we monitored both input and output of the three step-down transformers present, and total power delivered to each of five subpanels. The result is that the circuit-level monitoring captured 100 percent of building electricity consumption.

A second challenge at Building 3 was the lack of broadband data access. Several communications options were explored (including paying to lay cable to the building) but, in the end, a cellular connection was selected. Considerable experimentation was required to obtain a reliable signal with the bandwidth necessary to transmit Echo data.

Third, two smaller buildings are included in the Building 3 network. While these buildings include significant loads including HVAC systems, we monitored them only at the whole-building level, thus losing some detail that might have been of value in training the Echo system algorithms.

Operational Issues

There were no significant operational problems. The building was used in a routine manner during the study period. The only significant change occurred after the installation of a timer on the fan (see below).

Evaluation Issues

The delivery of power to two outbuildings through the electric service to the main building added unknown factors to the analysis. In particular, the larger outbuilding has an HVAC system, overhead doors, radiant heaters, and other loads very similar to the main building. We did not monitor these outbuilding loads at the circuit level, and they may have confounded identification of similar loads in the main building.

Our strategy was to collect sufficient circuit-level data to permit comparison of specific loads and anomalies identified with the Echo. We were particularly interested in observing the performance of the transformers and how they affected the Echo's sensitivity. Appendices B, C, D, and E focus on aspects of accuracy and sensitivity.

Building-Specific Results

Some findings for Building 3 are presented below. These results cover both the building's energy consumption patterns and the performance of the Echo. More general discussion of the Echo's performance is offered later.

Building 3's monthly electricity consumption, broken out by major end uses, is plotted in Figure 5-22.

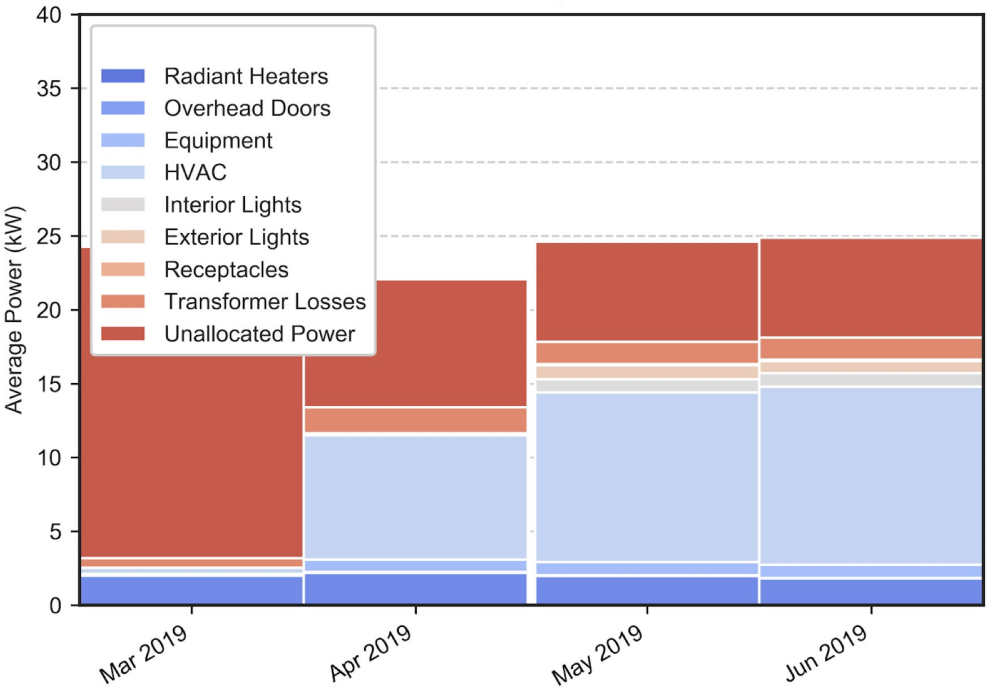


Figure 5-22. Month-by-month Electricity Use for Building 3, Broken Out by Major End Uses

Figure 5-23 shows a profile of the electricity consumption over one week. Based on circuit-level data, the baseload energy use of about 20 kW during unoccupied periods is made up of a continuously operating vehicle exhaust fan, operation of one HVAC unit, exterior lighting, transformer losses, and probably other loads.

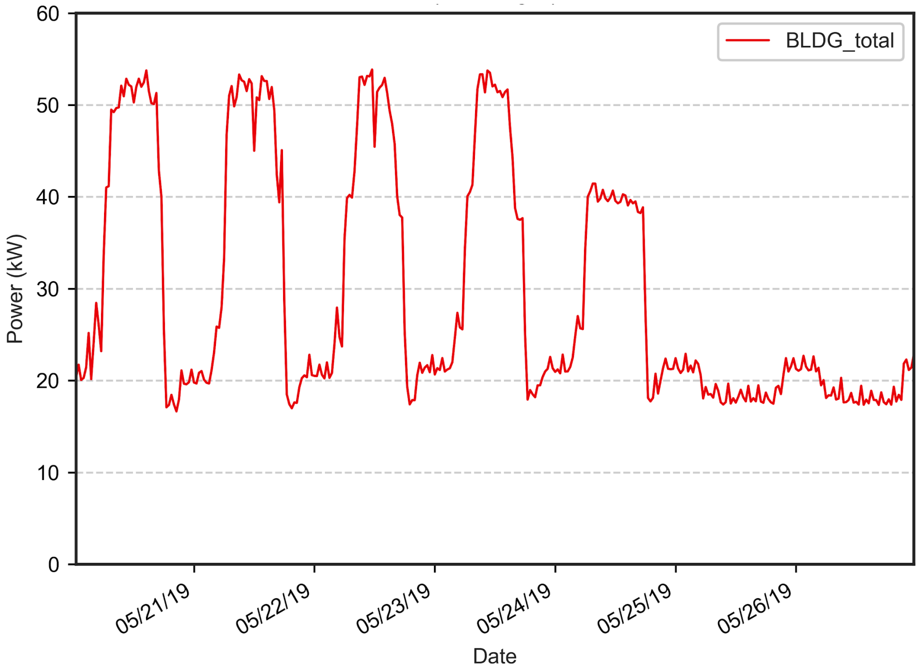


Figure 5-23. Electricity Consumption for Building 3 During a Typical Week

Some load-specific plots, based on circuit-level data, demonstrated patterns of energy consumption over time for the overhead cranes (Figure 5-24), overhead doors (Figure 5-25), air handlers (Figure 5-26) and air compressors (Figure 5-27).

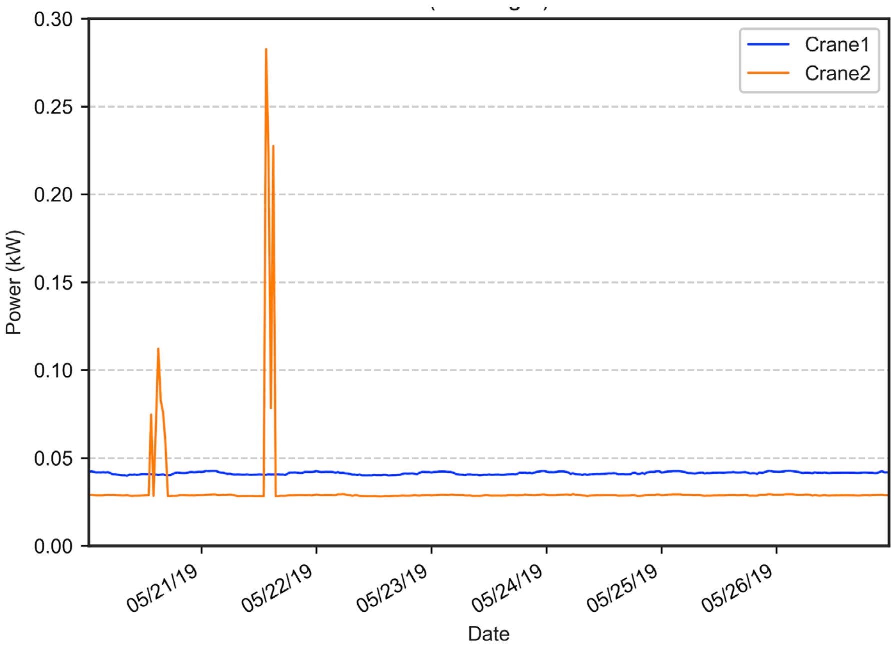


Figure 5-24. Building 3 Shop Cranes Are Used Infrequently and Account for a Small Fraction of Total Power Consumption

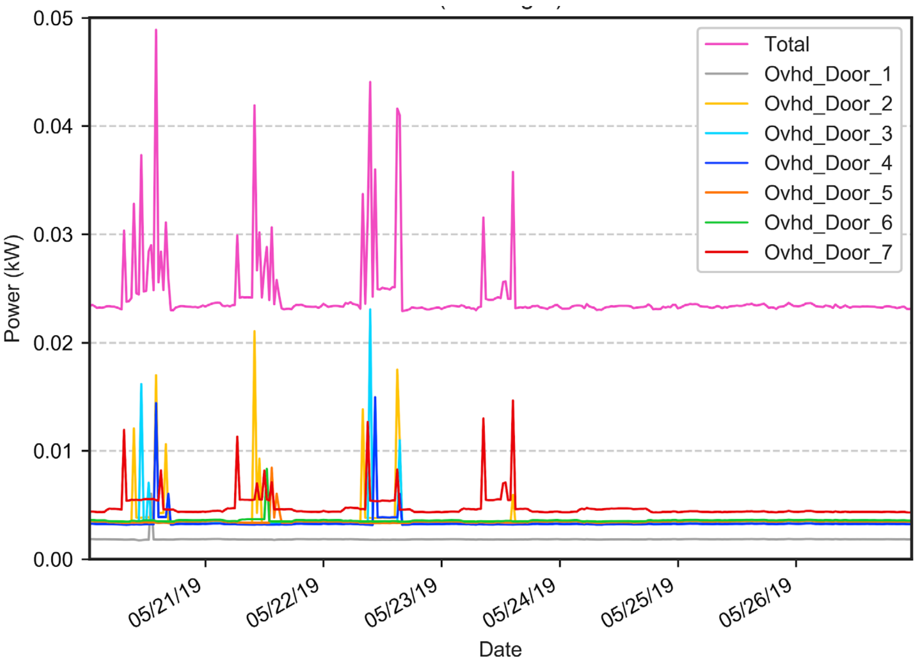


Figure 5-25. Building 3 Overhead Doors Are Used Most Work Days, but Account for Only a Small Fraction of Total Power Consumption

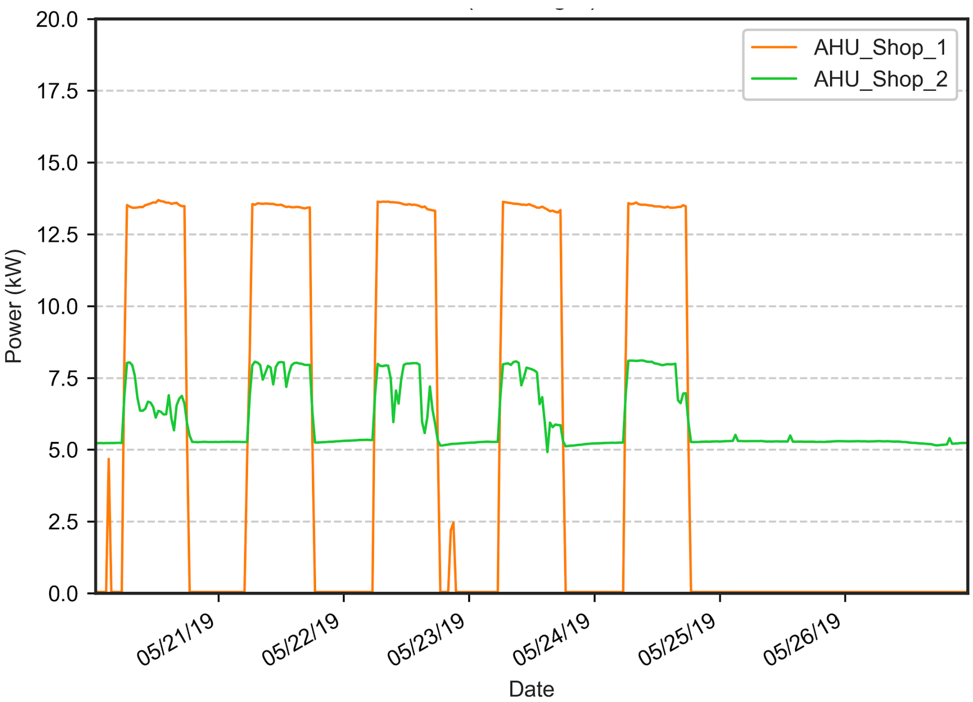


Figure 5-26. Building 3 Shop HVAC Units Operate Regularly During Occupied Hours

The Shop 2 unit runs continuously during unoccupied hours, and represents an energy-saving opportunity.

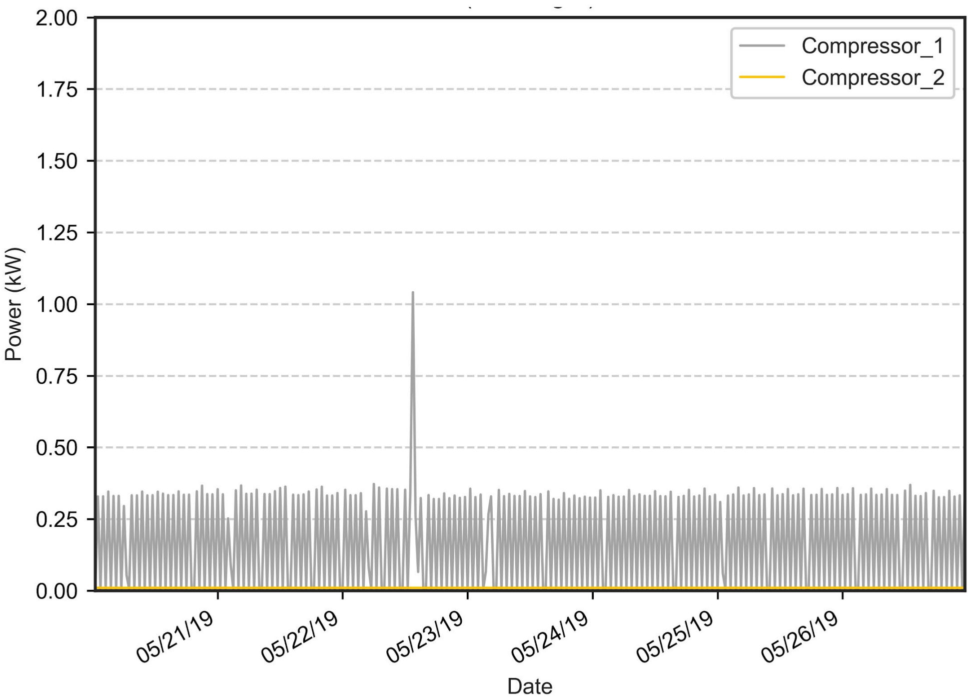


Figure 5-27. Building 3 Compressors

Compressor 1 cycles regularly, roughly every 45 minutes, suggesting a leak in the system. Compressor 2 was not observed to operate.

Building 3 contained three step-down transformers converting 480/277 VAC to 208/120 VAC. The two serving the shop floor are rated at 30 kilovolt-amperes (kVA), the third, serving the office wing, is rated at 75 kVA. While their sizing may be based on maximum expected loads, all of them appeared to be operating at a very low fractional load. Based on circuit-level data for the first 21 days of monitoring, the average power output of the office wing transformer was about 2.7 kW, with a nearly constant loss of 0.76 kW, for an average efficiency of 78 percent (see Figure 5-28). Average output of the transformer in Shop 1 was only 0.17 kW, with a loss of 0.39 kW and an efficiency of 30 percent. The Shop 2 transformer delivered an average of 0.57 kW and had losses of 0.60 kW, for an efficiency of 49 percent. Total losses of the three transformers sum to about 1.75 kW, or more than 15,000 kWh per year. Replacement of the transformers with more efficient models, and possibly resizing them, may be an attractive energy efficiency option.

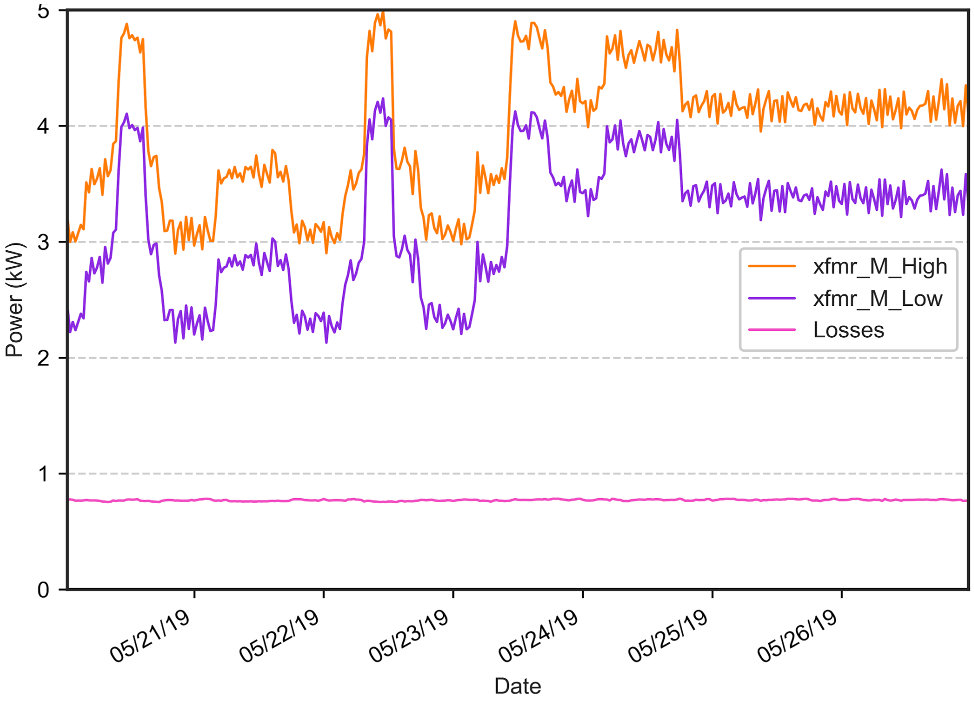


Figure 5-28. Power Profile for the Building 3 Office Wing Transformer, Showing Input, Output, and Losses

Losses are nearly constant over widely varying loads. This transformer operated at a typical efficiency of 78 percent, the highest of the three transformers.

The vehicle exhaust extraction system was identified in circuit-level data as one of the largest loads in Building 3, and one that offered a straightforward path to energy savings. Circuit-level monitoring of the fan circuit showed that it operated continuously, drawing about 4 kW (with some variation over time). Because it operated continuously, the Echo system was unable to identify it as a discrete load. Consulting with the DPW staff and a local contractor, we found that the exhaust fan was apparently connected to the direct digital control (DDC) automation system. However, that system had not been programmed to operate the fan during work hours and disable it during off hours; instead, it was controlled by a manual switch which building occupants simply left on at all times.

The contractor proposed installation of a manual countdown timer, allowing building staff to activate the fan for any period up to 12 hours, and the building manager agreed to train staff on the use of a timer. At the time of the planned installation, however, DPW staff modified the plan, and as implemented, it makes use of a manual switch to activate the fan for two hours at a time through the DDC system.

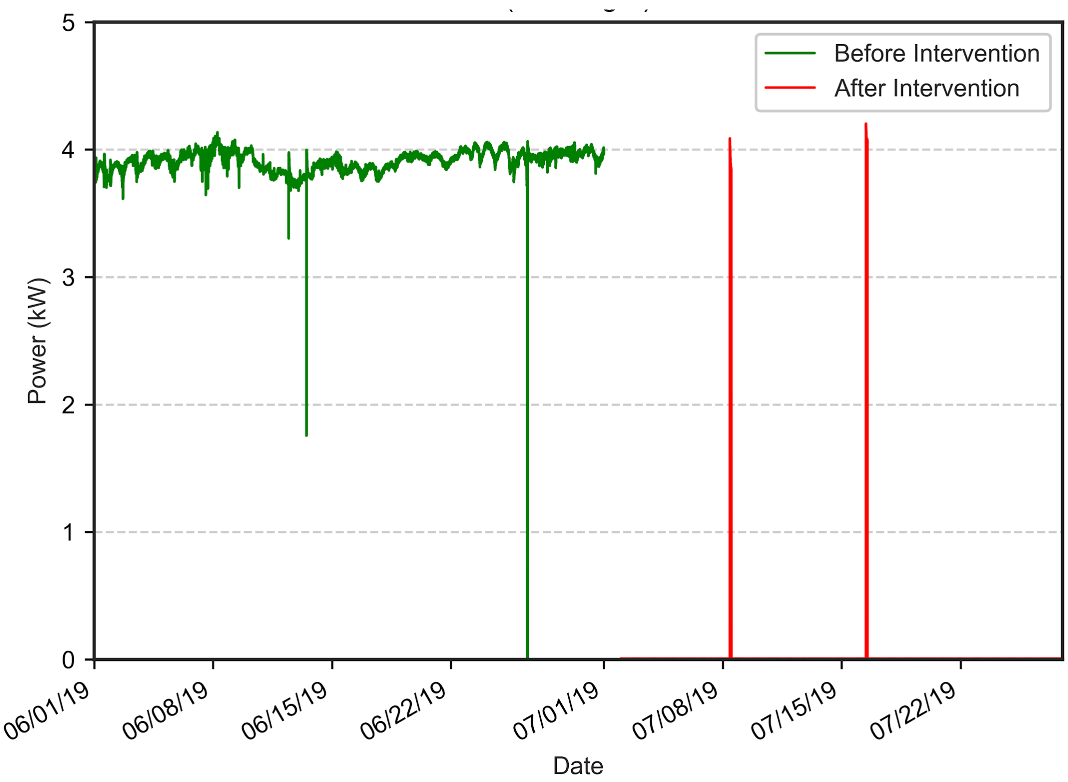


Figure 5-29. Building 3 Vehicle Exhaust Extraction System Power Consumption Before and After Adding Manual Controls

The system operated continuously prior to retrofit, and was used only occasionally over several weeks after retrofit.

The retrofit as implemented shows excellent energy savings of over 97 percent. Average power consumption during the month prior to retrofit was 3.91 kW, which dropped to 0.03 kW in the 28 days after retrofit. Assuming that this pattern of usage persists, the annual energy savings will be about 34,000 kWh, or $3,400 (at $0.10/kWh). The total cost of installation of the timer was $1,200, yielding a simple payback time of about four months.

Technical knowledge of the facility was important in developing a plan of action regarding the revised fan controls; it was clear that fan operation is required only when vehicle engines are running in the shop areas This is an example of the need for engineering and operations information (what is commonly called “audit information”) in the identification and implementation of energy savings strategies.

5.5 SAMPLING PROTOCOL

The principal objective of this project was to evaluate the effectiveness of a non-intrusive electricity metering technology. The “samples” for this project are the different types of data used to assess the Echo technology. The major types of data collected are described below, along with a description of how they were calibrated.

Circuit-level energy monitoring equipment. The eGauge monitoring technology (https://www.egauge.net/) is a multi-channel energy meter with 0.5 percent revenue-grade accuracy compliance and the ability to measure residential or commercial circuit panels, up to three-phase 277/480 VAC and 6900 amperes (A). It is ANSI C12.20 Revenue Grade Accuracy Compliant. Current transformers, manufactured by Continental Controls and J&D Electronics, have accuracy ratings of 1 to 2 percent of load when measuring current levels of 10 percent of full load or higher. CTs were sized to match the capacity of each circuit monitored.

Calibration checking included spot checks on individual circuit-level measurements using independent metering devices, comparison of the power consumption between the phases of multi-phase loads, and comparison of measured power to expected or rated power.

More significant as a source of error in field measurement of electric power are installation mistakes, including failure to fully latch CTs, loose connections of CTs or voltage signal wires, mistakes in identifying the circuit being measured, and incorrect assignment of a CT to a voltage phase. In each installation, we verified that the intended load was reliably measured, and in each case made return site visits to check and correct possible installation errors.

The Belkin Echo sensor. The Belkin sensor was equipped to measure current and voltage at a wide range of frequencies. The sensor itself was calibrated at Belkin’s laboratory according to standard procedures. The sensitivity of the Echo technology is described in Gupta et al. (2010).

WeMo smart plugs. WeMo smart plugs were used to meter electricity consumption of individual appliances and other equipment. These Belkin-manufactured units were calibrated at the factory and achieve less than 10 percent error at the typical loads. Note that data from these devices were collected but not ultimately used.

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6.0 PERFORMANCE ASSESSMENT

6.1 ASSESSMENT OF PERFORMANCE OBJECTIVES

This section assesses the performance of the Echo technology compared to the original technical performance objectives. Detailed discussions of specific findings follow.

This project's goal was to show that the Echo technology can economically provide information that reduces energy use. Success would be demonstrated by meeting three quantitative objectives:

1. Accurate measurement of building electricity consumption
2. Accurate itemization of electricity consumption and identification of energy-saving opportunities
3. Identification of actual savings

These are discussed below in the context of the metric, data requirements, and success criteria.

The accuracy of the Echo measurements was compared to the ground truth in the three buildings (Tables 6-1 and 6-2).

Table 6-1. Accurate Measurement of Total Energy Consumption

Performance Objective	Metric	Data Requirements	Success Criteria
Accurate measurement of total energy consumption	The difference between total consumption as measured by the Belkin Echo and the ground truth equipment (or the utility meter when applicable) over a fixed period of time, in kWh	Collect total energy measured 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 the ground truth system (or utility meter) over a said period of time

The comparisons for each building were performed for a typical week to minimize discrepancies caused by missing data. Data processing requirements were also formidable. Details of the comparisons are described in Appendix B. The circumstances of each comparison differed because of building-specific conditions. In Buildings 1 and 3, total electricity consumption was compared. In Building 2, however, Echo captured some energy consumption not reflected in circuit-level data, so a direct comparison was possible. In this case, *differences* in power consumption were compared.

Table 6-2. Accurate Disaggregation of Energy Consumed by Individual Loads

Performance Objective	Metric	Data Requirements	Success Criteria
Accurate disaggregation of energy consumed by individual loads	Energy Error metric and Event Detection metric	Comparison of 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 the actual total energy.

Echo was able to reliably disaggregate some large individual loads but was unable to disaggregate a large fraction of power consumption in the test buildings. The evaluation is described in detail in Appendix C. Several features contributed to the low identification rate. First, about 30 percent of a typical building's energy consumption was continuous, and therefore generated no events that Echo could identify. Second, event signals were less than the sensor's threshold of detection (because many device signals were less than 1 percent of typical power levels). The algorithms designed to identify devices based on their high-frequency signatures proved to be less successful than expected. It appears that they were confused by the dozens—possibly hundreds—of simultaneous events occurring in a commercial building. In addition, random high-frequency background noise caused by external sources complicated interpretation of the signal. The interpretation of high-frequency signals is discussed in Appendix C and Appendix D.

Once a load was detected, however, Echo was able to estimate that device's monthly energy consumption within 11 to 14 percent of the ground truth. Errors in estimates of daily energy use were much higher, 33 to 37 percent, but they tend to cancel over time. Table 6-3 summarizes those comparisons.

Table 6-3. Errors in Total Loads Estimated by Echo System as Compared to the Circuit-Level System

Month	Monthly Energy Estimation Error (%)	Daily Energy Estimation Error (Average) (%)
April	11	33
May	14	37

Energy-saving opportunities in the test buildings were identified with a combination of Echo and circuit-level data and building audits (Table 6-4). In Building 1, Echo revealed the high electricity consumption during nights and weekends. However it was unable to identify the devices causing the high consumption. The circuit-level data metering showed that the consumption occurred on circuits dedicated to office equipment and other plug loads. WeMo measurements confirmed that these loads were individually small and often drawing a constant amount of power—two features that frustrated Echo's ability to detect them. A building audit (combined with discussions with the building manager) indicated that many of these devices could be safely switched off while not in use (nights, weekends, permanently). This information provided the basis for an energy-saving recommendation. A reduction of 10 percent in total electricity use was observed after implementation.

Table 6-4. Energy Saving Informed by the Echo Technology

Performance Objective	Metric	Data Requirements	Success Criteria
Energy saving informed by the Echo technology	Reduction in energy consumption, measured in kWh	Establish an energy consumption baseline and compare it to results after the technology is deployed.	10% reduction compared to baseline

In Building 2, circuit-level data revealed that the fan-coil units were operating continuously. These units could not be detected with Echo algorithms. An energy-saving measure—resetting the controls for these fan-coil units—was proposed. However, it could not be implemented during the project period because the HVAC system was undergoing repairs.

In Building 3, circuit-level data revealed that a vehicle exhaust ventilation fan was operating continuously. Here, too, the fan consumption was essentially invisible to Echo because the device created no event edges or signatures. After consultation with the building managers, the fan control strategy was revised and, based on circuit-level data, fan energy consumption fell more than 95 percent. Engineering knowledge of the purpose of the fan was needed, in combination with monitoring data, to identify this fan system as an efficiency opportunity.

Clear Presentation to the Building Energy Managers

A secondary goal of the project involved delivering the information to the building managers and decision makers in such a way that they would undertake energy-saving measures identified by the Echo technology. Table 6-5 lists the original performance objective, metric, data requirements, and success criteria.

Table 6-5. Clear, Actionable Presentation of Information to Building Managers

Performance Objective	Metric	Data Requirements	Success Criteria
Provide clear, actionable data to the buildings energy manager(s)	Building energy manager(s) report a high level of satisfaction with the presentation and quality of the data.	Perform two interviews to collect feedback from the energy manager(s): (1) the first interview prior to installation to create a baseline; (2) the second interview post installation to capture the satisfaction level.	Increase in satisfaction over baseline

The original plan was to create an energy dashboard, where building managers could observe a building's energy consumption, be alerted to anomalies, and see suggestions for conservation measures. The dashboard would be supplied by Echo inputs, processed by cloud-based algorithms, and displayed on a website. Unfortunately, base data security policies prevented the kind of cloud-based dashboard originally envisioned. Interviews with building and base energy managers also made clear that they would not visit such a site frequently enough to justify its operation (assuming security restrictions could be overcome).

A modified information delivery approach was therefore adopted. After reviewing Echo and circuit-level data and performing building audits, we identified possible energy conservation measures. Then we met with building and energy managers to discuss our recommendations and the feasibility of implementing them. This highly personal (and labor-intensive) approach proved successful in Buildings 1 and 3. The recommendation for Building 2 overlapped with replacement of the building's HVAC system and could not be implemented. Interviews with building managers indicated that they were satisfied with the process and the results.

7.0 COST ASSESSMENT

An assessment of the costs of the Echo is presented below. The approach and methods used to assess costs evolved as the project progressed. This evolution reflected both the actual test conditions encountered and a more realistic understanding of the Echo's capabilities under real-world conditions. Nevertheless, the goal remained to provide policymakers a reasonable assessment of the Echo's costs and benefits.

7.1 COST MODEL

This project's cost model compares the cost of obtaining itemized energy data from Echo to that of obtaining the data from circuit-level measurements (such as that obtained through eGauge). The model draws upon cost elements that were tracked at JBLM or were estimated. Neither of the measurement systems delivers true itemized consumption data,[6] but both systems can often identify and quantify major loads with post-metering analysis.[7] 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.

There exists considerable uncertainty regarding estimation of costs in the model. The following examples illustrate the uncertainties. First, it was difficult to separate the costs associated with implementing the two monitoring technologies from those costs related to the research project. In Building 3, for example, additional circuit-level meters and Echos were installed to observe the impact of the high voltage transformers on data quality. This would not be done in a routine installation. Second, the monitoring technologies were installed, maintained, and removed at the same time, using the same crews. This made it difficult to allocate costs between the two systems. Third, installation and operation of the Echo system required considerable trial and error—which was to be expected—so costs were reduced to reflect a "routine" implementation. Finally, the per-device costs in a large-scale, multi-building installation would be lower than those in the current project.

7.2 COST DRIVERS

Many of the cost drivers are discussed below. However, three aspects are not adequately captured in the cost analysis even though they significantly impact cost.

First, the cost per building falls when it is part of a base-wide program. The nature and scale of that program will depend on local conditions. We did not have enough information to construct reasonable scenarios for these programs.

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[6] 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.

[7] An alternative cost model would use a system that acquired true itemized data. This system would resemble the 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 did not constitute a reasonable comparison system.

Second, regardless of the monitoring technology, expert engineering judgement is still needed to translate disaggregated energy consumption into recommendations that are actionable, feasible, and economic. Some of this expertise will reside on base—it did at JBLM—but staff are often already overburdened simply dealing with emergencies. Thus, procedures may be required to engage outside experts.

Third, the increasing requirements for base energy security and resiliency place new emphasis on understanding how energy is used on base and what is essential. These monitoring systems can therefore assist in meeting a base's energy security goals.

7.3 COST ANALYSIS AND COMPARISON

The costs have been adjusted to a prototype building, which is roughly the average of the three buildings that were examined. Table 7-1 lists the characteristics of the prototype building.

Table 7-1. Basic Site Description of Prototype Building for the Cost Model

Building Characteristics	**Value**
Floor area (square feet)	20,000
Electricity consumption (kWh/year)	180,000
End uses responsible for 50% of electricity consumption	4
Number of circuits present	100
Number circuits monitored	48
Broadband data access (without security)	No
Echo sensor phase compatibility	Three-phase
Period monitored (months)	12

The prototype building was also assumed to be served by a single three-phase power supply at either 480/277 V or 208/120 V, with step-down transformers within the building when both voltage levels are required. This arrangement generally means the Echo device can be installed at a single service entrance, regardless of whether other metering is present. We further assumed that a native, three-phase Echo sensor would be available rather than the virtual three-phase meter (assembled from three dual-phase meters) actually used in the project. If designed similarly to the residential version of the Echo, it could be easily inserted into existing kilowatt-hour meters, where present.

No explicit life cycle cost analysis was conducted. The monitoring period was assumed to be 12 months in order to capture seasonal variations but could be longer if changes in energy consumption needed to be tracked after retrofits or building modifications were implemented. Most of the costs are not sensitive to the period of measurement. At the end of the project, some of the measuring equipment can be reused, so there is a salvage value. This value was not considered.

The costs, which are costs for a single building, are summarized in Table 7-2 below. An explanation of each cost element follows, and the adjustments to these costs when scaling up to a base-wide program are then noted.

These estimates are based on the assumption that a private contractor is performing the installation, data collection, and analysis. Integration of either circuit-level or Echo technology into on-base systems (e.g., under the control of a department of public works) would have significant implications for the processes and costs of data communications and data analysis, and perhaps in other areas. Replacing commercial Internet communications with on-base communications networks would have further implications in terms of cost and cybersecurity.

Table 7-2. Estimated Costs for Echo and Circuit-level Monitoring Technologies in a Prototype Building (Rounded to Two Significant Digits)

Characteristic	Circuit-level ($)	Belkin Echo ($)
Project management	2,500	2,500
Installer training	500	500
Equipment	8,000	2,000
Installation and removal cost	9,500	3,000
Data communications	600	6,000
Data collection and management	8,400	5,000
System maintenance contingency	5,000	5,000
Analysis	15,000	45,000
Travel	6,000	6,000
TOTAL	**56,000**	**75,000**
Incremental cost of Echo		**19,000**

Project management

Project management costs for the two technologies are roughly equal. In both cases, the building must be assessed, which may include evaluation of energy loads and the potential for identifying energy savings, determination of building schedules and access limitations, and evaluating data communications options. In some cases a power shutdown must be coordinated. Periodic communication with the building manager is assumed. At the end of the metering period, the removal of the metering equipment must be coordinated.

A scaled-up deployment would have significantly reduced management costs, possibly down to 30 percent of this value per building. However, every building is different and will require personal attention.

Installer training

Both Echo and eGauge require installation by skilled, licensed electricians. (The electrician must also be familiar with base regulations and be approved for base activities.) Training is equivalent for the two technologies—both require familiarity with CTs and voltage phase connections.

A scaled-up program would incur this cost only once or twice, so the cost would fall proportionately to the number of buildings.

Equipment

These costs cover purchase of the eGauge or Echo. The eGauge is a mature, commercial product, so the costs are well understood and include eGauge devices, CTs, and associated cabling and data communication devices. For the Echo, the costs are based on a native three-phase sensor manufactured at the same scale as the eGauge. These do not exist, but Belkin did produce advanced prototypes of residential sensors.

A scaled-up deployment would have similar equipment costs per building.

Installation and removal

The Echo will be relatively easy to install because only one point of access—at the building service entrance—will be required. In contrast, a circuit-level monitoring system will require the electrician to identify panels, circuits, and install sensors in potentially many different locations, and to provide communications links between these locations. This is a complicated and time-consuming process. For this evaluation, we assumed that the equipment would be removed after the project ends (although this is not always necessary).

In a scaled-up deployment, Echo costs would be likely to fall more rapidly than circuit-level data.

Data communications

Both systems need a broadband communications link; however, the Echo requires a connection with higher data transfer rates. The costs of acquiring a reliable data connection are highly dependent on location and security regulations. In Buildings 1 and 2, commercial cable Internet service was easily accessible (and, independent of the base networks, so permissible to use). In Building 3, the cost of similar commercial Internet service was prohibitive, and cellular signals were weak. The solution required installation of external cellular antennas, and a 50 gigabyte per month (GB/mo) cellular data plan. At Camp Pendleton, all civilian communications were prohibited; this made the project infeasible.

A scaled-up deployment would have declining data costs per building, but the economies of scale would depend on the existing broadband infrastructure.

Data collection and management

Both systems require significant data collection and management systems. The eGauge system typically collects 30 megabytes (MB)/day for a prototype building. In contrast, the Echo generates about 500 MB/day! Handling these levels of data flows takes planning and testing.

A scaled-up deployment could see some decline in data costs per building. Echo systems rely on cloud-based data storage and processing, whose costs per building will drop rapidly.

System maintenance contingency

Both systems tested are susceptible to installation errors and hardware or communications failures, and project experience shows that site visits by management personnel are sometimes required to correct problems and verify proper performance, so a maintenance contingency fund is a necessary budget item. With fewer components, future Echo installations should require less maintenance than eGauge systems, but this cannot be proven with the current information.

A scaled-up deployment would have constant costs per building.

Analysis

The analyses of Echo and eGauge data to derive estimates of loads are completely different. For the eGauge, considerable analysis precedes data collection, where devices or equipment need to be associated with specific circuits. This must be done with on-site audits. Once these are confirmed, estimating energy consumption for those devices is straightforward. In contrast, the Echo requires inspection of the data to identify robust events (edges). When they are identified, an audit is needed to associate them with specific equipment. Echo must then be trained to reliably identify the events and estimate energy use. For these reasons, the Echo analysis cost per building is much higher—we estimate three times higher—than the eGauge. Note that the Echo cannot detect devices operating continuously (such as ventilation fans), so the two methods may not deliver similar results.

A scaled-up deployment using the Echo would have declining analysis costs per building, while the circuit-level metering costs would likely be constant. The Echo analyses would likely benefit from experience gained in previous buildings (such as event signatures), application of artificial intelligence, and other automated tools. This benefit from shared experience was even observed in the three JBLM test buildings.

Travel

Travel costs are likely to be the same for both methods. Visiting JBLM was a long trip for the project team, so the costs are probably higher than they would be for future projects. Other line items in this estimate include some allowance recognizing that the contractors performing the work may not be local to any specific site.

A scaled-up deployment would likely have lower travel costs for both technologies, especially if local contractors could be employed.

Costs of a Scaled-Up Monitoring Program

A base-wide monitoring program using Echo technology would be a more realistic application than the single-building example described above. The costs for both the Echo and the circuit-level technologies have economies of scale, but the Echo's economies are much steeper because Echos are cheaper and easier to install (and remove), and their analytical tools can be more easily shared. This assumes that a native three-phase meter is developed. The costs do not reflect the quality of the information supplied by either system.

Cost Performance Objective

The original performance objective, metric, data requirements, and success criteria are listed in Table 7-3.

Table 7-3. Cost performance Objective

Performance Objective	Metric	Data Requirements	Success Criteria
Simple, quick, and low-cost installation	Cost to install the Belkin technology compared to submeters measured in dollars	Track costs per device in each installation	Net savings of ~$1,500 in each building where 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. 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.

8.0 IMPLEMENTATION ISSUES

Both technical and institutional barriers prevented full implementation and achievement of the project's goals. These were described earlier in the context of establishing monitoring systems in the three buildings but not as higher-level obstacles to implementation.

Belkin's Echo was originally designed to measure residential split-phase power (and to be attached to their associated hardware). Unfortunately, all of the buildings at JBLM use three-phase power. Belkin developed a work-around that involved specially adapting triplets (and later pairs) of residential sensors to create a "virtual" three-phase sensor. This approach, while ultimately successful, required vastly more programming and processing and caused many gaps in data. Future DoD projects relying on non-intrusive metering should be based on a "native" three-phase sensor. At this time, Belkin has no plans to manufacture more meters, either for residential split-phase or for three-phase power. Thus, a future monitoring program based on this technology will require another vendor.

Most power sensors have a resolution of about 1 percent. This measurement uncertainty means that the switching on and off of many smaller loads will not be detected. If there are no clear "edges," then the algorithms cannot estimate energy consumption. For example, a measurement uncertainty of 1 percent in a building with a 20 kW load translates into 200 W. This means that devices drawing less than 200 W cannot be detected or identified, and their energy consumption cannot be estimated. This is a major weakness in all non-intrusive metering of commercial buildings because a large fraction of the devices in the buildings have power draws below that 1 percent threshold.

The power resolution limitation could be solved by metering individual circuits. Loads on individual circuits will be smaller, so the 1 percent resolution constraint would identify many more devices with loads below, say, 100 W. Circuit-level metering would have the additional benefit of fewer loads to disambiguate. However, JBLM buildings typically had dozens of circuits, which introduces a new task of aggregating the results. Also, metering of individual circuits might require greater intrusion, which defeats the goal of Echo approach.

In Building 1, about 70 plug-in devices were metered individually to validate the Echo itemization estimates. Belkin's proprietary WeMo "smart plug" system was used to measure each device's electricity use and transmit the measurements via Wi-Fi to a dedicated router. Each device was plugged into a WeMo module, which was then plugged into an outlet. The WeMo was designed for residential applications and has a good reputation for accuracy and reliability. However, the commercial environment is much more challenging. First, the deployment was huge—the largest ever attempted in a single building—and occupants were not sufficiently educated regarding the WeMos. Second, the system experienced a higher-than-usual number of failures (possibly caused by the high density of modules). As a result, many occupants disconnected the modules because of both real and perceived service interruptions. The project obtained little useful data from the WeMos. Fortunately, these validation data were not needed because the Echo system was never able to detect the kinds of loads measured by the WeMos.

The difficulties encountered with the WeMo measuring phase illustrate why comprehensive intrusive metering systems—the technology Echo was supposed to replace—are impractical, unreliable, and expensive.

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. If DoD wants to encourage use of third-party building evaluation programs, it will need to develop a simple, secure, and robust communications policy.

It is absolutely necessary to get buy-in from the base DPW. This project was pursued successfully at JBLM largely due to active engagement by DPW, but was unsuccessful at Camp Pendleton.

A final implementation issue concerns ownership of the algorithms and data. Belkin regards its itemization algorithms and data capture hardware as proprietary, but it will make its data formats and application programming interfaces (APIs) open, so that third parties can build alternative systems to utilize the data or create competitive itemization systems that are compatible with interfaces and applications initially developed for Belkin technology. Itemized data from DoD facilities will be secure DoD property. DoD will have full and final control over data access and retention.

With respect to data security, the system must be risk management framework-compliant before full deployment. Compliance was not required for this small project, so this could become an implementation issue if the Echo were fully deployed.

9.0 CONCLUSIONS AND RECOMMENDATIONS

This project's primary goal was to evaluate a monitoring technology in actual 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.

In the process of evaluating Echo, however, larger issues arose regarding monitoring and saving energy in DoD buildings. These are discussed below, along with some recommendations.

High Continuous Use of Energy in Buildings

High continuous energy use by diverse equipment (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. (This might also include energy consumed by buildings while nobody is in them.) But identifying the continuous loads is challenging. These loads are mostly invisible to Echo and other NILMS. Circuit-level metering can see high continuous consumption but provides limited insight into the causes. A more detailed energy analysis needs to accompany the data. The optimal mix of advanced metering and human input deserves further research.

Measurements of Higher Harmonics of Current

Another potentially useful device signature was identified in this project: harmonics in the current. Activity in the fifth harmonic appeared to correlate with operation of some electronic loads (see Appendix E). Current measurements require installation of current-sensing devices such as those used in this project, and adding these measurements would not reduce installation cost 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. Ultimately, a library of harmonics could simplify recognition of certain classes of loads (that is, resistive, motors, electronics). Harmonics might also give Echo (or a comparable meter) visibility into continuous loads.

Non-specific sources of HF Voltage Noise

This project's researchers had hoped to employ HF voltage noise as a means to identify devices and their operating behavior. The technology works in principle but we found that the HF device signatures were often obscured by other, seemingly random, HF noise. The sources of that noise could not be identified; indeed, it wasn't 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.

If successful, the Echo technology could become a more effective tool for device identification and estimation of energy consumption and fault detection.

Optimal Combinations of Metering Strategies

The original premise of this project was that an Echo could collect data cheaper and more conveniently than submetering or circuit-specific metering (such as the eGauge). Edge detection—the foundation of 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. Could combinations of metering strategies be more effective?

Disaggregation of larger loads may be also possible, using in-place building energy management systems (BEMS) data. This would require data collection at a time interval of perhaps one second to a maximum of one minute; lower resolution data are not likely to have much value in disaggregation. Disaggregation or itemization of the largest loads in a facility is likely to be possible using data at a one-minute time resolution; in these cases, startup and shutdown events that represent a large fraction of total power consumption are likely to be identifiable using "edges." Extension to smaller loads may be possible using data with a higher time resolution. Higher resolution makes smaller events clearly visible by eliminating the blending or averaging that occurs when multiple events occur within a minute. Motor startup current surges (which have very high value in load identification) are generally also clearly visible in one-second power data.

The use of BEMS data would depend on machine learning algorithms that match patterns (or features) of energy use to loads. Active training, in which loads are intentionally switched on and off and the known operating state of the loads becomes an input to the algorithms, may be necessary or at least helpful in getting these algorithms up and running. Other information such as typical hours of occupancy and minimum time between switching events (e.g., for a compressor) can help in developing accurate algorithms.

Technologies that offer circuit-level measurement similar to but at a lower cost than the ground truth monitoring system in this study may also be an attractive alternative. Alternatives to the eGauge system used in this study could be installed during new construction at a much lower cost or when installed in a large number of buildings, e.g., in a campus-wide effort. Installation of energy-sensing circuit breakers is an alternative in new construction.

In any case, metering data, whether it be at the level of individual loads or disaggregated from building-level measurements, is not in itself sufficient to inform energy savings decision making. Engineering and operations knowledge of the facilities under study is a critical piece of the puzzle. The size of a load in relation to the building size and function may provide clues to equipment inefficiencies, for example, in lighting, HVAC, and other loads. The operating schedule of loads must be interpreted in the context of building function and occupancy; 24-hour-a-day lighting and ventilation may be necessary in some facilities but wasteful in others. In addition, the procedures and needs of building occupants and managers must be considered. Capturing this additional information often takes the form of an energy audit, but information gathering and sharing could take many different forms depending on the specific project.

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 missed opportunities.

The data/information dilemma

So much data and so little information. The virtual three-phase Echo generated roughly 1 TB of data per day! Very high rates of data generation and transmission have direct and indirect costs. Most obviously they require installation of operation of more sophisticated communications infrastructure. Less obvious costs include trenching to extend existing cable networks to installing cellular hookups. They also increase electricity consumption. Finally, the transfers also potentially interfere with other, mission-critical data transfers. Once the data have left the base, massive cloud-based facilities are required to store the (mostly useless) data. DoD should review the incremental value of building energy (and other operations) data and develop general guidelines. For example, analysis (and reduction) should take place locally as much as possible. Another example—when are short-term measurements sufficient?

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APPENDIX A POINTS OF CONTACT

POINT OF CONTACT	ORGANIZATION	PHONE FAX E-MAIL	ROLE IN PROJECT
Patrick McLaughlin	Energy Engineer Environmental Division Directorate of Public Works Building 2012, Rm 323 Joint Base Lewis-McChord, WA	253-966-1792 patrick.m.mclaughlin37.civ@mail.mil	Technical assistance to JBLM PoC
Sakhawat Amin	Energy Program Coordinator (STS) Department of the Army Public Works Building 2012 Liggett Ave. Joint Base Lewis-McChord, WA 98433-9500	253-966-9011 sakhawat.amin.ctr@mail.mil	Point of Contact for JBLM coordination
Omid Jahromi	Lucida Research LLC	omid@lucidaresearch.com	Belkin Principal Investigator for majority of project
Alan Meier	Lawrence Berkeley National Laboratory, Building 90-2058, 1 Cyclotron Road, Berkeley, CA 94720	510-486-4740 akmeier@lbl.gov	Principal Investigator for LBNL activities. Principal author of final report.
Dan Cautley	Slipstream	dcautley@slipstreaminc.org	Subcontractor responsible for circuit-level monitoring and some evaluation
Matt Proper	Thompson Electrical Constructors	matt@thompsonconstructors.com	Installation of monitoring equipment
Brian Van Harlingen	Belkin	brianv@belkin.com	Chief Technical Officer and PI at project termination
Timothy Tetreaut	ESTCP	timothy.j.tetreault.civ@mail.mil	Program Manager
Sarah Medepalli	Noblis	Sarah.Medepalli@noblis.org	ESTCP Program Support

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APPENDIX B ACCURACY OF MEASUREMENTS OF TOTAL ELECTRICITY CONSUMPTION

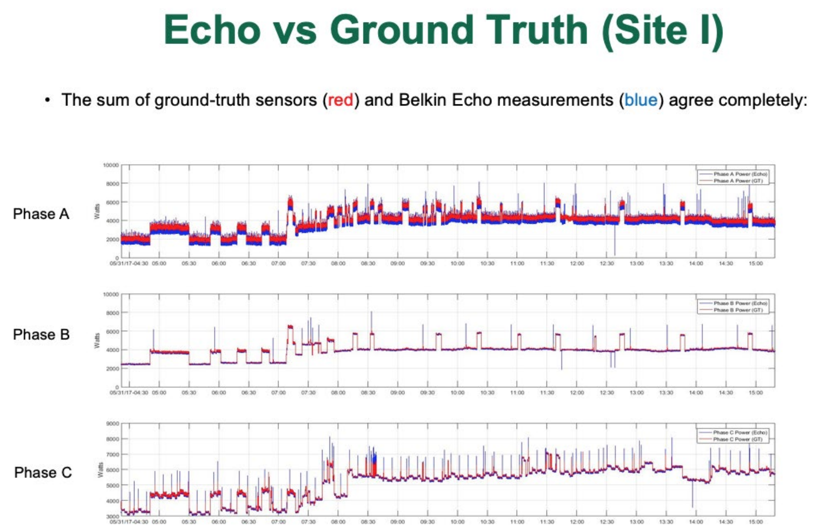
This appendix evaluates the accuracy of the Echo's measurement of total electricity consumption. High accuracy of the Echo's electricity measurements is crucial: if the Echo cannot reliably measure the building's total electricity consumption, then all subsequent calculations are suspect. Measurement errors can occur at two stages in the Echo technology: at the sensor and when processing the measurements.

The dual-phase Echo sensors were calibrated in the Belkin test facilities. Sensor error was less than 1 percent over the range of power measured. Sensor accuracy was not verified in the field. Note that the sensors used in the ground truth measurements also had potential inaccuracies.

In this project, the Echo's measurement of energy consumption was unusually complex because there were no native three-phase Echo sensors. Instead, a "virtual" three-phase Echo was constructed by placing a dual-phase sensor on each line, and then digitally combining the results into a three-phase energy consumption. The procedure to digitally combine the three phases introduced new sorts of potential errors. For example, the clocks on all three sensors needed to perfectly agree (which they mostly did). Extensive programming, computation, and quality control were necessary to ensure an accurate synthesis of the single-line measurements.

The virtual Echo measurements of electricity consumption were compared to ground truth in all three buildings. Comparisons were performed over a typical week. A week was selected to minimize discrepancies caused by missing data. These measurements were not straightforward because the installations of the two metering systems differed.

Figure B-1compares the measured electricity consumption reported by Echo compared to the ground truth.



Echo vs Ground Truth (Site I)

- The sum of ground-truth sensors (red) and Belkin Echo measurements (blue) agree completely:

Figure B-1 In Building 1, Echo's Measurements and Ground Truth Differed by Less than 1 Percent.

The comparison of Echo data to ground truth data in Building 2 was not as straightforward. First, it was impossible to install a whole-building, ground-truth sensor at the service entrance. This problem was circumvented by constructing a virtual ground truth from the sum of the circuit-level measurements. Unfortunately, a few of the circuits were not monitored, resulting in a sum that was less than Building 2's actual total consumption. But a verification of accuracy could still be made by examining the *changes* in power consumption. For example, when a pump increased power use 400 watts, was the same increase observed in data from both circuit-level meters and the Echo? These "deltas" were compared and found to agree almost perfectly (within less than 1 percent). Figure B-2 shows how closely the two measurements tracked. It is still possible that Echo contained a constant error, but the close agreement in changes in power demand is reassuring.

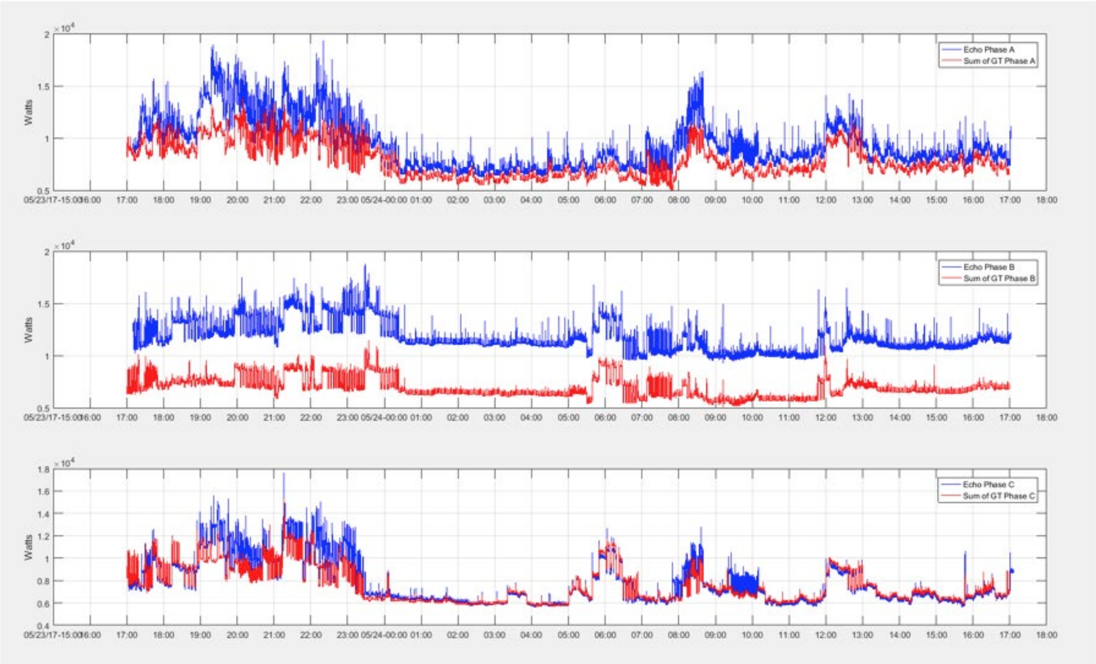
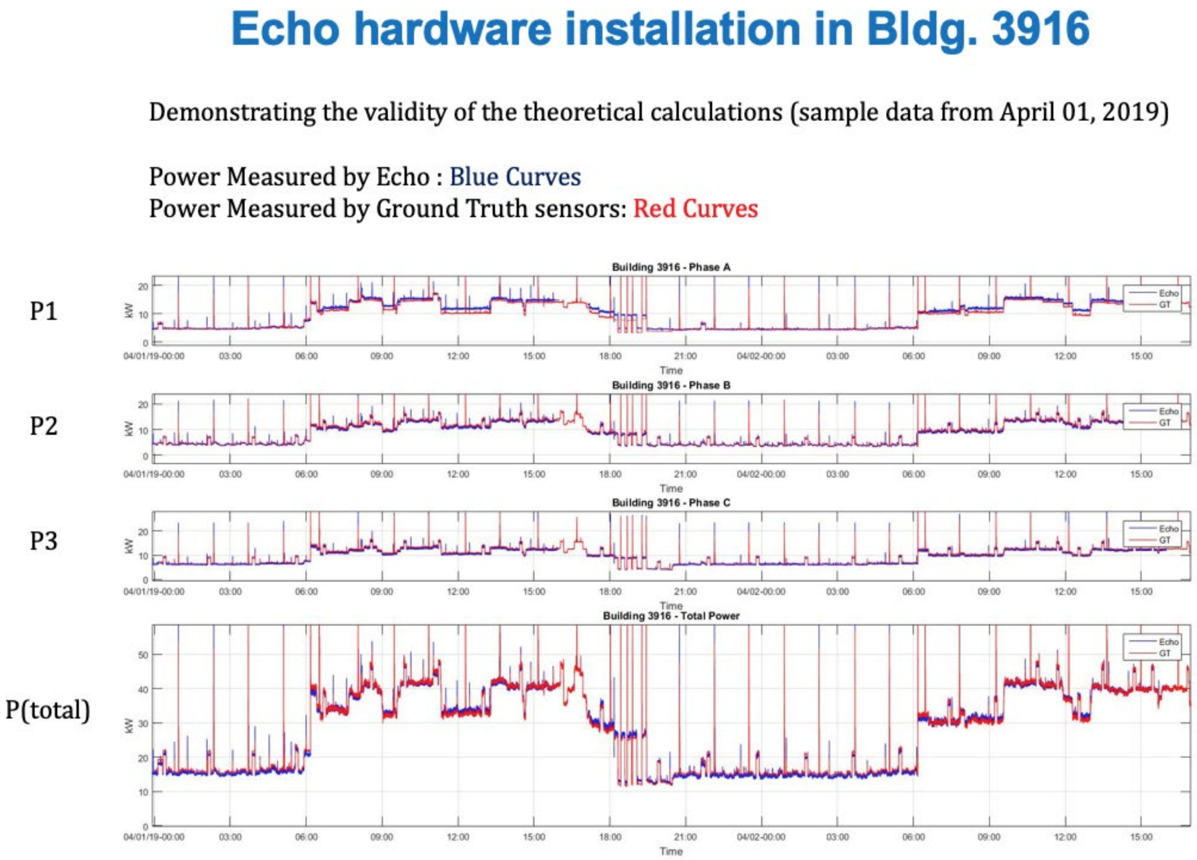


Figure B-2. Echo vs. Ground Truth for Building 2

In Building 3, the comparison was straightforward because the two sensors were measuring the same situation (Figure B-3). Here the Echo's measurements of total power consumed by Building 3 agreed almost perfectly with ground truth (less than 1 percent error). Note the periodic, 80 kW power spikes. These are caused by the compressor startup.



Echo hardware installation in Bldg. 3916

Demonstrating the validity of the theoretical calculations (sample data from April 01, 2019)

Power Measured by Echo : Blue Curves
Power Measured by Ground Truth sensors: Red Curves

Figure B-3. Echo Hardware Installation in Building 3916

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APPENDIX C ASSESSMENT OF THE ECHO'S ABILITY TO ACCURATELY IDENTIFY A LOAD AND ESTIMATE ITS ELECTRICITY CONSUMPTION

In this appendix, we examine the Echo's ability to accurately identify a load and estimate its electricity consumption. Some key terms are defined in Table C-1.

Table C-1. Key Terms and Definitions for Interpreting Electricity Load Patterns

Term	Definition
Device	An appliance, load, or piece of equipment that draws electrical power. For example, an air handling unit (AHU) and a drinking fountain are devices.
Event	The collection of behaviors over time in which a device goes from one mode to another and then returns to the original mode. For example, an event occurs when a compressor, which is initially quiescent, switches on, operates for a period of time, and then switches off.
Transition	A device's behavior while it switches from one operating mode to another.
Edge	The graphical depiction of the transition, typically in the voltage or current space.

Introduction

To accurately estimate the electricity consumption of a device, the Echo must successfully perform four steps:

1. Identify when an event begins
2. Identify the device
3. Identify when the event ends (and the time it has persisted)
4. Measure the additional energy consumption attributed to that device during that event

This assumes that the device "cycles," that is, periodically switches on and off. Devices with constant, continuous consumption will not be seen at all.

These requirements apply to all NILMS and require coordination of sensing and algorithms to disaggregate electricity consumption by device. Some sort of training and/or reference library is also required by all methods. Ultimately, the Echo's accuracy can be measured in its ability to correctly attribute energy consumption to a device.

The key to this process is identification of transitions (or edges). The Echo must identify the device's transitions at the initiation of an event and at its termination. These transitions can easily be obscured by coincident events by other devices. When the Echo fails to identify the initiation, it will fail to capture the energy consumption during the device's on-cycle. If the initiation of the next cycle is successfully identified, then one cycle of energy use will not be captured. This error results in an underestimate of the device's energy consumption. On the other hand, when Echo fails to identify the termination transition, it will assume that the device is operating until the next termination signal is identified. This will result in an overestimation of the device's consumption.

Note that both types of errors may occur for the same device and that their cumulative effect over many cycles could cancel (to some extent).

The Echo was able to identify—itemize—only the largest loads in the test buildings. There are several reasons for the Echo's failure to recognize the dozens of other loads in the test buildings:

- Hundreds of similar events occurred simultaneously.
- Upstream noise prevented use of high-frequency signatures.
- Event signals were less than the sensor's threshold of detection (because device signals were less than 1 percent of typical power levels).
- Some devices consumed a high level of power continuously, with little variation caused by variation in usage.
- The circuit-specific measurements—ground truth—included several devices, so the Echo's estimate of a device's energy consumption could not be compared with the ground truth

Numerous actions were taken to minimize these problems and maximize the number of devices that could be identified. For example, it was observed that most event edges are asymmetric because of the inrush current. The termination edge was easier to resolve, and a more accurate indicator of power use. In the end, however, only a few large devices, such as air handlers and pumps, could be reliably identified and compared to the ground truth.

Results

We examined the Echo's ability to detect the operation of AHU1 in Building 3. The results are based on data for the months of April and May. The Echo's accuracy was examined at several different time scales, and using two aggregation techniques. This was a good test for the Echo because the AHU's energy consumption is very regular.

Figure C-1 shows the hourly and daily energy estimates from the Echo and the ground truth for April 2019. The Daily consumption chart shows that, while the air handler's daily energy consumption barely changed from one day to another, the Echo saw a range in energy use as a result of failing to identify both initiation and termination transitions.

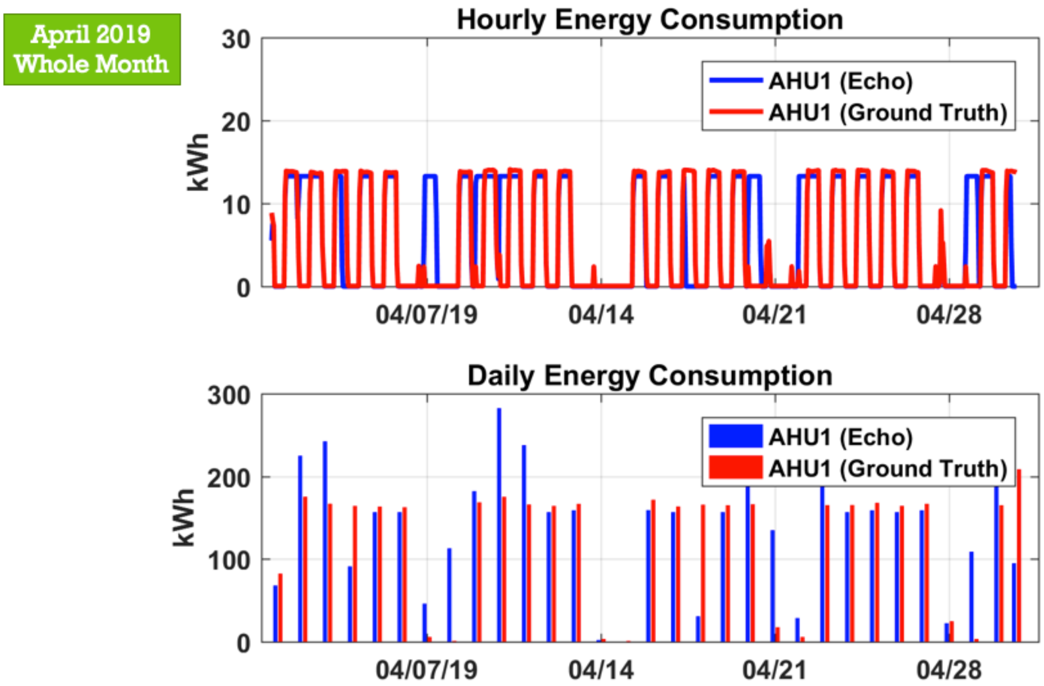

Figure C-1. Hourly and Daily Energy Estimates from the Echo and the Ground Truth for April 2019

Some examples of detection errors are shown more clearly by zooming in on a shorter time range. Figure C-2 compares the Echo to the ground truth for one week.

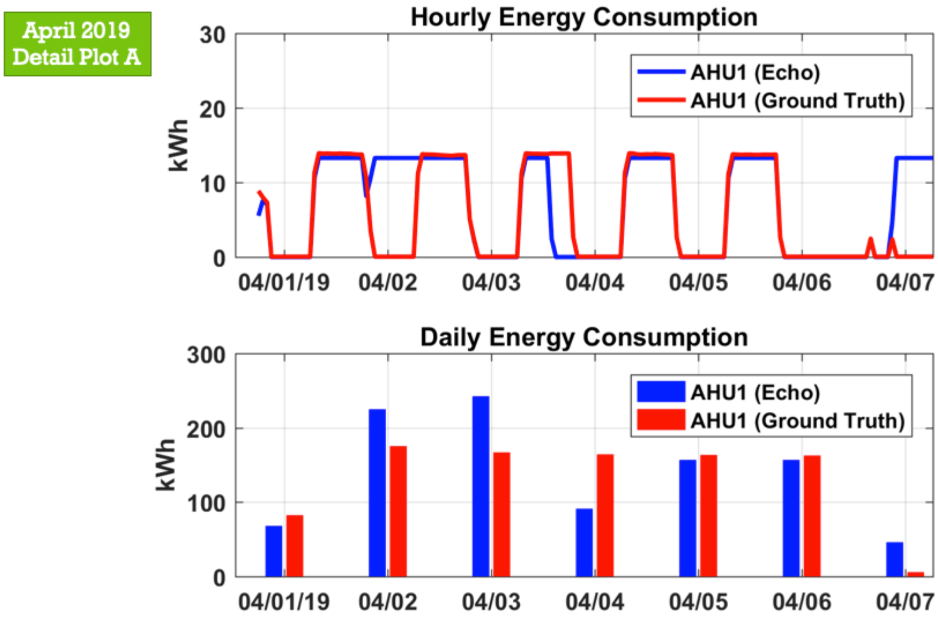

Figure C-2. Comparison Between the Echo and Ground Truth Data for One Week

On other days, Echo's estimates coincided almost perfectly with the ground truth. This occurred during one week in May, and is shown in Figure C-3. We were unable to find any explanation for periods of accurate detection and failures. Operation of other devices probably interfered with the signal, but we were unable to pinpoint the cause.

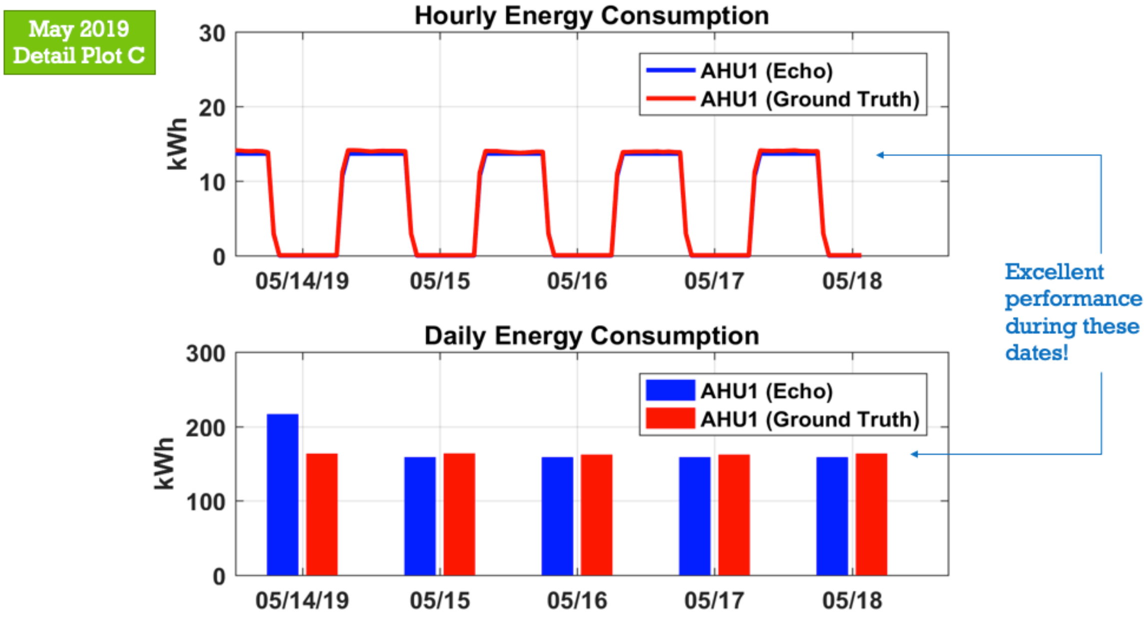

Figure C-3. Comparison of Echo and Ground Truth During One Week in May

The estimation errors during April 2019 are shown in Figure C-4.

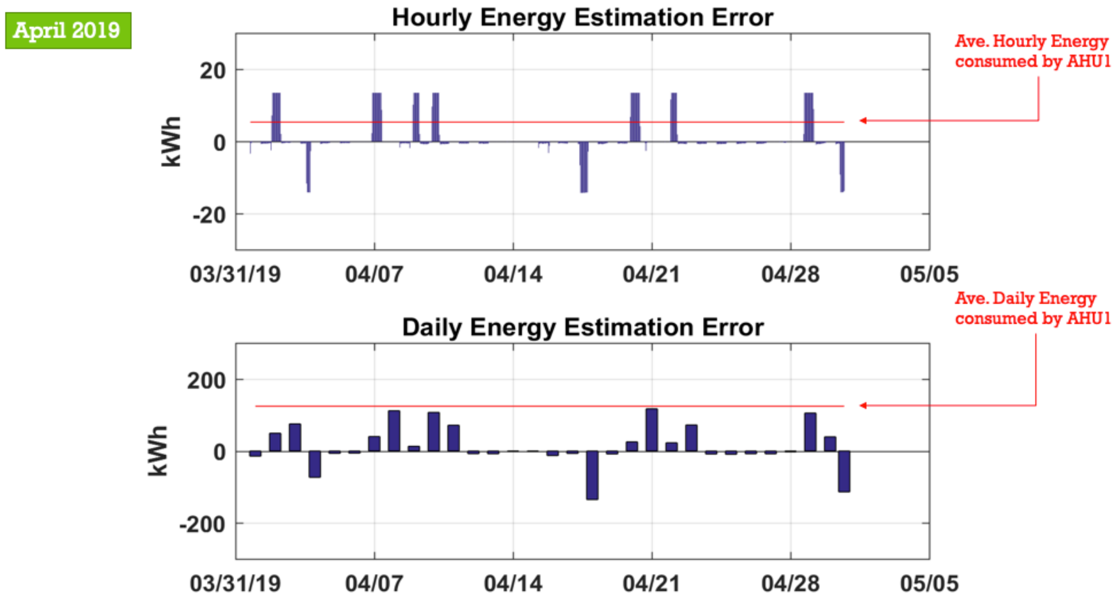

Figure C-4. Estimation Errors During April 2019

The red lines indicate the ground truth average energy consumed. Tall bars represent large errors. For hourly estimations, most errors were relatively small; however, some hours had errors larger than the actual consumption. There is no particular pattern regarding overestimation or underestimation of errors.

The daily estimations had smaller errors; none exceed daily energy use but many were still large. Again, there is no particular pattern regarding overestimation or underestimation of errors.

The results are summarized in Table C-2. As expected, the daily estimation errors were large. However, these errors tend to cancel over time, leading to substantially lower errors in estimates of monthly energy use.

Table C-2. Estimation Error Results

Month	Monthly Energy Estimation Error (%)	Daily Energy Estimation Error (Average) (%)
April	11	33
May	14	37

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APPENDIX D MEASUREMENTS OF HIGH FREQUENCY VOLTAGE NOISE

Some electrical loads create a high frequency (HF) perturbation (noise) on the voltage waveform of the power grid. These perturbations occur particularly when a device uses a switch-mode power supply (SMPS). The HF perturbations are especially useful because they bracket the device's length of operation. The device's energy consumption can be estimated when operating time is paired with the observed change in power consumption (assuming that the device consumes constant power).

The Echo contains sophisticated hardware to extract and process HF noise that might exist on top of the main 60 Hz voltage waveform. Once properly extracted and processed, the HF noise can be used to identify certain class of devices.

The Echo system performs the following steps to extract and process HF noise from the voltage waveform:

1. The Echo sensor measures HF frequency "noise" in the voltages across two lines of the building's incoming power feed (shown schematically in Figure D-1). The HF noise is sampled at 2 megahertz (MHz). (The sampling process is extremely data-intensive; it generates 345 giga samples per day.)

2. A portion of the waveform—less than a quarter cycle—is processed.

3. A "noise-clipper" algorithm checks the sampled voltage data and suppresses excessively large values or spikes. This step is necessary to prevent overloading of the system's front-end by the very strong noise generated by light dimmers.

4. The window of sampled data is converted to the frequency domain using Fast Fourier Transform (FFT).

5. The log-amplitude of the FFT is calculated and converted to an 8-bit image.

6. The 8-bit image is compressed using a JPEG-2000 algorithm and submitted to the cloud.

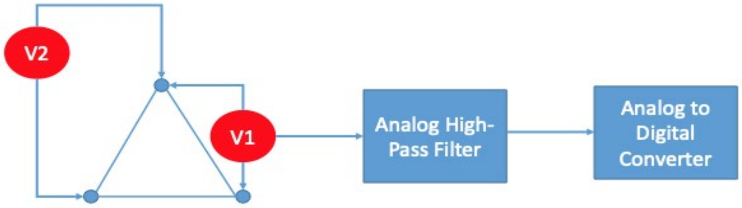

Figure D-1. Partial Schematic of Procedure for Extracting HF Voltage Spectra and Converting Them into Digital Signals.

Note how HF noise is extracted from across two lines of power.

Earlier research in controlled conditions demonstrated that the procedure could indeed identify HF signatures of many devices; however, the authors observed that identification became more difficult in buildings with many devices. This project confirms that device identification is more difficult "in the wild." We were able to identify only a few devices, and with less confidence than in less crowded, controlled conditions. An example of a successful correlation of HF spectra with the operation of a specific device—a variable frequency motor drive in Building 3—is shown in Figure D-2.[8]

Sample HF noise spectra for a three-phase electrical system are shown in Figure D-2. The plots show two HF noise spectra captured across two pairs of voltage lines (analogous to V1 and V2 measurements shown previously in Figure D-1). A third plot shows current in all three lines. Electricity consumption occurs where there is non-zero current (Power = V x I).

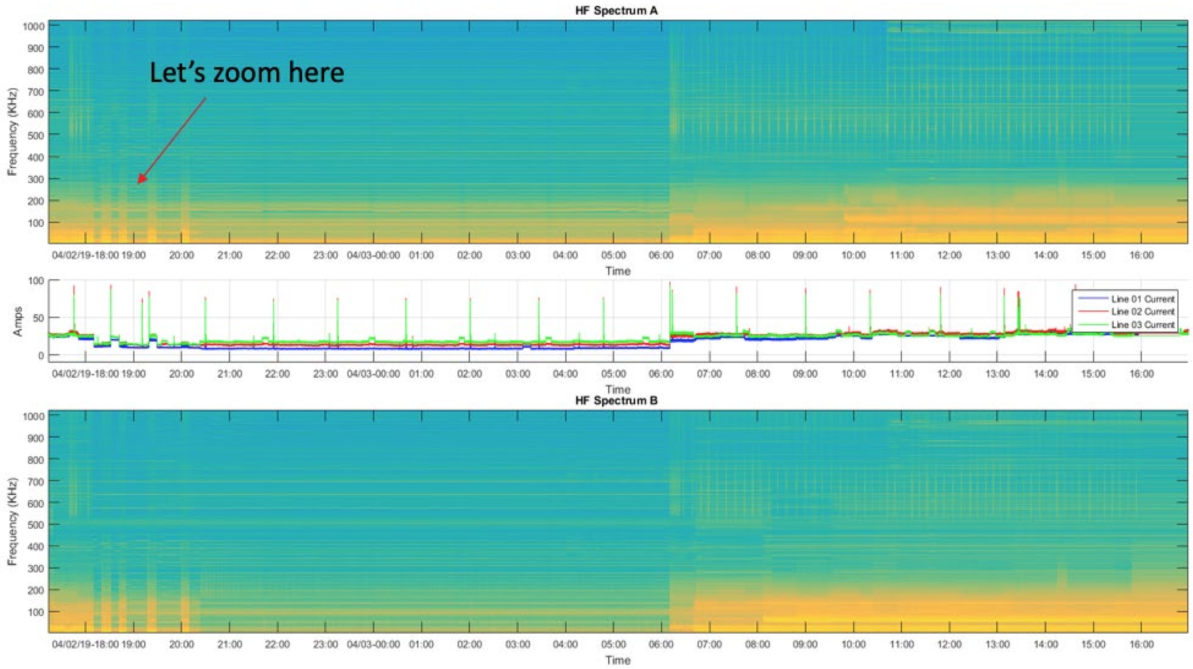

Figure D-2. Sample HF Noise Spectra for a Three-phase Electrical System in Building 3

Figure D-3 focuses on a two-hour period in that day. At this resolution, many HF "events" are visible. They correlate with increases in the building's measured current draw, so we can be sure than these HF events are associated with a device inside the building. Note that a positive correlation with current is needed to verify that an observed HF event is indeed related to a device inside the building under observation. Voltage noise can be created by devices connected to the power grid but located outside the building. Noise can also created by sources not connected to the power grid, such as AM radio transmitters, etc.

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[8] When observable, HF spectra could help identify variable-speed devices because they lack sharp voltage edges. However, the HF spectra do not help with estimating power consumption of such devices. It is most helpful in determining the time intervals during which such devices are operating.

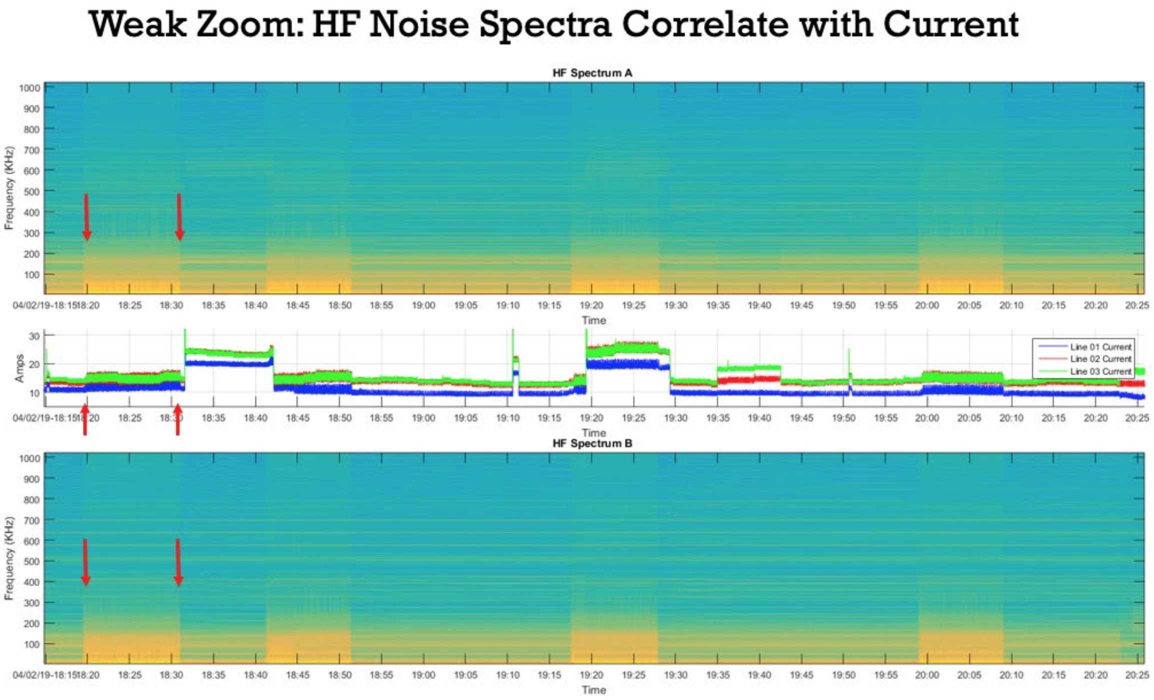


Figure D-3. Focus on a Two-hour Period in the HF Noise Spectra for a Three-phase Electrical System

A stronger zoom showing 40 minutes reveals details of the HF voltage signatures (Figure D-5). There are distinct HF bands during the device's operation. The termination transition is sharper than the initiation, probably because an in-rush occurs during the initiation. Since current consumption also occurs during these times, the device is drawing power.

However, there are also many HF voltage events without corresponding current events. Progressively expanded spectra are shown in figures D-4 through D-7, this time for April 26 in Building 3. Figure D-4 shows a 24-hour period. Note the appearance of a distinct HF spectral pattern—vertical bands with breaks—at about 6 AM.

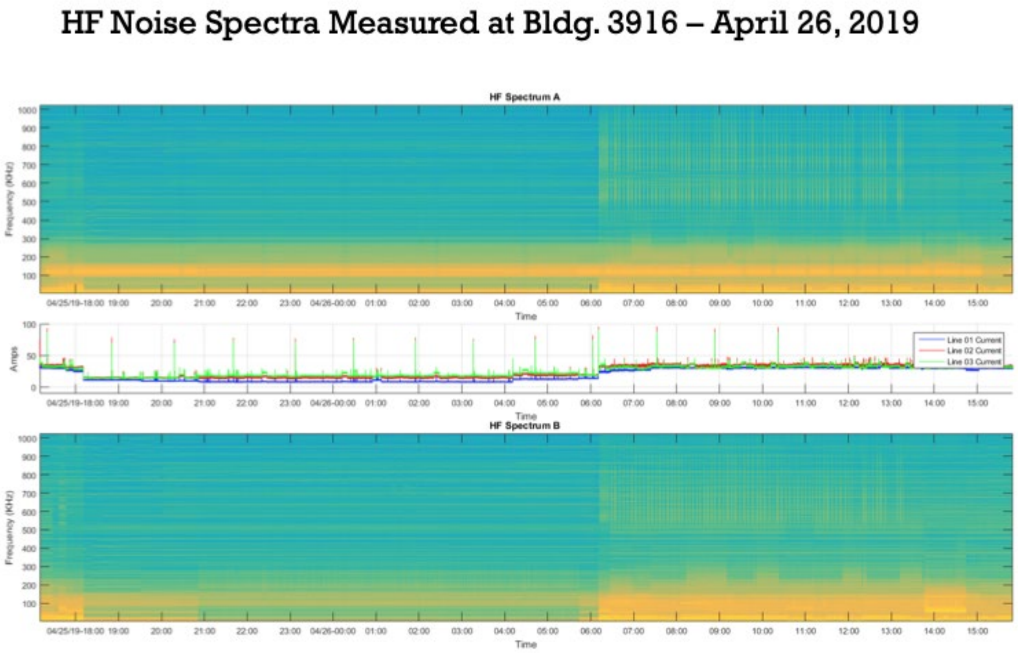
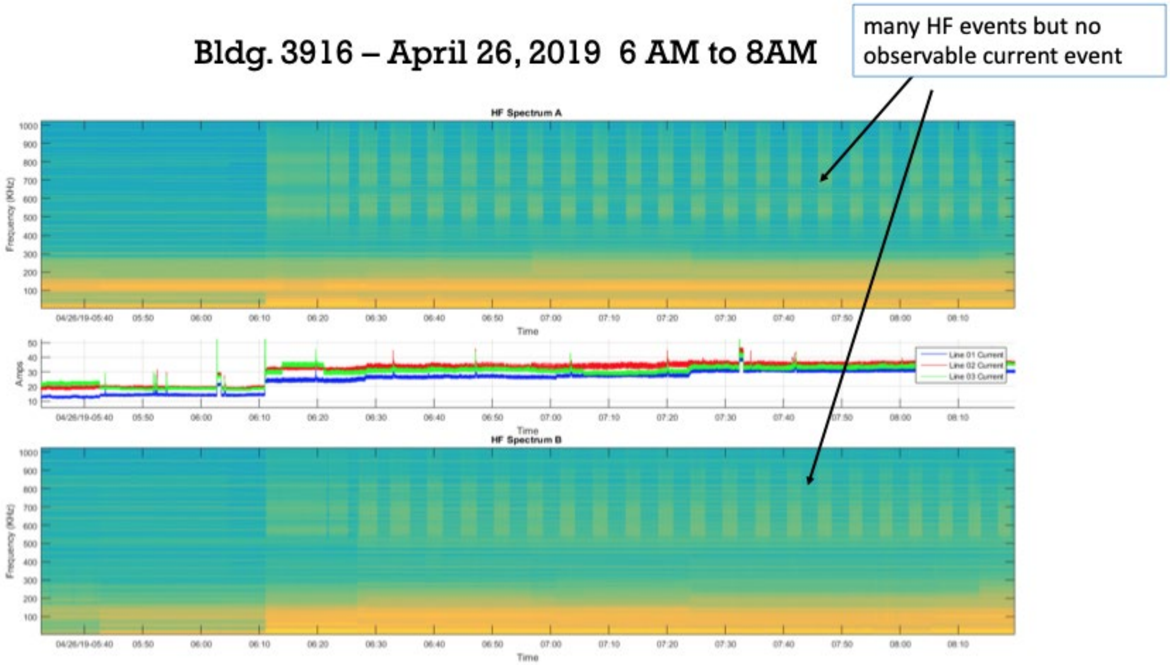

HF Noise Spectra Measured at Bldg. 3916 – April 26, 2019

Figure D-4. A 24-hour Period for April 26 in Building 3

The details of this pattern are more apparent after further magnification (see figures D-5, D-6, and D-7). The spectra changes during the transition and then remains stable during operation.


Bldg. 3916 – April 26, 2019 6 AM to 8AM

many HF events but no observable current event

Figure D-5. Building 3916 Data, April 26, 2019, 6 AM to 8 AM

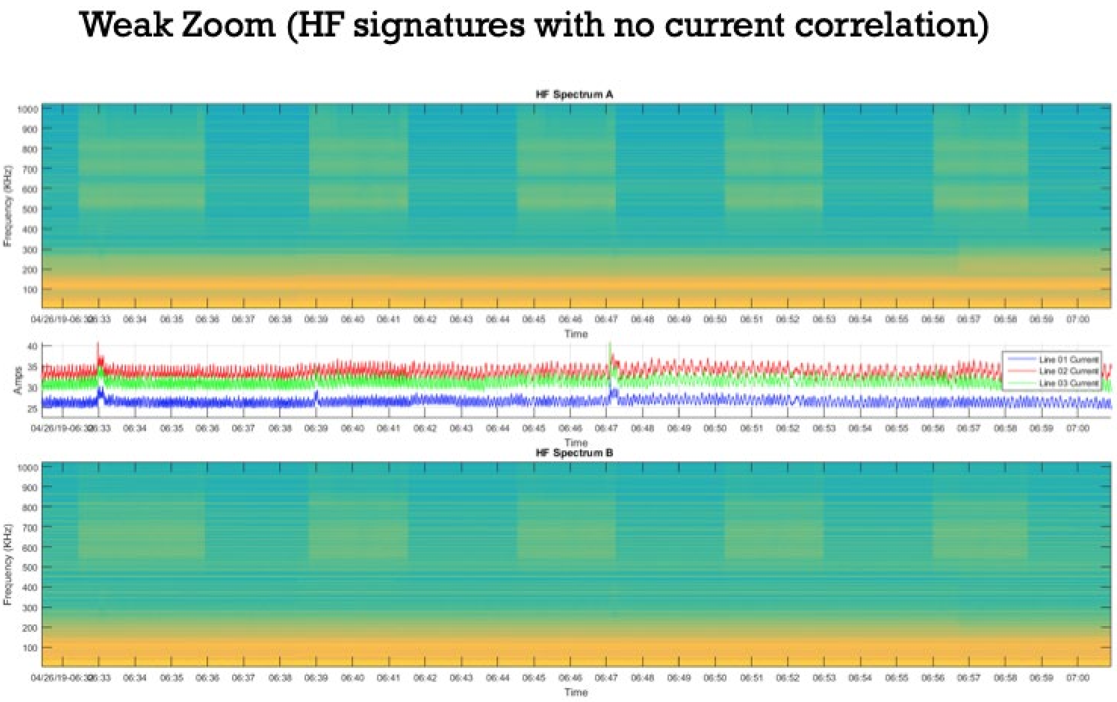


Figure D-6. Weak Zoom

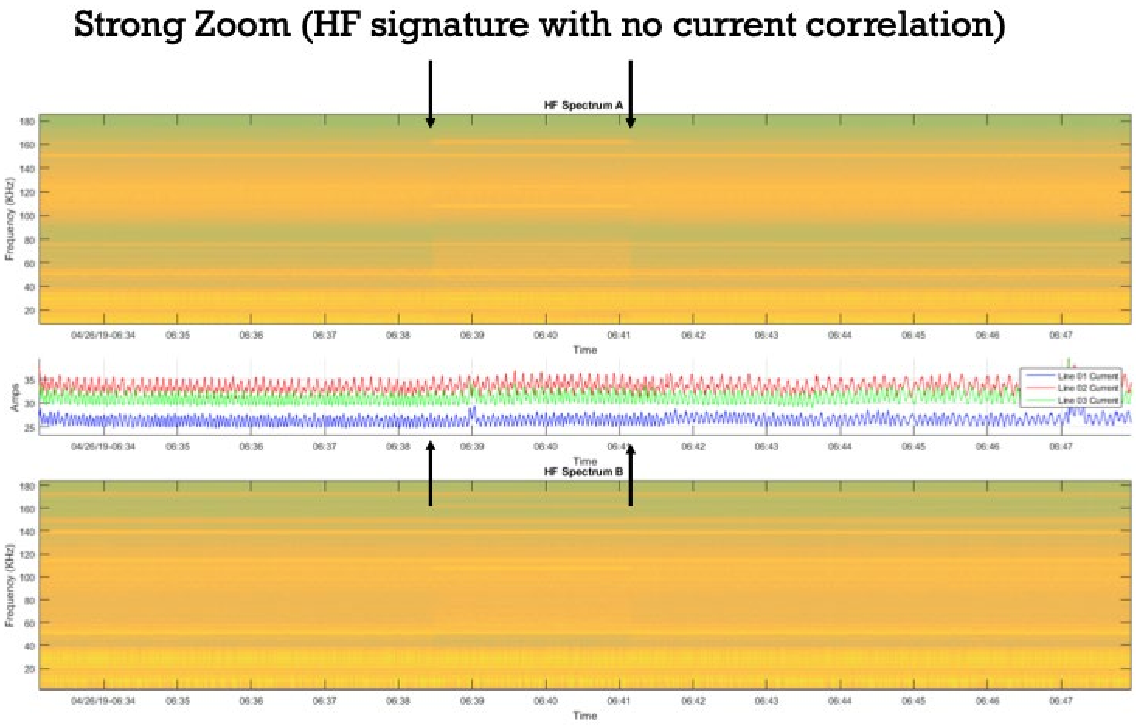


Figure D-7. Strong Zoom

The successively magnified spectra show that HF events will occur that are not associated with a change in current. We were unable to pinpoint the sources of this HF noise, or even if they originated from inside or outside the building. In any event, they greatly complicated the application of HF voltage spectra as a means of monitoring device behavior. These spectra may still be useful even if they say nothing about power consumption because they may indicate a device's existence. On the other hand, the device may be in another building or far away.

Both examples show that a device's "steady-state" signature can be unique and persist as long as the device is operating. This is a significant advantage over transition (or "edge") information, which is often the only information than can be collected when NILM is applied to power data.

APPENDIX E INFORMATION REVEALED IN HIGH FREQUENCY CURRENT MEASUREMENTS

Some loads can be identified using the fifth harmonic of current measured by the Echo. Close inspection of Echo data for Building 3 (Figure E-1) revealed that clusters of compact fluorescent lamps generated a unique signal on the fifth harmonic of current. This is shown in Figure E-1.

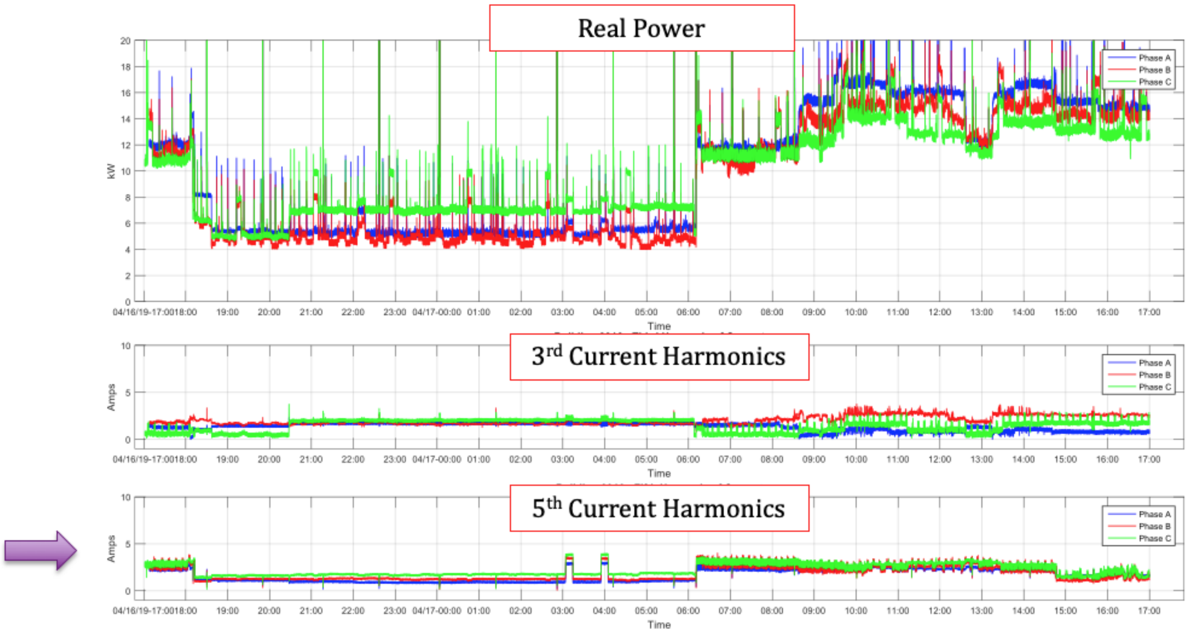


Figure E-1. Close Inspection of Echo Data for Building 3

The lights were switched on until about 18:00, then switched off during the night. In the morning, at about 06:30, the lights were switched on again. It appears that some may have been switched off during the afternoon. The third harmonic hints at this behavior, but the fifth harmonic clearly shows the behavior. The signal was exceptionally clear because the load was in itself unusual and because they were connected directly to the 480 V three-phase side.

Ultimately, it may be possible to extract HF noise from current measurements and infer device energy behavior. This feature deserves further research. For example, current harmonics may be able to infer operation of various types of equipment (electronics, resistive, motors).