FINAL REPORT

Intelligent Building Management with Holistic Digital Lighting

ESTCP Project EW-201720

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This project demonstrated the deep energy savings possible by going beyond simple lamp replacements and instead incorporating advanced lighting controls enabled by a fine-grained sensor network with Light Emitting Diode (LED) luminaires. The project developed a holistic method to lighting retrofits, applicable to both high-bay and office environments on military installations. This holistic method integrated sensed occupancy needed for the advanced lighting controls into the building automation system and optimized the HVAC control and plug-loads accordingly. Other lighting retrofits incorporate ambient light sensors and occupancy sensors, but at a much coarser level. While those attempts need to control a zone of lighting around each sensor, this innovative approach to combine the sensor with the luminaire allows for a finer level of control which translates into deeper energy savings.

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ACRONYMS AND ABBREVIATIONS

ACST	Advanced Connected Sustainability Technologies
AFB	Air Force Base
AFF	Above Finished Floor
AHU	Air Handling Unit (HVAC)
AIRR	Adjusted Internal Rate of Return
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS	Building Automation System
BEA	Business Energy Advisor
BLCC	Building Life Cycle Cost
BMS	Building Management System
BTU	British Thermal Unit
CARB	California Air Resources Board
CERL	Construction Engineering Research Laboratory
cd	candela
CFR	Code of Federal Regulations
CHP	Combined Recovered Heat and Electrical Power
CPO	ComfortPoint Open (Honeywell)
CRI	Color Rendering Index
DoD	Department of Defense
DoE	Department of Energy
DPW	Directorate of Public Works
EBI	Enterprise Building Integrator (Honeywell)
EEM	Enlighted Energy Manager
EGW	Enlighted Gateway
EIA	U.S. Energy Information Administration
EO	Executive Order
EPA	U.S. Environmental Protection Agency
ERC	Enlighted Room Control
ERDC	Engineer Research and Development Center
ESG	Energy Services Group (Honeywell)
ESPC	Energy Savings Performance Contract
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
fc	Footcandles
FEMP	Federal Energy Management Program
FRCS	Facility Related Control Systems
GSA	General Services Administration

GUI	Graphical User Interface
HBS	Honeywell Building Solutions
HID	High intensity discharge
HVAC	Heating Ventilation and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
ICS	Industrial Control Systems
IDF	Intermediate Distribution Frame
ILP	Industrial Lighting Products
IoT	Internet of Things
IPMVP	International Performance Measurement and Verification Protocol
ISO	International Organization for Standardization
kBTU	Thousands of British Thermal Units
kW	Kilowatt
kWh	Kilowatt-Hour
LED	Light-emitting diode
MW	megawatt
NDAA 2007	National Defense Authorization Act of 2007
NIC	Network Interface Card
NIST	National Institute of Standards & Technology
NOAA	National Oceanic and Atmospheric Administration
OBC	Occupancy-Based Control
OC/ALC	Oklahoma City Air Logistics Complex
O&M	Operation and Maintenance
PNNL	Pacific Northwest National Laboratory
PoE	Power over Ethernet
SCADA	Supervisory Control and Data Acquisition
SCFM	Standard Cubic Feet per Minute
SERDP	Strategic Environmental Research and Development Program
SOP	Standard Operating Procedure
TB	Terminal Box (HVAC)
TCLP	Toxicity Characteristic Leaching Procedure
TLED	Tubular light-emitting diode
UFC	Unified Facilities Criteria

VAV	Variable Air Volume (HVAC)
VFD	Variable Frequency Drive
VOC	Volatile Organic Compound

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ABSTRACT

INTRODUCTION AND OBJECTIVES

Light has a profound impact on people. Beyond basic visual needs, light also influences the health and wellness of building occupants. Lighting directly consumes about 30% of the energy in typical office buildings and up to 60% in typical non-refrigerated warehouse buildings (Business Energy Advisor [BEA-2016]). As many buildings in the Department of Defense (DoD) portfolio start to age, lighting retrofit projects become cost effective, but not all solutions offer the same savings. The objectives of this project were to demonstrate energy reductions from lighting, HVAC, and plug-loads at Tinker AFB in Oklahoma City, OK, in both an office area (5,000 ft^2) and a high-bay area (21,000 ft^2), through a commercially available advanced lighting control system by integrating the dense sensor network from the lighting system with the pre-existing Building Management System and enable occupancy-based HVAC control.

TECHNOLOGY DESCRIPTION

This project, EW-201720, demonstrated the deep energy savings possible by going beyond simple lamp replacements and instead incorporating advanced lighting controls enabled by a fine-grained sensor network with light-emitting diode (LED) luminaires. The project developed a holistic method to lighting retrofits, applicable to both high-bay and office environments on military installations. This holistic method integrated sensed occupancy needed for the advanced lighting controls into the building automation system and optimized the HVAC control and plug-loads accordingly. Other lighting retrofits incorporate ambient light sensors and occupancy sensors, but at a much coarser level. While those attempts need to control a zone of lighting around each sensor, this innovative approach to combine the sensor with the luminaire allows for a finer level of control which translates into deeper energy savings.

PERFORMANCE AND COST ASSESSMENT

The cost effectiveness of this demo system was compared against a lower-cost TLED lighting retrofit using the BLCC5 tool. Assuming Oklahoma energy prices ($0.0524/kWh for electricity, $1.81/MMBtu for natural gas), this demo system achieves simple payback in 17 years, with a Savings-to-Investment Ratio (SIR) of 0.93. **Lighting:** The demonstrated lighting system achieved an energy savings of 69% of baseline usage in the high-bay area over the high-bay demo period. In the office area, the pendant fixtures achieved an energy savings of 71% of baseline usage, and the troffer fixtures achieved an energy savings of 67% relative to baseline usage. **Plug-loads:** The energy savings achieved by plug-loads over the demo period was 4% of the baseline for total plug-load energy consumption over the demo period. **HVAC:** The HVAC energy savings in the high-bay area was 30% of baseline consumption. This significantly exceeded the performance objective of 20% savings. The HVAC energy savings in the office area was 12% of baseline. The energy savings of the total system (office + high-bay areas) was 26% of the total baseline, which met the performance objective. The cost effectiveness has been impaired by extraordinary declines in energy prices. However, the system is still an attractive investment option at prevailing U.S. average energy prices, and it is very attractive assuming higher energy costs such as California energy prices.

IMPLEMENTATION ISSUES

Initially, the first issue faced was related with cyber security concerns, the approval process delayed the start date, and later caused control and data issues because of the tight controls in place. Integration of the HVAC system proved challenging due to significant mechanical and control issues with the HVAC system. A few smart occupancy sensors caused issues with sensitivity, with some reporting false positive, and others false negative detected occupancy. Finally, the plug-load controllers also initially faced an issue with no connectivity or communications to the controller because of mismatched firmware versions.

EXECUTIVE SUMMARY

INTRODUCTION

Light has a profound impact on people. Beyond basic visual needs, light also influences the health and wellness of building occupants. Light directly consumes about 30% of the energy in typical office buildings and up to 60% in typical non-refrigerated warehouse buildings (Business Energy Advisor [BEA-2016]). As many buildings in the Department of Defense (DoD) portfolio start to age, lighting retrofit projects become cost effective, but not all solutions offer the same savings. The opportunity cost of realizing only mediocre savings with an energy retrofit represents 15 to 20 years of lost opportunity.

OBJECTIVES

The objectives of this project were to demonstrate energy reductions from lighting, HVAC, and plug-loads at Tinker AFB in Oklahoma City, OK, in both an office area (5,000 ft^2) and a high-bay area (21,000 ft^2), through a commercially available advanced lighting control system by integrating the dense sensor network from the lighting system with the pre-existing Building Management System and enable occupancy-based HVAC control.

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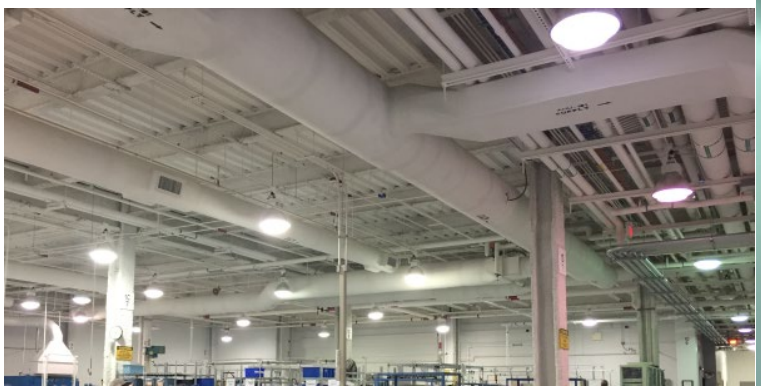
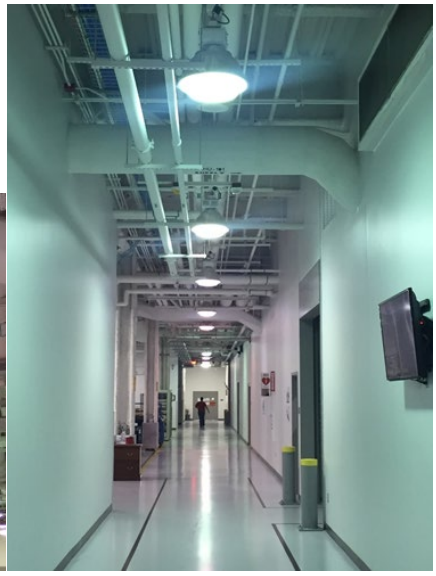
Other lighting retrofits incorporate ambient light sensors and occupancy sensors, but at a much coarser level. While those attempts need to control a zone of lighting around each sensor, this innovative approach to combine the sensor with the luminaire allows for a finer level of control which translates into deeper energy savings.

Office Area with New LED Lighting Systems Installed.

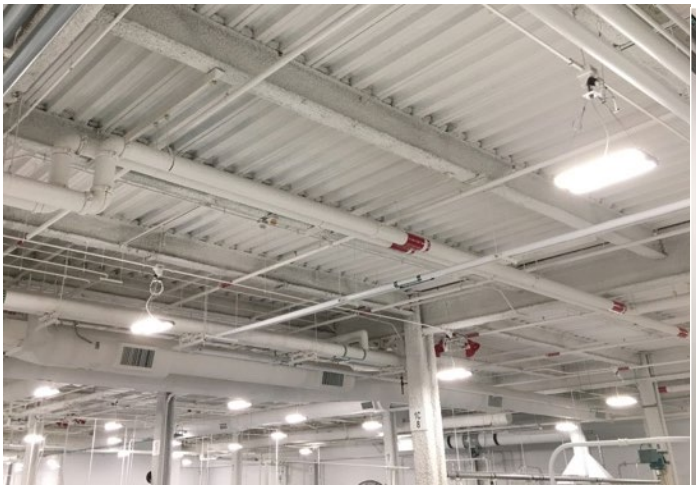
Phase 1: Pendant design with direct/indirect lighting (left), and Phase 2: Troffer design (right)

Office Area with Original Baseline Fluorescent Lighting Fixtures.





High-bay Area with Original Baseline Lighting Fixtures.



High-bay area with new LED lighting systems installed.

PERFORMANCE ASSESSMENT

Lighting

The Enlighted lighting system achieved an energy savings of 69% of baseline usage in the high-bay area over the high-bay demo period. In the office area, the pendant fixtures achieved an energy savings of 71% of baseline usage over the pendant demo period. The troffer fixtures achieved an energy savings of 67% relative to baseline usage over the troffer demo period. While the overall energy savings did not meet the target goal of 80% reduction, the savings remain notably substantial and may meet or exceed this target goal in spaces with more daylight. The lower level of energy savings achieved by troffer lights (compared to pendants lights) is explained by decreased level of occupancy-based savings for troffer lights. This was due in part to overly-sensitive occupancy sensors in the troffer demonstration. This caused troffer lights to remain powered at times throughout the night when the work space was unoccupied, increasing energy consumption relative to the pendant lights (whose occupancy sensors were not abnormally sensitive). For further discussion, see Section 8.1.4.

Plug-Loads

The energy savings achieved by plug-loads over the demo period was 4% of the baseline for total plug-load energy consumption over the demo period. This did not achieve the plug-load performance objective goal of 20% energy reduction relative to baseline. The failure to meet the performance objective can be explained by the behavior of the occupants in the office space, who predominantly connected electrical appliances into uncontrolled plugs instead of occupancy-controlled plugs. For instance, energy consumption from controlled plugs during the baseline period was 17% of the total plug consumption. During the demo period, the energy consumption of controlled plugs was 6% of the total plug energy consumption. We note that during the demo period, the energy consumption of uncontrolled plugs was 90% of the baseline total consumption. Hence, even if (hypothetically) controlled plugs had used no energy during the demo period, they would have achieved a savings of at most 10% of the baseline, and the savings target of 20% reduction would not have been reached.

If we compare the energy savings achieved by controlled plugs in the demo period to the baseline energy consumption of controlled plugs only, the savings is 38% of baseline. Thus, occupancy-controlled plugs achieved substantial energy savings relative to their baseline energy consumption with occupancy control disabled. Hence, we conclude that the primary limiting factor in realized energy savings was the limited usage of controlled plugs by the office space occupants.

HVAC

Occupancy-based control of the HVAC system achieved an energy savings of 30% of baseline consumption in the high-bay. This greatly exceeded the performance objective of 20% savings. In the office area, occupancy-based control achieved a savings of 12% of baseline. Hence, the office area did not achieve the performance objective. We believe this was caused by the occupancy sensors, which became overly-sensitive in the office area during the second Phase of the demonstration (after May 1, 2019). The sensors intermittently detected occupancy during overnight periods, when the space was actually unoccupied. This interfered with the energy savings of the HVAC system, since HVAC setbacks are not applied when occupancy is detected in a zone.

The energy savings of the total system (office + high-bay areas) was 26% of the total baseline, which did meet the performance objective.

COST ASSESSMENT

The NIST BLCC5 tool was used to assess the costs of this demo system against a cheaper base case upgrade option (TLED lighting retrofit only, without holistic building management). The total costs of this demo were calculated as $124,747 (with pendant light fixtures in the office area), compared to an estimated $26,000 for TLED retrofit. Assuming Oklahoma industrial energy prices*, which are quite low—$0.0524/kWh for electricity and $1.81/MMBtu for natural gas, this demo system achieves simple payback in **17 years** (assuming a 20-year study), with a Savings-to-Investment Ratio (**SIR**) of **0.93** and an Adjusted Internal Rate of Return (**AIRR**) of **2.64%. (**Discounted payback is not reached in a 20-year study.) Oklahoma energy prices have witnessed dramatic declines in the past four years due to increased domestic energy production, which decreased the cost effectiveness of the demo solution. However, the demo is quite cost effective in locales with higher energy prices: assuming California industrial energy prices* ($0.1527/kWh for electricity, $6.84/MMBtu for natural gas), simple payback occurs in 6 years and discounted payback in 7 years, with **SIR** of **2.86**, and **AIRR** of **8.53%**. Assuming average U.S. industrial energy prices* ($0.0744/kWh for electricity, $3.09/MMBtu for natural gas), simple payback occurs in **12 years** and discounted payback in **14 years**, with an **SIR** of **1.34** and **AIRR** of **4.51%**. The cost effectiveness has been impaired by extraordinary declines in energy prices. However, the system is still an attractive investment option at prevailing U.S. average energy prices, and it is very attractive assuming higher energy costs such as California energy prices, climate areas with a significant heating or cooling load, installations with abundant natural lighting for daylight harvesting, or buildings with periods of sparse or intermittent occupancy. Furthermore, energy savings could be enhanced by stricter or more aggressive configurations with smaller groups of lighting fixtures or shorter occupancy-controlled timeouts. (*Energy prices from eia.gov as of August 2019).

IMPLEMENTATION ISSUES

Cyber security concerns caused some issues with our project. First, the approval process delayed our demonstration start date. Furthermore, cyber security constraints caused control and data issues with the HVAC system. For instance, duplicate IP addresses and network congestion disrupted the operation of HVAC control devices, resulting in data loss. The strict cybersecurity policies restricted our ability to run diagnostic tools, troubleshoot communication issues, and debug faulty devices at the site, which impaired our ability to promptly detect and resolve the issues. Integration of the HVAC system proved challenging due to significant mechanical defects with the HVAC system. A few smart occupancy sensors caused issues with sensitivity, with some reporting false positive, and others false negative detected occupancy. Finally, the plug-load controllers also initially faced an issue with no connectivity or communications to the controller because of mismatched firmware versions. Although these issues caused delays in our project, or reduced our effective demonstration period, ultimately all issues were addressed and resolved.

1.0 INTRODUCTION

The Intelligent Building Management with Holistic Lighting project demonstrated a holistic approach to intelligent building controls using state-of-the-art technology that integrates lighting, HVAC, and plug-loads with granular occupancy information from a dense grid of smart sensors installed throughout the demonstration areas. This system helps the Department of Defense (DoD) reduce energy consumption and costs, reduce maintenance and operational costs, as well as improve lighting quality within its buildings.

1.1 BACKGROUND

Current Technology State of the Art

Recent advances in lighting, sensors, and cloud connectivity have facilitated new commercial offerings for building controls with substantial opportunities for increased energy efficiency. These environmentally conscious systems are making inroads in the market because of the benefit and value they provide through reduced energy consumption, reduced operating costs, and improved comfort. Advances in light-emitting diodes (LEDs) have allowed increased lighting quality, performance, and reliability. These conditions have enabled a wide range of new applications for LED technology including indoor lighting for commercial buildings. Technical advances in building controls have similarly become more connected with centralized systems that can monitor and control multiple building functions simultaneously and effortlessly.

Current State of Technology in DoD

DoD facilities are ever-evolving and the department is making substantial efforts to remain current by adopting state-of-the-art technology. For example, Tinker Air Force Base, the site selected for our demonstration, is currently under contract with a Department of Energy (DoE) funded energy savings performance contract (ESPC) project to renovate multiple buildings and implement cost-saving renewable energy conservation measures.

Technology Opportunity

Our Intelligent Building Management with Holistic Digital Lighting system went beyond simple lamp replacement. This project studied the impact of advanced digital lighting by evaluating two advanced lighting designs: a simple retrofit replacement and an advanced pendant mounted fixture with direct/indirect lighting capability. Additionally, our system integrated occupancy sensing features of the advanced lighting solution with the heating, ventilation, and air conditioning (HVAC) controllers to deliver calculable reductions in lighting costs and HVAC operating energy costs.

1.2 OBJECTIVE OF THE DEMONSTRATION

The project objectives were A) to demonstrate technology integration between Honeywell Building Solutions (HBS) systems and Internet of Things (IoT) light fixtures from Enlighted, Inc.; B) to deliver reductions in energy consumption from lighting, plug-loads, and HVAC using holistic occupancy-based control, while maintaining or improving occupants' comfort; and, C) to demonstrate this technology at Tinker Air Force Base (AFB) in Oklahoma City in two different areas: (1) an office space of approximately 5,000 square feet, and (2) a high-bay area of approximately 21,000 square feet.

The holistic occupancy-based control is the characteristic of our system that incorporates the dense grid of occupancy sensors installed throughout the demonstration areas as an input to control multiple building systems, including lighting, HVAC, and plug-loads, while additionally incorporating advanced lighting design principles that, in addition to occupancy, account for daylight, ambient lighting, task lighting, and the lighting control system. This system is further described in Section 2, and this high-level quantitative objective is captured as performance objectives PO1, PO2, and PO3 described in Section 3. The occupants' comfort refers to maintaining comfortable illumination levels while the areas are occupied. This high-level qualitative objective is captured as performance objective PO4 in Section 3.

1.3 REGULATORY DRIVERS

A recent overview of LED lamp retrofit options notes the limits of performance and energy savings realized by simple lamp replacement approaches. [CLTC2014] A recent General Services Administration (GSA) study of advanced lighting control states, "*While energy savings have been achieved through the wide proliferation of efficient lamps and ballasts, advanced lighting controls have become a significant and largely untapped energy savings strategy ... there is considerable potential ... to achieve deep energy savings*." [GPG2012] Military installations can achieve deeper energy and cost savings by implementing integrated LED luminaires (fixtures) with integral lighting control technology. For additional savings, the rich set of lighting sensor data can be integrated into HVAC control systems to provide a more holistic and comprehensive energy solution.

Digitalization of lighting technologies and the use of sensors for granular dimming and integration creates a truly unprecedented opportunity, but it must be tested for comparison with more traditional, lower cost options. The strategic impact of these choices must be based on appropriate data. Every retrofit that produces mediocre energy savings and uses no controls represents 15 to 20 years of lost opportunity. The opportunity cost to DoD and the American taxpayer would be tremendous. This study enables data-based decisions to ensure DoD retrofits have the best overall outcome.

Office buildings at many military installations are fairly similar to commercial buildings in terms of occupancy schedules and energy consuming equipment. A study of commercial energy use showed that lighting is the second largest energy use category [Belzer2006]. Therefore, advanced lighting control technology can bring valuable new sensing and control capability to buildings on military installations. Smart lighting systems enable greater building intelligence and provide significant energy and cost savings. A recent GSA study of occupant responsive lighting showed that advanced lighting controls could produce significant energy savings [GSA2012]. The GSA's Green Proving Grounds program at the Metcalfe building in Chicago and Summit Building in Atlanta achieved savings of 69% over the GSA average, and 75% over the national average, with LED fixtures using advanced lighting controls [GPG2015].

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

This project demonstrated the deep energy savings possible in building lighting projects by going beyond simple lamp replacements. By incorporating advanced lighting controls enabled by a finely-grained sensor network embedded with new LED luminaires. The project developed and implemented a fully integrated method for lighting retrofits, applicable to both high-bay and office environments. Furthermore, this holistic method integrated sensed occupancy (which is needed for the advanced lighting controls) into the building automation system and optimized the HVAC control accordingly, which resulted in measurably improved reductions in building energy consumption and operating costs. Because of the technology's ease of installation, low maintenance costs, and potential for reducing operating costs of buildings, we fully expect and recommend that the technology be applied to multiple DoD locations, including office spaces and high-bay areas.

Other lighting retrofit strategies incorporate ambient light sensors and occupancy sensors, but at a much coarser level. While those strategies attempt to control a zone of lighting around each sensor, our innovative approach to combine the sensor with the luminaire allows a finer level of control, which translates into substantial energy savings.

The Enlighted advanced lighting system (shown in Figure 1) uses distributed smart sensors, each associated with an individual light fixture. Each smart sensor unit measures space temperature, light level, occupancy, and lighting power; the sensor unit also contains digital signal processing, control, and AES-128 encrypted wireless communications capability. This dense network of sensors performs finely-grained control of light levels based on measured occupancy and ambient light levels and provides a rich stream of building data for use in optimizing HVAC control.

A separate Enlighted system was procured for research, analysis, development, testing, and troubleshooting. This development equipment consisted of the basic Enlighted components (1 Enlighted Energy Manager, 1 AIRE, 1 Gateway, and 2 Smart Sensors) which were configured and remained at a Honeywell ACST R&D Labs location (offsite) throughout the demonstration period. This test equipment was transferred and delivered to the installation site at the end of the project.

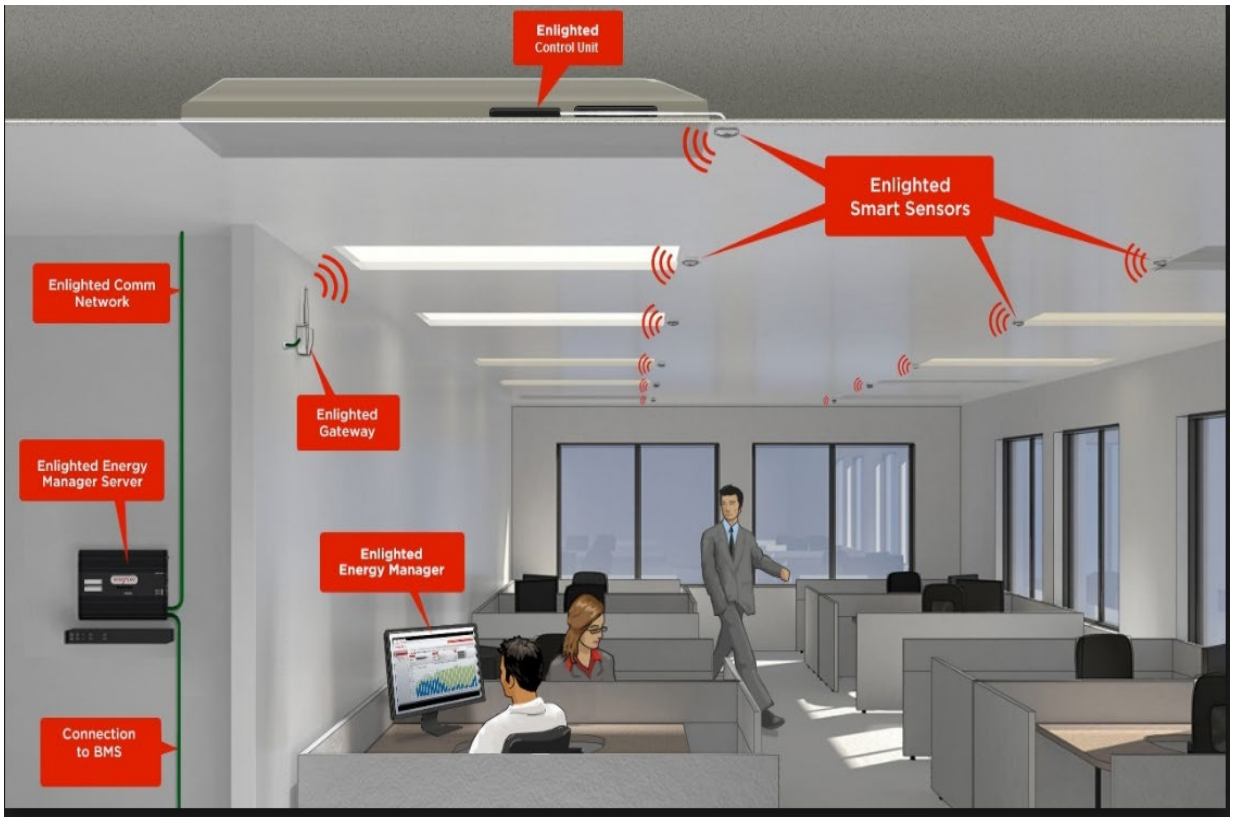


Figure 1. Enlighted System Overview.

The Enlighted system is easy to design, install, commission, and service. Lighting control profiles may be configured to match occupant needs. Once configured, each sensor (and fixture) operates without centralized control. The solution is elegant and future-proof, with the following key features and lighting system considerations:

- Daylighting. The daylighting feature is one of the most effective ways to improve visual performance and reduce energy use. While any changes to the existing daylighting conditions were beyond the scope of this demonstration, the existing daylighting conditions in the office demonstration area were measured on-site for each Phase and are included in the metrics and analysis. The industrial demonstration area with high-bay lighting did not have any existing daylight, so daylight analysis is not included for this area.
- Ambient lighting. The ambient lighting was coordinated with the interior furniture and equipment layouts to provide enough light for navigating the space and the simplest tasks, while providing increased light levels near specific working areas. Providing a balance between indirect lighting and direct lighting by illuminating the ceiling and walls helps balance contrast, reduces shadows, and improves brightness perception.
- Task lighting. Task lighting, such as desk lamps and under-shelf lights, located closer to the task area were used for visual tasks which require higher illuminance levels. While this project did not provide any new task lighting fixtures, the existing task lighting was evaluated and added to the plug-load control and monitoring in the office area to study the energy and user satisfaction of existing task lights.

- Controls. Addressable lighting controls respond automatically based on building schedule, occupancy, and daylight conditions. Manual controls are available for individuals or small groups to balance lighting needs to suit their own preferences. For the pendant lighting design in the first phase of the office area, the indirect lighting component was configured in unison with the downlight component. The uplight/downlight components responded to localized occupancy of individual small areas by turning off when unoccupied. A similar approach was configured for the second phase, with the troffer lighting fixture design in the office area.

The heart of the Enlighted system is its smart digital sensor algorithms which collectively enable the greatest possible energy savings, without compromise to the lighted environment.

Other key elements of the system include the Enlighted Gateway and the Enlighted Energy Manager (EEM). The Enlighted Gateway aggregates wireless communications between the network of Enlighted Smart Sensors and the EEM appliance. The Gateway uses an IEEE 802.15.4 wireless network (with a secure proprietary mesh protocol using AES-128 Encryption) for communications with the smart sensors and a wired TCP/IP network for communications with the EEM.

The EEM's simplified lighting control management enables building managers to configure and adjust individual lighting profiles. It includes a reporting capability to track lamp and fixture outages, carbon reduction, energy usage, and financial savings. The EEM securely interfaced with pre-existing HVAC controllers and equipment. This integration enabled the rich set of smart sensor data to optimize HVAC system utilization.

The Enlighted system was coupled with replacement LED light fixtures containing integral sensors, providing a comprehensive solution. Lighting integration allows building operators to monitor power usage (savings) in a familiar environment which is already in use. Software-based maintenance (system configuration changes) ensure that continuous optimization is as easy as possible. Task tuning can be adjusted as work area purpose or business needs change or evolve over time.

Plug-load control. In office settings, plug-loads can account for as much as 20% of electricity consumption. These loads include computer monitors, task lighting, coffeemakers, vending machines, and other appliances. Plug-loads typically consume electricity even in standby mode or when switched off [E Source]. Controlling these loads based on occupancy data from advanced lighting sensors provides significant energy and cost savings with direct bottom line benefits.

HVAC optimization. This project's system used the AIRE interface from the Enlighted system for advanced HVAC optimization. AIRE allows the Enlighted sensors in light fixtures to be geo-located and mapped to the floor plan based on mechanical zones. Using occupancy data, mapping, and groups, advanced analytics are used to make optimization recommendations to the Honeywell's HVAC controllers via BACnet resulting in measurable energy savings.

This interface was used to improve control of variable air volume (VAV) terminal box (TB) controls in the HVAC system. The thermal zone served by a VAV-TB is regulated by a temperature set point value for thermal comfort, as well as a minimum air flow set point to comply with indoor air quality (IAQ) standards as laid out in the building code.

Both set points can be adjusted based on actual sensed (vs scheduled) occupancy. A zone (e.g. conference room) does not need to be heated/cooled to the occupied set point if there is no actual occupancy, which results in HVAC energy savings.

Figure 2 displays the flow of occupancy data that the smart sensors input to the VAV controller. The data is used to determine the active minimum air flow set point and the zone's temperature set point. The savings are realized by not having to condition as much outside air and by reducing the conditioning of air delivered to unoccupied spaces; less energy is required to provide the supply air to the VAV terminal boxes.

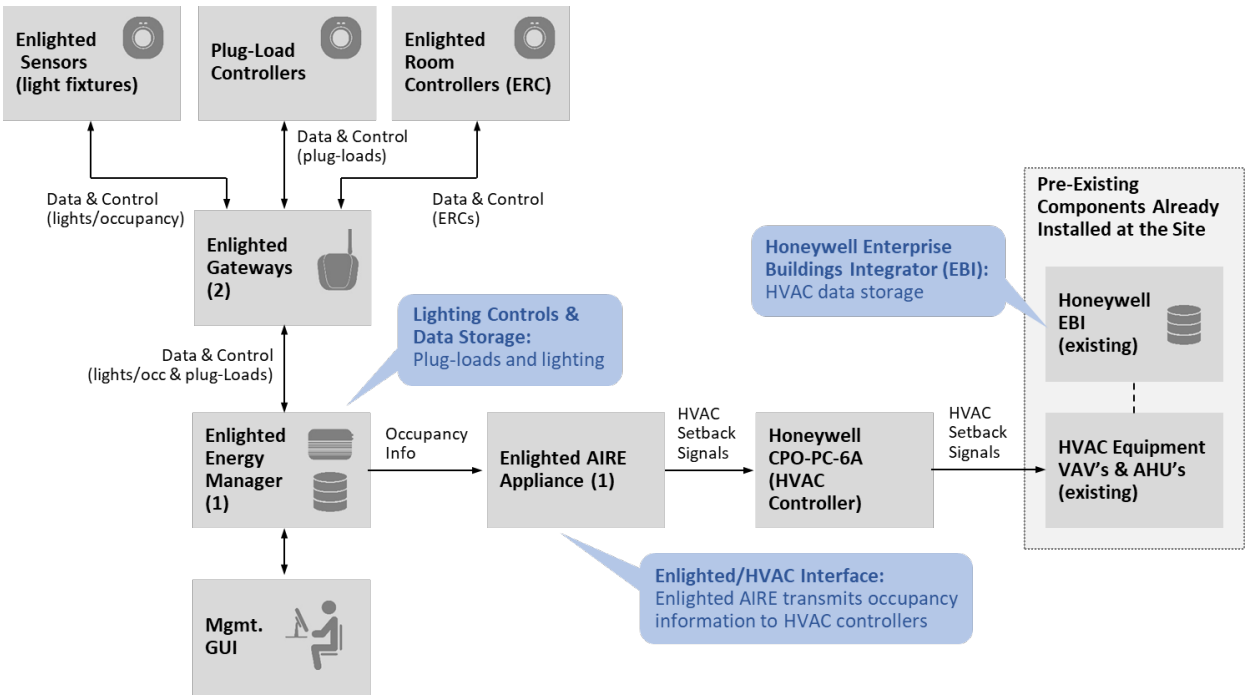


Figure 2. Logical Data Flow

2.2 TECHNOLOGY DEVELOPMENT

This project demonstrated commercially available off-the-shelf technologies, so technology development was limited to configuring the system, configuring the network, and configuring the HVAC controllers to handle the Enlighted messages which enable occupancy control for the HVAC system.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

As mentioned in the technology overview, our proposed technology provides many performance advantages, including improved energy efficiency, improved lighting quality, cost improvements from simplified system operation and management, lowered maintenance cost, and increased lifetime for the light fixtures. However, even with all the benefits and advantages, the system may encounter barriers to acceptance because of security concerns associated with a digital automated lighting control system.

This project demonstrated a data-driven approach to holistic lighting retrofits. The approach is broadly applicable to office spaces and high-bay environments across the DoD portfolio. Using a holistic and lifecycle cost approach, we have realized dramatically deeper energy and cost savings for the US taxpayer.

2.3.1 Lighting Benefits

Historically, lighting energy benefits have come from component retrofits such as lamp and ballast replacements within existing lighting fixture housings. Now that there has been a change in lighting technology with the widespread availability and adoption of LED lights and controls, additional savings and value can and should be realized. Component retrofits do not take advantage of the value of technology integration, application, and benefit to mission. Consider the following benefits of a highly efficient holistic approach to lighting improvements, and the value which accrues well beyond lighting:

- Integrated LED fixtures with proper electronics and light distribution significantly exceed the performance of tubular LED (TLED) lamp retrofits. Using TLED lamps inside of a legacy fixture misses the opportunity to improve fixture efficiency as much of the light remains trapped inside of the old fixture. Additionally, the tremendous variety of existing ballasts raises significant concern about safe combinations of TLED lamps [DOE-SSL-Fact-Sheet].

- The aesthetic impact of new fixtures compared to old-style parabolic troffers is also noteworthy and makes a dramatic improvement in the environment. Where possible, the use of direct/indirect fixtures to create a sense of overall brightness throughout a space has been shown to improve occupant satisfaction. Further, studies show a causal link between these improvements in lighting and business outcomes. Overall, an improvement in lighting influences satisfaction within workplace, which may reduce turnover. Savings from worker retention far exceed cost savings from energy [NRC-Canada].

- In situations where personal control is an option, the ability to control light levels has been shown to positively impact worker motivation and persistence and vigilance on difficult tasks [Light Right Consortium].

- Embedding sensing and controls within individual fixtures represents a leap forward across multiple categories. Dimming savings are multiple, ranging across granular dimming based on occupancy, daylight, task tuning, and scheduling.

- While the integration of integrated digital sensing into dated infrastructures is driven by and paid for by energy savings, the value does not end there. Smart sensors provide the opportunity to save money in real estate due to space planning, optimized space utilization, reduced maintenance, and reduced janitorial costs. Additional sensor applications include asset tracking and management, safety and risk reduction, and multiple other benefits that will empower buildings as a smart interface in support of non-real-estate missions.

2.3.2 HVAC Benefits

The sensors integrated within the lighting fixtures provide unprecedented granularity for sensing occupancy, light levels, lighting power, and indoor temperature. In addition to lighting level optimization for productivity and energy savings, the HVAC systems, the largest energy consumers in buildings, can be optimized based on occupancy and granular temperature sensing. In this project, we used the occupancy information to optimize VAV terminal box and air handler controls for dynamically changing occupancy to produce energy savings. Zhang, et al. [Zhang13] evaluated the savings potential from use of occupancy-based control (OBC) of terminal boxes for large office buildings with VAV HVAC systems using both common and advanced occupancy sensors. The study showed that energy savings vary considerably across climate zones. Lighting using common occupancy sensors to turn off lights when no occupants are present provides relatively small savings of 1.1% across all climate zones. Adding OBC to lighting and terminal boxes results in greater savings, up to 8%. Use of advanced occupancy sensors for both lighting and terminal box control saw the largest savings, ranging from 5% to 23%. (Note: this study did not use changes to lighting or fixtures, only added occupancy-based control.) The study concluded that at a national scale, the construction-volume-weighted average energy savings are 7.8% for OBC with advanced occupancy sensors and 5.9% for common occupancy sensors. The site-specific savings are higher and different from the nationally averaged numbers.

3.0 PERFORMANCE OBJECTIVES

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

Table 1 describes the quantitative performance objectives (POs) for this project, while Table 2 expands on the data requirements.

Table 1. Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
PO1: Lighting Energy Usage	Energy used in building (kWh)	See Table 2: Lighting/Lights	80% reduction compared to baseline	69% - high-bay 71% - office pendants 67% - office troffers
PO2: HVAC Related Energy Usage	Energy used in building (MMBtu)	See Table 2: HVAC and Weather	20% reduction compared to baseline	30% - high-bay 12% - office area 26% - combined
PO3: Instrumented Plug-Load Usage	Energy used by circuit (kWh)	See Table 2: Plug-loads	20% reduction compared to baseline	4% - from all measured outlets 38% - from controlled outlets only
PO4: Lighting Quality	Responses to Light Right Survey	See Table 2: Lighting Quality	25% Increase	37% - high-bay (-44%) - office pendants 5% - office troffers

Table 2. Data Collection & Storage Requirements.

System	Component	Data Point	Stored in	Need Historized
HVAC	Air handling units: AHU 101 and AHU 202)	Supply air: dry bulb temperature and enthalpy	EBI	Historized
		Mixed air: dry bulb temperature and enthalpy	EBI	Historized
		Supply air fan power	EBI	Historized
		Return air fan power	EBI	Historized
		Total AHU air flow	EBI	Historized
		Heating load, measured by hot water coil BTU meter	EBI	Historized
		Cooling load, measured by chilled water coil BTU meter	EBI	Historized
	Variable air volume boxes (VAVs) attached to AHUs 101 and 202	VAV air flow	EBI	Historized
		VAV reheat on/off status	EBI	Historized
		VAV discharge air dry bulb temperature	EBI	Historized

Table 2. Data Collection & Storage Requirements. (Continued)

System	Component	Data Point	Stored in	Need Historized
Lighting	Lights	Energy consumption by light fixtures - measured by meter in electric panel	Dent Energy Meters	Historized
		Energy consumption by light fixtures - measured by Enlighted	Enlighted EM	Historized
	Occupancy	Raw granular occupancy info per fixture	Enlighted EM	Historized
		Occupancy setback control signal (BACnet from AIRE to VAVs)	EBI	Historized
Plug-Loads	Plug-loads	Energy consumption from circuits - measured by Enlighted	Enlighted EM	Historized
Weather	Outdoor temperature	Outdoor temperature for Tinker / OKC	[NOAA-CDO]	Historized
Lighting Quality	Surveys	Qualitative questionnaire/surveys filled out by users (before & after)	-	-
	Lighting levels	Measured in footcandles for light level, glare, room surface contrast (before & after)	-	-

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

3.2.1 PO1: Lighting Energy Usage

- Definition: Energy consumption from lighting in office buildings and high-bay areas.
- Purpose: Reduction of lighting energy usage is the main performance objective. The demonstration solution is compared with the previously installed equipment.
- Metric: The performance metric for lighting energy usage is kilowatt-hours (kWh). The reduction in energy consumption of our solution relative to the previously-installed lighting system is also reported as a percentage.
- Data: Lighting energy consumption data was collected through two separate systems: A) Dent energy meter data loggers (primary) and B) the Enlighted system (alternate). Both systems measured and stored lighting energy consumption data (kWh) separately as a historized time series. The main data collection difference is that the Dent energy meter data loggers were installed before the Enlighted system to collect energy usage data from the baseline period. In contrast, the Enlighted system measured only energy usage data after the baseline period, after the new lighting fixtures were installed.

  Dent energy meters, specified in Appendix B.9, were installed before our system's installation to measure the energy usage from the previous lighting fixtures for a 12-month period as a baseline for the analytic comparison. Data was measured and stored continuously from the start of the baseline period through the end of the demonstration period. Data from the energy meters was retrieved periodically throughout the demonstration.

Energy usage data from the Enlighted system is measured in kWh by the Enlighted sensors at each light fixture and was continuously sampled at five-minute intervals. The sensors at each light fixture were connected to the Enlighted Energy Manager, which stores the data. The data was retrieved/downloaded from the Energy Manager through a physical connection in a manual process with a laptop connected to the Enlighted private network. Data was retrieved monthly throughout the demonstration. Data from the Enlighted Energy Manager consists of both five-minute interval data as well as hourly data.

- Analytic Methodology: We compared the energy consumption of the Enlighted lighting system against the previous lighting system. Energy savings realized by the Enlighted system (compared to the previous lights) are reported separately for the high-bay test area, the office test area, and the entire test area (office + high-bay). Energy savings are also reported as total savings (energy saved over the entire duration of the demonstration period) and as monthly savings for each month of the demonstration period. Total energy savings are reported both in kWh and as a percentage reduction relative to the baseline energy consumption.

  To determine the energy consumption of the Enlighted system, we measured energy (in kWh) usage for all lighting circuits in the test areas using Dent data loggers. Lighting energy consumption is summed into monthly totals. As a consistency check, we compared energy consumption data from the Dent loggers with lighting energy consumption recorded and aggregated by the Enlighted system.

  To determine the baseline energy consumption of the previous lighting system, we used Dent data loggers to measure the energy consumption of lighting circuits in the test areas during a baseline period of 12 months before the Enlighted system was installed. We are separately computing the total lighting energy consumption in the high-bay test area, the office test area, and the total area (office + high-bay). From this baseline data, we computed the mean daily energy consumption of the lights in the office test area, the high-bay test area, and the combined test area. The mean daily energy consumption values determined during the baseline period were used to compute baseline energy consumption for each month in the demonstration period (which began after the Enlighted system was installed) using the formula

  Monthly energy (baseline) = (mean daily energy) * (number of days in the month)

  Note: As previously discussed in Sections 1.1 and 2.1, and further discussed in Section 5.1, there were two lighting designs in the office area using different light fixtures. Each lighting design was evaluated for a period of five months. Since the different fixtures consume different amounts of energy, we performed the above lighting energy analysis separately for both lighting designs. We are also separately reporting the energy savings of each lighting design relative to the baseline energy consumption.

- Success Criteria: 80% reduction in energy consumption of our solution against the baseline energy consumption of the existing system.

- Results: The Enlighted lighting system achieved an energy savings of 69% of baseline usage in the high-bay area over the high-bay demonstration period. In the office area, the pendant fixtures achieved an energy savings of 71% of baseline usage over the pendant demo period. The troffer fixtures achieved an energy savings of 67% relative to baseline usage over the troffer demo period. These did not meet the 80% reduction goal.

The main reason that troffer fixtures achieved a lower energy savings than pendants was that occupancy sensors were overly-sensitive during the troffer period; hence, occupancy-based savings were lower for troffers than pendants. See Section 6.1 for further discussion.

3.2.2 PO2: HVAC Energy Usage

- Definition: Measured energy consumption from the HVAC system in the selected areas.
- Purpose: Compare the HVAC energy consumption of the demonstration solution in the selected areas against previously-installed systems.
- Metric: The metric is the energy consumption of the HVAC system used to cool and heat the selected areas. HVAC energy consumption is reported by source, with electrical energy reported in kWh, and natural gas energy reported in thousands of British thermal units (kBTU) and millions of British thermal units (MMBtu). The reduction in energy consumption of our solution relative to the baseline is also reported as a percentage.
- Data: The following data was collected (also, see Table 2): dry bulb temperatures of supply and mixed air at air handling units (AHUs), enthalpy of supply and mixed air at AHUs, discharge air temperature and air flow through all VAVs downstream from each AHU that supplies air to demo areas, total air flow through each AHU, and electric energy consumption of return and supply air fans in each AHU that supplies air to a selected area. British thermal unit (BTU) meters on AHU hot water and chilled water coils measured heating and cooling loads.

  Outdoor local weather data (outdoor temperature) was also collected throughout the demonstration, sampled and time-stamped both hourly and daily, for analysis of the impact to HVAC energy usage. Outdoor weather data was obtained from the NOAA Climate Data Online system [NOAA-CDO], which is an online archive that contains historical national weather data.
- Analytical Methodology: We separately determined the HVAC energy consumption of the selected areas from three sources: heating, cooling, and fans. We used the measured quantities available from the HVAC data (described in Table 2) to calculate energy consumption. Contributions from heating, cooling, and fans were added to determine the total HVAC energy consumption. (For in-depth details of the analysis, see Section 6.2.)

  Energy used by return and supply fans in AHUs were measured by electricity meters and stored in EBI. Since the AHUs supplied air to additional spaces outside of the demo areas, we computed the energy attributed to each demo area using VAV air flows with the formula:

  Fan energy = (area air flow)/(AHU air flow) * (total measured fan energy),

  where '(area air flow)/(AHU air flow)' is the fraction of the AHU's total air flow that was delivered to the demo area and 'total measured fan energy' was measured by the electric meter attached to the AHU fan.

  Energy used for cooling air supplied to demo areas was computed with the formula:

Chilled water energy = (area air flow)/(AHU air flow)*(cooling load)/(chiller efficiency),

where 'cooling load' was measured by BTU meters on chilled water coils at air handlers, and 'chiller efficiency' is the rated efficiency of the building's chillers. As a consistency check, we validated the chilled water energy measurements by separately computing cooling power load with the following physics formula:

$$\text{power (cooling)} = (\text{instantaneous area air flow})*(h_{mixed} - h_{sup})/(\text{chiller efficiency}),$$

where h_{sup} and h_{mixed} are the enthalpies of supply and mixed air, and 'chiller efficiency' is the estimated efficiency of the chiller system (also known as the coefficient of performance). Cooling power was integrated over time to compute cooling energy.

(Note that BTU meters were installed on AHU hot water coils, but they did not measure any heating load at AHU 101 or AHU 202, so we omit their analysis methodology.)

The VAV boxes serving the demo areas were powered by hot water from the boilers, so the energy consumption of VAV reheat elements was computed via physics formula. First:

$$\text{Reheat power} = (\text{VAV air flow})*c_p*(T_{dis} - T_{sup})/(\text{boiler efficiency}),$$

where 'VAV air flow' is air flow through the VAV box, cp is the specific heat of air, Tsup is supply air temperature from the AHU, and Tdis is the VAV discharge air temperature (measured after the reheat coils). Power was integrated over time to determine energy consumption of each VAV reheat, and energy was summed across all VAV reheats for a total.

We used total measured energy consumption of the demo areas to quantify HVAC energy savings of our occupancy-controlled solution against the baseline (without occupancy control). To control for seasonal variations in heating and cooling loads, dynamic HVAC control was enabled and disabled for alternating periods of time: dynamic HVAC control was enabled for two subsequent days, then disabled for the third day. This on/off sequence repeated throughout the data collection phase allowed comparison of HVAC energy usage with and without dynamic HVAC control throughout different heating and cooling seasons. This process was crucial to the removal of transient effects, like equipment breakdown. We interpolated between baseline measurements (which occurred every 3 days, repeating) to create baseline values for comparison to occupancy-controlled measurements (which occurred 2 out of 3 days, repeating). Energy savings were computed (per day) as the difference between the interpolated baseline energy consumption and the measured energy consumption on days with occupancy control enabled. From daily quantities, we computed the mean daily energy saving and consumption value, and then extrapolated those to a yearly total by multiplying by 365.25 days per year.

- Success Criteria: 20% reduction in energy consumption.
- Results: The mean daily total HVAC energy consumption of the high-bay area during baseline days (with no occupancy control) was 1,114 kWh / day. The projected yearly baseline consumption was 406,800 kWh. (This includes energy consumption from heating, cooling, and fans; individual components were converted to common units [kWh] and added to form a total.) The mean daily total HVAC energy savings in the high-bay area was 335 kWh / day, and the projected yearly total HVAC energy savings in

the high-bay was 122,300 kWh. Hence**, total HVAC energy savings in the high-bay area was 30% of the baseline** consumption. This **greatly exceeded the performance objective of 20% savings**.

The mean daily total HVAC energy consumption of the office area during baseline days (with no occupancy control) was 312.4 kWh / day. The projected yearly baseline consumption was 114,100 kWh. (This includes energy consumption from heating, cooling, and fans; individual components were converted to common units [kWh] and added to form a total.) The mean daily total HVAC energy savings in the office area was 39 kWh / day, and the projected yearly total HVAC energy savings in the office area was 14,230 kWh. Hence, total HVAC energy savings in the office area was **12% of the baseline consumption**. **This did not meet the performance objective of 20% savings**. We hypothesize the missed performance objective in the office area was caused by overly sensitive occupancy sensors in the office area. The sensitivity of occupancy sensors was increased during the second Phase of the demonstration (on May 1, 2019), after office occupants complained that lights were going off when people were present. After the adjustment, sensors detected intermittent occupancy in the office area all the time, including overnight when the space was not occupied. This reduced energy savings of the lighting system. Additionally, it also reduced energy savings in the HVAC system, since setbacks were not applied when occupancy was inaccurately detected. Hence, overactive occupancy sensors conceivably prevented the HVAC systems from reaching its full potential in the office area.

If we calculate the combined the energy consumption and savings of the office and high-bay areas, we find that the **combined energy savings was 26% of the baseline**. So overall, the entire demo (high-bay + office) did meet the 20% savings objective.

3.2.3 PO3: Plug-Load Usage

- Definition: Measurement of electrical energy consumption from plug-loads.
- Purpose: The plug-load system reduced energy consumption from standard, non-critical, electric office appliances that plug in to wall outlets. The energy reduction was achieved through automatic occupancy sensors that disable power after hours when the areas are not occupied.
- Metric: The performance metric for plug-load energy usage is kWh. The reduction in energy consumption attributed to our solution (with occupancy-controlled plug-loads) relative to the previous energy consumption (without occupancy-controlled plug-loads) is also reported as a percentage.
- Data: Plug-load energy consumption data was collected by the Enlighted system, measured in kWh, and stored in the Enlighted Energy Manager as a time series. Each plug-load controller connected to uncontrolled outlets, whose power is uninterrupted, and to controlled outlets, whose power can be disabled when the test area is unoccupied. The Enlighted system collected energy consumption data from both controlled and uncontrolled outlets connected to each plug-load controller. The data was retrieved/downloaded from the Energy Manager through a physical connection in a manual process through a laptop that connected to the Enlighted private network. Data was retrieved regularly throughout the demo period.

- Analytic Methodology: We compare the energy consumption of plug-loads before and after the activation of occupancy-based plug-load control. Because energy savings accrued through the controlled plugs (only), we separately analyzed controlled and uncontrolled plugs.

  To determine a baseline for energy consumption, the Enlighted system collected plug-load energy data for a baseline period of almost three months. For this baseline period, plug-load controllers were configured to maintain power to all outlets, regardless of sensed occupancy. Using the plug-load energy data from the baseline period, we compute the mean daily baseline energy consumption of controlled plugs. The mean daily baseline energy consumption was used to compute the baseline energy consumption of controlled plugs for each month in the demonstration period (when occupancy-based plug-load control is enabled) using the formula:

  monthly energy (baseline, controlled) = (mean daily energy, controlled) * (number of days in the month)

  After the baseline period, plug-load controllers were reconfigured to disable power to their controlled outlets after business hours when the areas are not occupied, achieving energy savings relative to the baseline. We measured the total energy consumption of all plug-loads by summing the total energy consumption of each plug-load controller (which is connected to controlled and uncontrolled outlets) in kWh. A baseline for total energy consumption was determined by adding the baseline consumption of controlled plug-loads to the measured consumption of uncontrolled plugs. Energy consumption was aggregated into monthly totals and compared to the total baseline.

  Energy savings realized by the occupancy-controlled plug-load system is reported as total savings (energy saved over the entire duration of the demonstration period) relative to the baseline and as monthly savings, reported for each month of the demonstration period. Total energy savings are reported both in kWh and as a percentage reduction relative to the total baseline energy consumption.

- Success Criteria: 20% reduction in energy consumption.
- Results: The computed total plug-load energy savings over the demo period was 12.27 kWh. The baseline for total plug-load energy consumption over the demo period was 330.86 kWh. Hence, the plug-load energy savings was **4%** of the total baseline usage (which included critical loads from uncontrolled outlets). This did not meet the plug-load performance objective goal of 20% energy reduction relative to baseline.

  The failure to meet the performance objective can be explained by the behavior of the occupants in the office space, who predominantly connected electrical appliances to uncontrolled plugs, which were intended for critical loads. For instance, energy consumption from controlled plugs during the baseline period (15 kWh) was only 17% of the total consumption (87 kWh). During the demo period, the energy consumption of controlled plugs (20 kWh) was only 6.27% of the total plug energy consumption (319 kWh). We also note that during the demo period, the energy consumption of uncontrolled (critical load) plugs (298.61 kWh) was 90.3% of the baseline total consumption (330.86 kWh).

Hence, even if (hypothetically) controlled plugs had used no energy during the demo period, they would have achieved a savings of at most 9.7% of the baseline, and the savings target of 20% reduction would not have been reached.

If we compare the energy savings achieved by controlled plugs in the demo period (12 kWh) to the baseline energy consumption of controlled plugs only (32 kWh), the savings is **38%** of controlled plug baseline. Thus, occupancy-controlled plugs achieved substantial energy savings relative to their baseline consumption (with occupancy control disabled). Hence, we conclude that the primary limiting factor in realized energy savings was the behavior of office occupants, who preferentially used uncontrolled plugs for their appliances.

3.2.4 PO4: Lighting Quality

- Definition: Lighting Quality from lighting level measurements and occupant surveys.
- Purpose: Compare perceived lighting quality and lighting metrics before and after retrofit of the lighting and control system.
- Metric: The Light Right Survey, published by the Pacific Northwest National Laboratory [PNNL], was used to measure occupants' perceptions of lighting quality in both the office and industrial spaces. Responses to the Light Right Survey before and after retrofit are compared and correlated to lighting measurements. The lighting measurements were taken with daylight only (where applicable) and with both daylight and electric light. Measurements are compared to lighting recommendations and criteria from the Illuminating Engineering Society (IES) Recommended Practice for Office Lighting [IES-RP-1-12], Lighting for Industrial Facilities [IES-RP-7-17], and the Department of Defense Unified Facilities Criteria [UFC]. Lighting measurements include:
  - Light level sufficiency per IES illuminance recommendations
    - Average horizontal illuminance at task-plane (footcandles)
    - Horizontal uniformity at task-plane (max/min footcandles)
  - Glare
    - Vertical illuminance at eye level (footcandles)
    - Max luminaire luminance (candela per square meter)
    - Max window luminance (candela per square meter)
  - Room surface contrast
    - Average ceiling luminance (candela per square meter)
    - Ceiling luminance uniformity (max/min candela per square meter)
    - Average wall luminance (candela per square meter)
    - Average wall uniformity (max/min candela per square meter)
- Data: Data for the perception of lighting quality was collected from the Light Right Survey before and after the retrofit. Illuminance data was measured with a recently-calibrated Konica Minolta CL-500A Illuminance Spectrophotometer. Luminance data was measured using a recently-calibrated Konica Minolta LS-110 Luminance Meter.

- Lighting quality measurements were collected based on the grid specified in Figure 3 and Figure 4 for both the high-bay and the office areas.

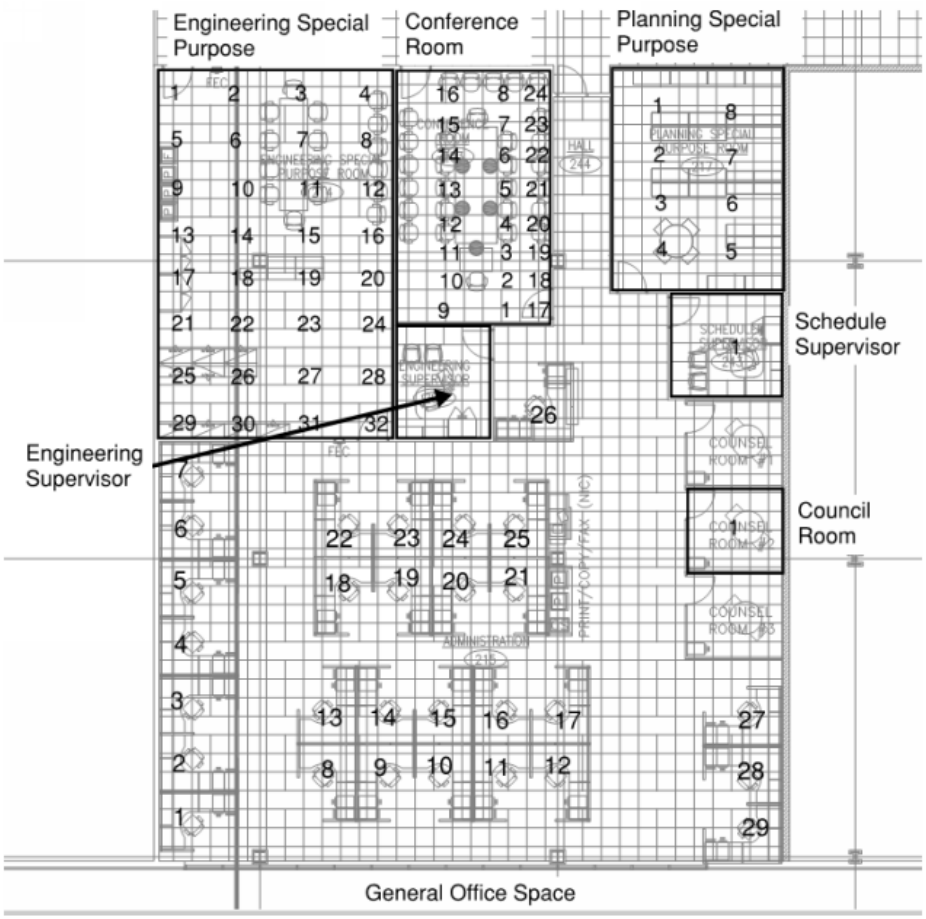


Figure 3. Lighting Quality Measurements Sampling Grid (office area).

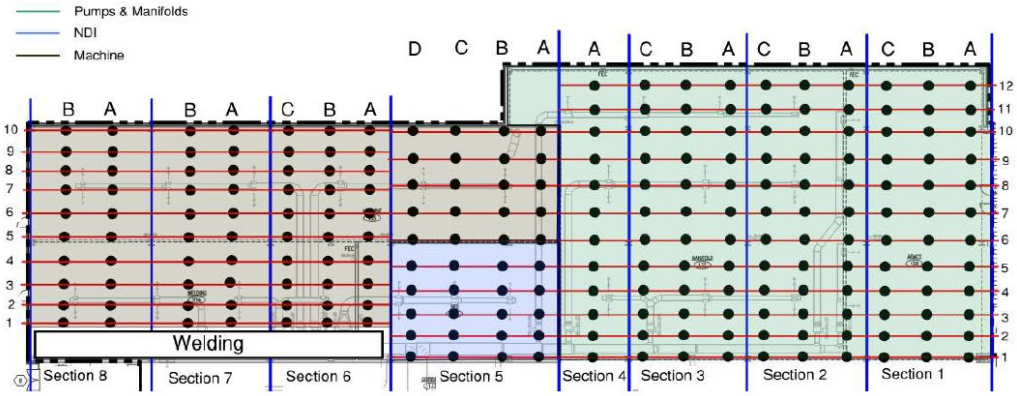


Figure 4. Lighting Quality Measurements Sampling Grid (high-bay area).

- Analytic Methodology: The Light Right Surveys were administered by Air Force staff via online surveys in the administrative area, and paper surveys were given to those working in the industrial area. The office area had three (3) survey periods: one period during the baseline lighting system, one period during the holistic direct/indirect LED (pendant) lighting system with controls, and one period during the LED retrofit kit (troffer) lighting system with controls. Lighting measurements were recorded under these three (3) lighting systems and compared to IES and UFC lighting criteria and correlated with the survey data to understand the interaction of lighting quality perception and lighting metrics.

- Success Criteria: 25% improvement in building occupants' responses to surveys.

- Results: High-bay Area: Occupants thought that the new LED lights provided sufficient, or in some cases, too much light for all administrative tasks in the space, such as paper tasks, filing, and working on a computer. Overall, occupants responded very positively to the increased light levels and distribution for performing industrial tasks, such as welding, machining, and assembly. The number of occupants experiencing glare or discomfort did not change with the new lights, but instead, the number of occupants reporting flickering from the lights showed a decrease. Further, occupants stated that the new lighting illuminates their work surfaces and the room surfaces evenly, and the new LED lights in the area are attractive. Overall, the occupants are delighted with the new LED lights are prefer them over the original baseline lighting system. Overall survey results in the industrial area showed a **37%** improvement from the original lighting, meeting the success criteria.

  Office Area: Occupant surveys results in a preference for the Phase 2 troffer lighting. For the most part, occupants found the Phase 1 pendant style lighting to appear dimmer than the Original baseline lighting and the Phase 2 lighting. Occupants did not like the layout of the Phase 1 lighting and would have liked to see it better coordinated with the furniture layout. Occupants agree that the Phase 2 lighting did a better job at evenly lighting their work surfaces, as well as the room surfaces, and presented a good image for the organization. The Phase 1 pendant lights resulted in a **44% decrease** of occupant satisfaction (compared to baseline lighting) based on the surveys, while the Phase 2 troffer lights resulted in a **5% increase** relative to baseline lighting. For additional discussion see Section 8.1.1.2 and Section 8.2.

4.0 FACILITY/SITE DESCRIPTION

The demonstration site was Tinker Air Force Base in Oklahoma City, Oklahoma, building 3907.

4.1 DEMONSTRATION FACILITY/SITE LOCATION AND OPERATIONS

The demonstration performance site was Tinker Air Force Base in Oklahoma City. Honeywell Energy Services Group (Honeywell ESG), who was under contract for an ESPC project at Tinker AFB as a part of their Task Order 3 (TO3), Lighting Energy Conservation Measures program, helped identify and secure the specific areas for the demonstration. This group also assisted in coordination with on-site Air Force staff for our ESTCP project.

The specific demonstration spaces within Tinker AFB were selected and approved. Building 3907 was the site for both the office area and the high-bay area spaces required for the demonstration. Building 3907 is located close to 9101 SE 49th St, Oklahoma City, OK 73150. Building 3907 is a newer two-story, 140,000 square feet, brick and stucco/dryvit building with a pitched gable metal roof. It is occupied by the Oklahoma City Air Logistics Complex (OC-ALC). OC-ALC's energy manager, Joseph Cecrle, was the site sponsor for our ESTCP demonstration project.

4.1.1 Office Area

The office space area is an administrative area of approximately 5,000 square feet located on the second floor. The office area consists of an open office area with cubicles, two conference rooms, plus a few private offices. (Rooms: 244, 215, 203, 214, 208, 217, 243). The office area has a south-facing bank of windows, which facilitated our demonstration of daylight harvesting.

Figure 5 shows the demonstration area including office area spaces:

- Conference rooms (Rooms: 203, 214)
- Private offices (Rooms: 208, 217, 243)
- Cubicle area (Rooms: 215, 244)

Figure 5. Building 3907, Second Floor, Office Area

Figure 6 shows a section of the office area with the baseline fluorescent lighting fixtures prior to installation of our advanced lighting system.

Figure 6. Office Area Baseline: Fluorescent Lighting Fixtures

Figure 7 shows the same section of the office area with the advanced LED pendant lighting fixtures from Phase 1.

Figure 7. Office area Phase 1: New LED Pendant Lighting Fixture Design.

Figure 8 shows the same section of the office area after installing the Phase 2 troffer retrofit kit LED lighting fixture design.

Figure 8. Office area Phase 2: New Troffer Retrofit Kit LED Lighting Fixture Design.

4.1.2 High-Bay Area

The high-bay areas located on the first-floor include three adjacent sections with an area of approximately 21,000 square feet. These rooms house a mechanical shop, a production area, plus the first-floor hallway/corridor.

Figure 9 is a plan of the first floor including these high-bay areas:

- Pumps & manifold area (Rooms: 137, 138)
- NDI/machine/welding area (Rooms: 134, 135, 136), excluding fluorescent welding task-lights.
- Hallway/corridor (Rooms: 109, 119, 133)

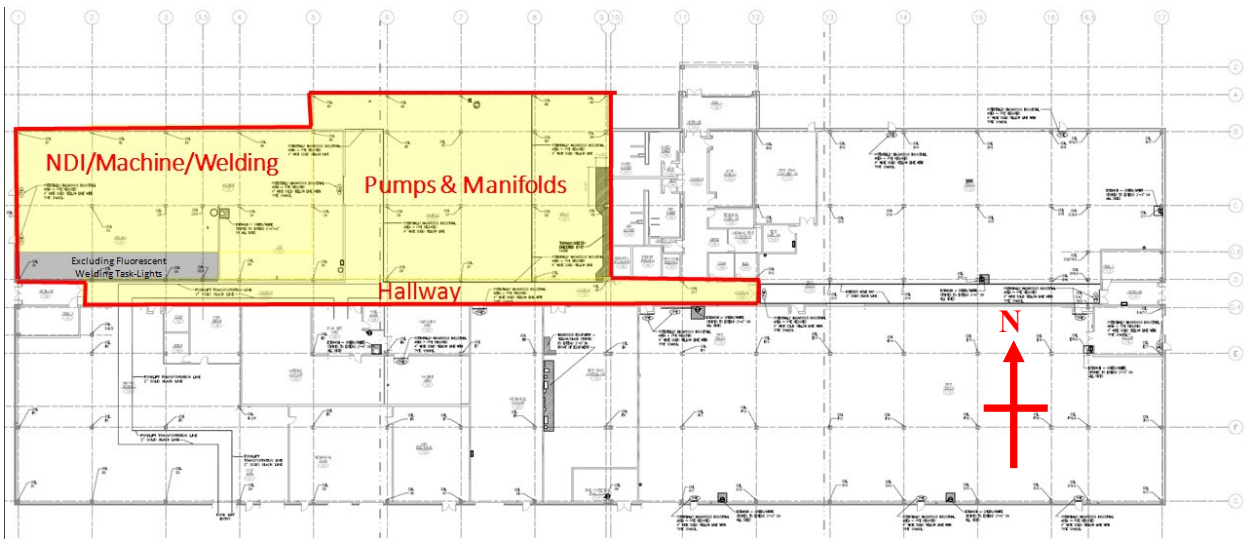


Figure 9. Building 3907, First Floor, High-Bay Areas

Figure 10 show sections of the high-bay area with the baseline high intensity discharge (HID) lighting fixtures, while Figure 11 show the same sections after the installation with the new LED high-bay lighting fixtures.

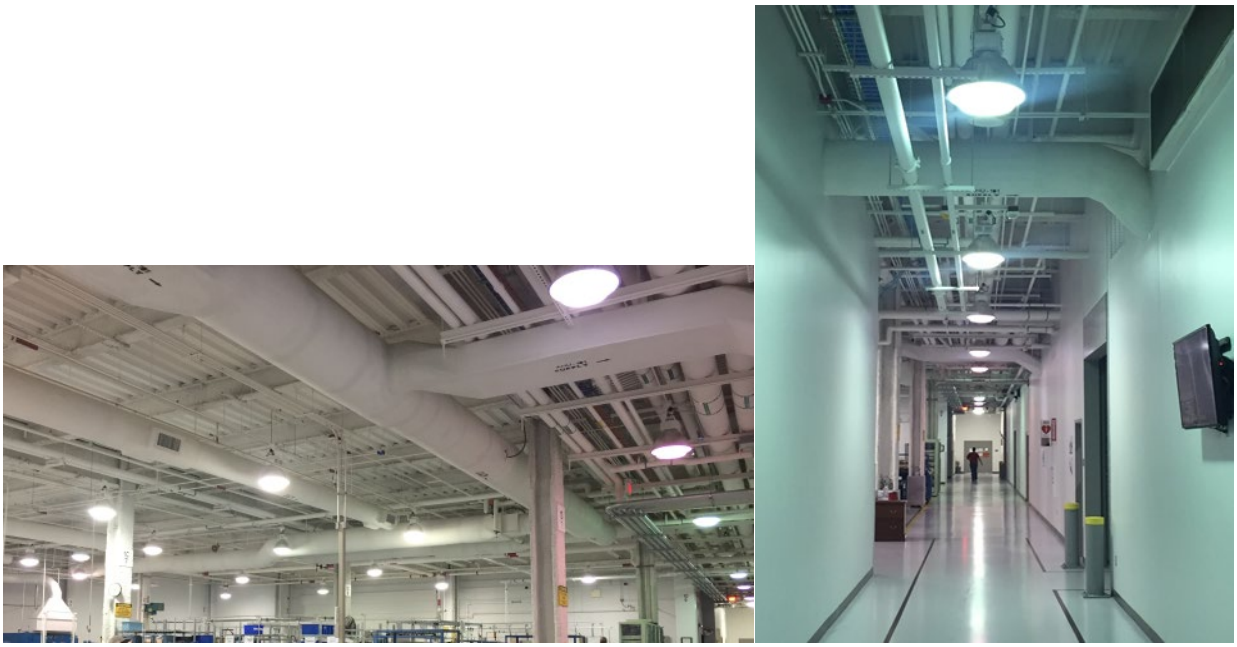


Figure 10. High-bay Area: Baseline Lighting Fixtures.

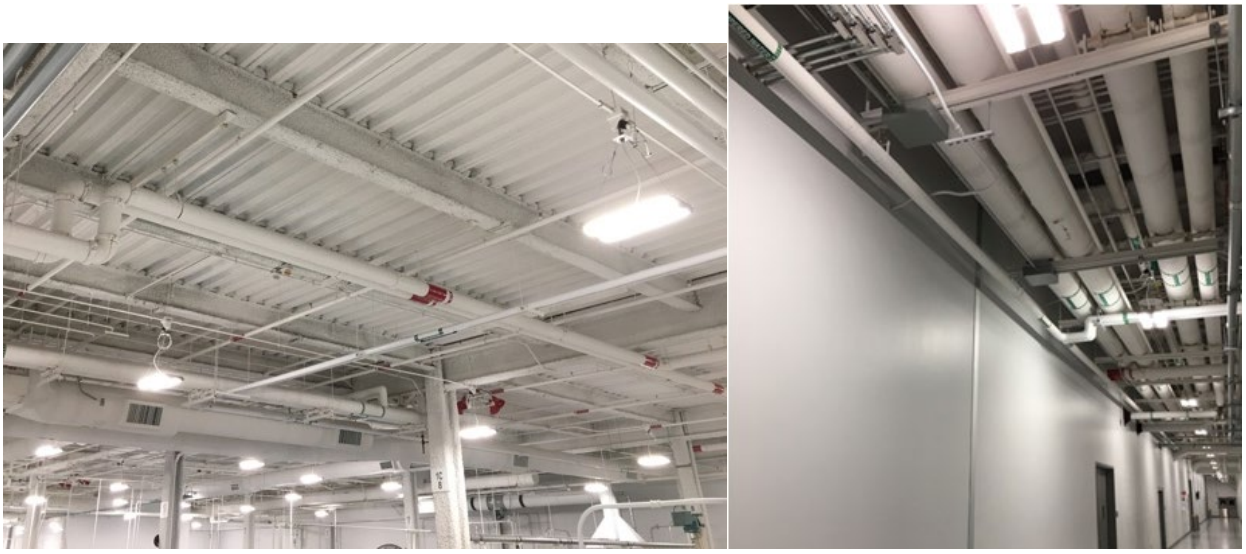


Figure 11. High-bay Area: New advanced LED Lighting Fixtures.

4.1.3 Demonstration System Controls

The control devices were installed in a new locked enclosure in room 242 of building 3907. Room 242 is a locked mechanical room that houses two air handler units, including one of the air handlers for our demonstration area, AHU 202.

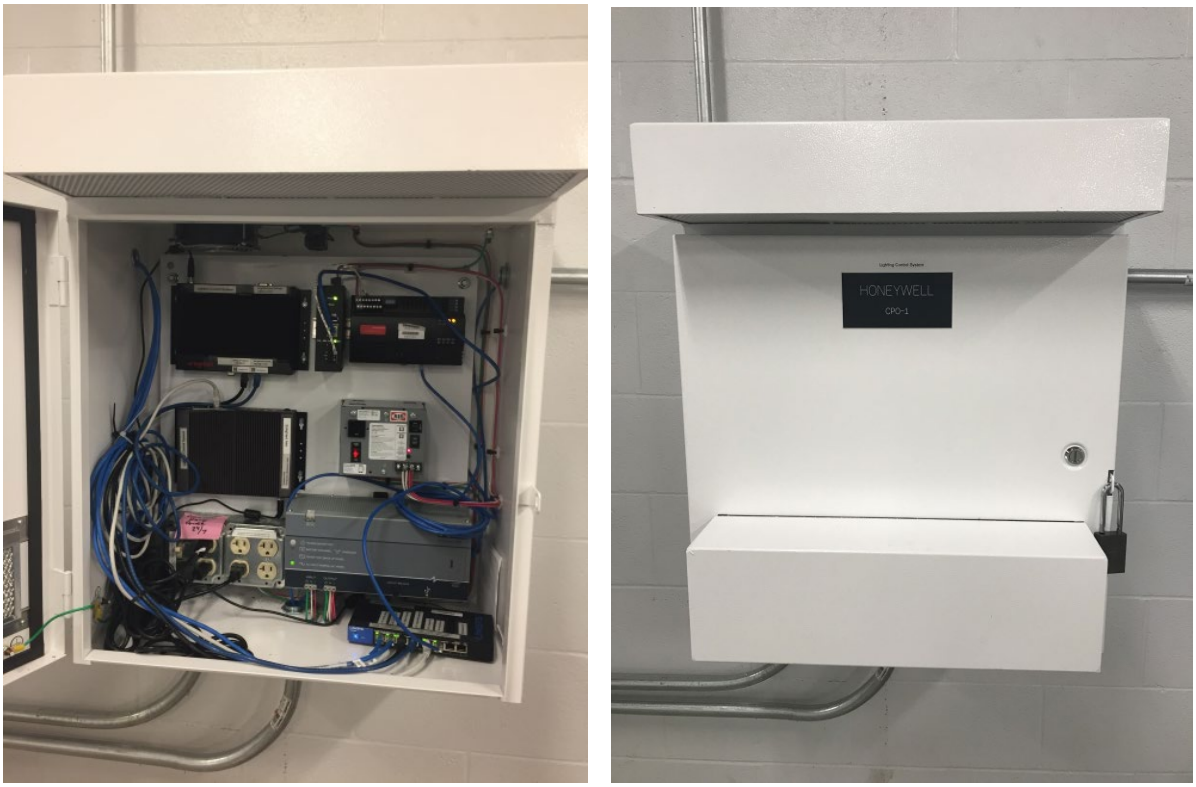


Figure 12. Demonstration System Controls Installed.

4.1.4 Demonstration Schedule

Building 3907 was under a plan to retrofit and upgrade the existing HVAC controls as part of Honeywell ESG's TO3 just prior to the start of our demonstration period. TO3 replaced the existing Lonworks-based Distech controllers that were not integrated into Tinker's overall Honeywell Enterprise Buildings Integrator (EBI) Control System, with new Honeywell ComfortPoint Open (CPO) controllers which were integrated into the EBI system. The TO3 upgrade of the HVAC controls was planned to start in November 2017 and to be completed in January 2018. However, installation of the TO3 HVAC control system did not complete until December 2018, delaying our demonstration project. Since this project depended on integrating with existing EBI-connected HVAC equipment, the commissioning date and demonstration start date for this project was delayed by about one year, from the December 2017 baseline assumption, to December 2018. The advantage of waiting for TO3 to upgrade the facility's HVAC controls was that this ESTCP project avoided the additional expense of the effort set out in Task 7, "VAV and Controls," noted as "Line item 0006/Option 3" in the contract, and we were able to extend the baseline data collection period for lighting energy from the original 4-weeks plan to 1 year.

As part of the Lighting Energy Savings and Lighting Quality Performance Objectives, the lighting design solutions for the office space area consisted of two different lighting designs (different lighting fixtures). The demonstration evaluated the performance, in both energy savings and quality, between the baseline existing lighting system and each of the two new lighting designs. However, since our selected office space area had no separation in the open cubicle area to simultaneously accommodate two different lighting designs, the 10-month lighting demonstration period was split in time, with two consecutive five-month demonstration periods for each of the new lighting designs, with a one-week installation/switch-out period in between the two demonstration periods. These two periods are referred to as Phase 1 for the pendant lighting fixture design, and Phase 2 for the troffer retrofit kit lighting fixture design.

4.2 FACILITY/SITE CONDITIONS

Our system had the advantage that it was readily available and generally compatible to be installed in almost any commercial building, either as a new green-field construction or as a system upgrade for renovation. To achieve the greatest benefits from energy consumption reductions, the following selection criteria was applied:

4.2.1 Geographic Criteria

As cited above, [Zhang13] demonstrates a wide range in potential energy savings from advanced occupancy-based controls based on the climate region. Colder climates have higher potential for energy savings. The potential for savings in annual energy cost reductions are also affected by the unit cost of energy. The chosen demonstration site at Tinker Air Force Base in Oklahoma City, Oklahoma, is approximately mid-latitude in the continental U.S., and it experiences both heating and cooling seasons. This situation is ideal, as it allowed a separate assessment of potential energy savings in heating and cooling in a variety of outdoor weather conditions. Hence, the results of this study are broadly applicable to many other Department of Defense facilities.

4.2.2 Facility Criteria

Our system can be installed in almost any commercial building. However, for this demonstration, we sought a facility which offered two types of spaces: 1) an office area of approximately 5,000 square feet and 2) a high-bay area. Potential facilities meeting those requirements were evaluated based upon separate general facility and office area criteria.

- General facility criteria:
  - HVAC equipment controllers must allow for a BACnet interface to support occupancy-based HVAC integration.
  - HVAC system must utilize AHU and VAV Terminal Box controls for integration with occupancy-based control.
  - Outdoor facing windows that provide daylight to demonstrate daylight harvesting.
  - Light-colored ceilings, walls, and desks to allow distribution of light in open areas.
  - Standard light fixture mounts, to ensure easier retrofit kit compatibility for easier installation.

- Office Area Criteria:
  - Open office/cubicle areas ideally having cubicle walls lower than 5 feet to allow distribution of light in the open areas.
  - Ceiling height of at least 9 feet. Lower ceilings restrict light distribution and prevent use of pendant-mounted light fixtures.
  - Tile ceiling with clean tiles provides easier installation.

4.2.3 Facility Representativeness

The areas selected for this demonstration are representative of typical DoD facilities. Although every building is unique, our system is generally compatible with any facility; however, the impact of energy consumption reductions depends on both the geographic region and the pre-existing condition of the facility and equipment in the building.

4.2.4 Other Selection Criteria

The building selection process for this project was coordinated with the energy manager on site, as there was a separate larger effort (part of an ESPC project) to renovate lighting in most buildings at the site. Selection criteria also included a building which had not yet been recently renovated.

Other criteria considered for the selection of the areas for this project was the co-location of both office and high-bay areas within the same building.

5.0 TEST DESIGN

- Fundamental Problem: The fundamental problem this demonstration sought to address was whether the data from a densely spaced smart sensor network could be integrated and used to effectively control lighting systems, HVAC systems, and non-critical plug-loads to reduce facility energy consumption without negatively affecting occupant comfort or work space satisfaction. As a result, the smart sensors were installed on each light fixture in the demonstration areas and have the capability to detect motion, space temperature, and light levels.
- Demonstration Questions: To address the problem, this demonstration sought to answer the following questions:
  - Will the use of dense smart sensor data, combined with modern lighting technologies result in lighting energy reductions of up to 80% as compared to baseline energy usage?
  - Will the use of dense smart sensor data result in up to 20% reductions in HVAC energy by setting back zone temperature setpoints in areas which are determined to be unoccupied?
  - Will the use of dense smart sensor data result in up to 20% reductions in plug-load energy consumption by interrupting power to non-critical loads in areas which are determined to be unoccupied?

  A secondary question addressed by this demonstration was whether our demonstrated combination of a dense smart sensor network and carefully selected replacement luminaires could improve occupant satisfaction with lighting in personal work spaces.

5.1 CONCEPTUAL TEST DESIGN

Hypothesis #1: Occupancy data and light level data from a densely spaced smart sensor network can be integrated and used to control lighting systems to realize significant reductions in lighting energy consumption.

- Independent variable: We controlled the "ON" time and illumination levels of lighting systems in work spaces in response to outputs of a densely spaced smart sensor network.
- Dependent variable(s): We measured and recorded both the "ON" time of lighting circuits and the actual energy consumption of those circuits.
- Controlled variable(s): Variables held constant include the following:
  - Worker population
  - Work schedules
  - Production schedules

  We note that we had no direct control over the number of workers, their work schedules, or production schedules. To address this, we requested inputs from first-line supervisors concerning any significant changes (plus or minus 10%) in worker population or significant work schedule reductions (such as furloughs or layoffs) or work schedule increases (such as overtime, double shifts, or weekend operations).

We also requested production updates in each work area to determine if there were significant changes in production which may directly impact system performance. However, no significant changes in production or schedule were reported.

- Lighting Test Design: Our approach differed between the first-floor high-bay production area and the second-floor administrative office area:
  - High-Bay Area. In the first-floor high-bay area, after capturing the baseline data, we replaced all existing HID luminaires with new LED-based luminaires. We also equipped each of the new luminaires with a smart sensor which controls (ON/OFF/lighting level) the lighting system. The smart sensors also wirelessly communicate their instantaneous occupancy status, space temperature and energy consumption to a master system which records and stores the fixture's status for later analysis. The lighting system was operated, and performance data was recorded in this configuration for 10 months.
  - Office Area. In the second-floor administrative office area, after capturing the baseline data, the original fluorescent luminaires were replaced with highly efficient pendant-style LED-based luminaires which incorporated their own smart sensors which controlled (ON/OFF/lighting level) the lighting system. The smart sensors also wirelessly communicated their instantaneous occupancy status, space temperature and energy consumption to a master system which recorded and stored the fixtures' status for later analysis. The office area lighting system was in this configuration for 5 months while data was being collected.

  After 5 months, we removed the pendant-style luminaires and installed a new troffer luminaire lighting system retrofitted with LED-based technology. We also equipped each of the retrofitted troffer luminaires with a smart sensor with the same functionality as described above. The lighting system was operated, and performance data was recorded in this configuration for the final 5 months of the demonstration.

- Test Phases: We conducted the test of lighting controls in phases. First, we took baseline electrical energy measurements of the high-bay production area and office area lighting circuits for 12 months. The baseline systems included existing HID fixtures (high-bay area) and fluorescent fixtures (office area) and no smart sensor controls.

- In the first-floor high-bay area, after capturing the baseline data, we replaced all existing HID luminaires with new LED-based luminaires equipped with smart sensors. The retrofitted first-floor high-bay area lighting systems were operated, and performance data was measured/recorded in this configuration for 10 months.

  In the second-floor office area, after capturing the baseline data, we first replaced the existing fluorescent lighting systems with highly-efficient pendant-style LED-based luminaires which incorporated their own smart sensors. These lighting systems were operated, and performance data was measured/recorded in this configuration for 5 months.

  After 5 months, we removed the pendant-style luminaires and installed a new troffer retrofit kit luminaire lighting system with LED-based technology and fitted with smart sensors. The office area lighting systems were operated, and performance data was measured/recorded in this configuration for the final 5 months of the demonstration.

Hypothesis #2: Occupancy data and space temperature data from a densely spaced smart sensor network can be integrated and used to adjust zone temperature setpoints in areas determined to be unoccupied, which will result in significant reductions of HVAC energy usage.

- Independent variable: We set back (heating mode) or set up (cooling mode) the zone temperature setpoints in work areas which are determined to be unoccupied by a densely spaced smart sensor network.
- Dependent variable(s): We measured and recorded HVAC energy (heating or cooling) delivered to the demonstration work areas.
- Controlled variable(s): Variables held constant include the following:
  - "Occupied" mode space temperature setpoints.
  - Worker population
  - Work schedules
  - Production schedules
- Test Design: We had no direct control over the number of workers, their work schedules, production schedules, or weather conditions. To address this, on alternate days, we operated the HVAC systems by switching between fixed (for 1 day) and adjusted zone temperature setpoints (for 2 days). This schedule dampened out unexplainable influences on HVAC energy usage attributable to daily variances in worker population, worker schedules, production schedules, weather, and other unidentified factors.

  We measured heating and cooling energy required to condition the building by: measuring the heating and cooling loads of air handling units with BTU meters installed on hot and cold water pipes, measuring energy consumption of air handling units' fans with electricity meters, and measuring the airflow rate at each VAV box. Since VAV boxes had reheat functionality, we also measured the delta temperature (ΔT) between the supply air temperature entering the VAV box and the discharge temperature of air leaving the VAV box; this allowed us to compute reheat energy consumption. Enabling/disabling the setpoint temperature reset function on alternate days (2 days occupancy controlled /1-day fixed schedule) allowed us to compensate for day-to-day fluctuations in worker population, worker schedules, production schedules, and other factors.

Hypothesis #3: Occupancy data from a densely-spaced smart sensor network can be integrated and used to control non-critical plug-loads to realize significant reductions of facility energy usage.

- Independent variable: We controlled the "ON" time of non-critical plug-load circuits in work spaces in response to outputs of a densely spaced smart sensor network.
- Dependent variable(s): We measured and recorded both the "ON" time of non-critical plug-load circuits and the actual energy consumption of those circuits.
- Controlled variable(s): Variables held constant include the following:
  - Worker population
  - Work schedules

- Test Design: We installed plug-load controllers in 15 locations in the administration area. However, one plug-load controller was subsequently determined to have been incorrectly wired, and its data invalid. Hence, it was excluded from the analysis, so only data associated with 14 plug-load controllers was analyzed. Although our intent was that non-critical appliances be plugged into controlled plug-load outlets, we had no control over whether the workers chose to plug into controlled outlets. In an attempt to influence adoption and proper usage, we clearly labeled "Controlled" and "Uncontrolled" outlets and provided an explanation as to the difference between "Controlled" and "Uncontrolled." Initially, we requested workers' permission to plug non-critical appliances (e.g., radios, desk lamps, monitors, etc.) into the controlled outlets while leaving critical appliances (desktop computers, copiers, vending machines, etc.) plugged into uncontrolled outlets. After installation of the plug-load controllers, we operated plug-loads for a baseline period of three months with occupancy control of the plugs disabled. Plug-load energy consumption data was collected through the Enlighted system. Then, we activated occupancy control of the "Controlled" plugs and operated the system for a demo period of 6 months, and similarly collected plug-load energy usage data.

Hypothesis #4: A well-designed, energy-efficient lighting system combined with a densely spaced smart sensor network can improve workers' satisfaction with the lighting environment in their workspace.

- Independent variable: We controlled the architecture and control scheme of the lighting systems in work spaces by replacing existing lighting systems and installing occupancy-based and lighting level-based lighting controls.
- Dependent variable(s): We measured and recorded workers' perception of the lighting systems in their workspaces via worker surveys.
- Controlled variable(s): Variables held constant include the following:
  - Worker population
  - Work schedules
  - Production schedules

  We note that we had no direct control over the number of workers, their work schedules, or production schedules. However, for purposes of our worker survey, we assumed these to be constant. We also had no control over which persons, or how many persons responded to the survey or other factors that might impact worker's overall job satisfaction, which could affect their attitude towards the workspace lighting system. Again, we had to assume any such factors had no effect. We tried to obtain as many survey responses as possible from both the office and the high-bay areas, and we encouraged survey participation by sending multiple reminders, and allowing ample time for occupants to complete the survey. However, since completion of the survey was not mandatory, and responses were anonymous, we could not guarantee responses from a consistent occupant population between the baseline and the post-install surveys.
- Test Design: We asked the occupants to complete a survey with twenty-one questions. The survey was based on the "Light Right" survey developed by the Pacific Northwest National Laboratory [PNNL]. Occupants filled out the provided surveys voluntarily and anonymously. Management collected completed surveys and forwarded them to us for analysis.

- Test Phases: The survey was administered three times. First, it was administered to workers in the high-bay area and office area at the beginning of the demonstration to capture workers' perception of the existing lighting systems in their primary work areas. The existing lighting systems were then replaced by advanced LED-based lighting systems. In the high-bay area, the worker survey was re-administered approximately twelve months following the replacement of the existing lighting systems.

  For workers in the office area, the survey was re-administered approximately three months following the first LED retrofit installation. After the second lighting system was in place for approximately three months, the survey was administered to workers in office areas a final time after the Phase 2 troffer fixtures installation.

5.2 BASELINE CHARACTERIZATION

Baseline characterization is described below.

- Reference Conditions: Reference conditions for each of the performance objectives are listed below:
  - PO1: Lighting Energy Usage – Baseline electrical energy consumption on selected lighting circuits was measured and recorded for 10 months.
  - PO2: HVAC Related Energy Usage – Baseline HVAC heating and cooling energy delivered to the demonstration work areas was measured and recorded for one third of the demonstration period as we alternated system control between two days with occupancy optimized control and one day of regular non-occupancy control.
  - PO3: Instrumented Plug-Load Usage – Baseline electrical energy consumption on selected non-critical plug-load circuits was measured and recorded for nearly three months.
  - PO4: Lighting Quality – Workers' perception of their workspace lighting was measured via a survey based on PNNL's Light Right survey.

  Initial Lighting Conditions – Office Area: The office area was originally lighted using recessed 2x4, 3-lamp T8 fluorescent troffers regularly spaced throughout the offices and conference rooms. On average, work surfaces were lighted to 147% of criteria, and vertical light levels were 188% of criteria. Luminaires had a color temperature of roughly 3700K and a Color Rendering Index (CRI) of 82.

  Initial Lighting Conditions – High-Bay Area: The high-bay area was originally lighted using pendant mounted HID luminaires that were irregularly spaced throughout the area. Luminaires would vary in color as they aged and were not replaced promptly. On average, work surfaces were lighted to 61% of criteria and vertical light levels were 50% of criteria. Luminaires had a color temperature of roughly 4300K and a CRI of 75.

- Baseline Collection Period:
  - PO1: Lighting Energy Usage – 12 months.
  - PO2: HVAC Related Energy Usage – Effectively one third of our HVAC demonstration period which corresponded to about 5 weeks.
  - PO3: Instrumented Plug-Load Usage – 3 months.

- PO4: Lighting Quality – An initial survey was taken before replacement of existing light systems.

- Existing Baseline Data: There was no previously available utility energy data prior to this demonstration project.
- Baseline Estimation: This demonstration project did not rely on baseline estimations.
- Data Collection Equipment:
  - PO1: Lighting Energy Usage – Lighting energy usage was collected with Dent Instruments electric power loggers. These devices measured and recorded lighting circuit voltage, amperage and power factor on fifteen-minute intervals. In addition, the Enlighted Energy Manager system collected lighting energy data on five-minute intervals.
  - PO2: HVAC Related Energy Usage – BTU meters were added to the hot and chilled water coils of the AHUs to measure the hot and chilled water load of each AHU. AHU mixed air and supply air temperature sensors were used to measure the temperature of each AHU's air before/after the heating and cooling coils. Sensors in the AHUs also measured the enthalpy of mixed and supply air. Air flow rates were measured at VAV boxes using the VAV boxes' internal flow sensor. Temperature sensors were added to the VAV boxes containing reheat coils to measure the temperature of the supply air entering the VAV box and the temperature downstream of the reheat coil. All flow rate, heating/cooling load, and temperature data were measured and collected at one-minute intervals and recorded in the existing Honeywell EBI building automation system at six-minute (average), one-hour (snapshot) intervals.
  - PO3: Instrumented Plug-Load Usage – Energy usage on instrumented plug-load circuits was collected with the Enlighted Energy Manager system. The Enlighted system measured and recorded plug circuit energy consumption at five-minute intervals.
  - PO4: Lighting Quality – An initial paper survey was administered before replacement of existing light systems. Illuminance data was measured with a recently-calibrated Konica Minolta CL-500A Illuminance Spectrophotometer. Luminance data was measured using a recently-calibrated Konica Minolta LS-110 Luminance Meter.

1.1 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

- System Design: The demonstrated system includes a densely spaced network of smart sensors. One smart sensor was installed on each lighting fixture. The smart sensors combine the capability to sense motion (occupancy), space temperature, and light levels.
- Components of the System: System components are described and illustrated in Appendix B.
- System Depiction: Figure 2 depicts the architecture of the Enlighted system.

  Figure 2 shows how the Enlighted system interacts with the pre-existing Honeywell EBI and the management graphical user interface (GUI). Lighting performance data, space temperature data, and plug-load energy consumption data was sent to the Enlighted Energy Manager system, where it was stored and available for download and analysis. HVAC data was sent to the Honeywell EBI system, where it was stored and available for download and analysis.

- System Integration: The demonstrated systems replaced existing HID lighting fixtures with LED fixtures in the first-floor high-bay areas. In the office area, the demonstration replaced the baseline fluorescent lighting – first with LED pendant lighting fixtures and, after a five-month Phase 1 period, with LED-based retrofit troffer kits installed in the original fluorescent troffer fixtures. Each of the demonstrated lighting fixtures contained Enlighted smart sensors. The Enlighted smart sensors interact directly with their associated fixtures to turn them ON/OFF in accordance with their sensed occupancy and to adjust lighting outputs to maintain proper illumination levels. The Enlighted smart sensors communicate occupancy, lighting level, space temperature and real time power usage to the Enlighted Energy Manager, where the data is stored and is available for download and analysis. Space occupancy data was transmitted to the Honeywell EBI system and used to adjust space temperature setpoint setback (+/- 2 °F) in accordance with sensed occupancy.

  High-Bay Area Lighting System:

  - The baseline high-bay luminaires in the industrial high-bay area were replaced with the Flex Essential High-Bay luminaire. Additional information and detail about the high-bay luminaires is documented in APPENDIX B: HARDWARE INVENTORY.

Figure 13. New LED High-Bay Luminaire.

  - All lights in the high-bay area were updated to new LEDs, and the layout remained unchanged as shown in Figure 14.

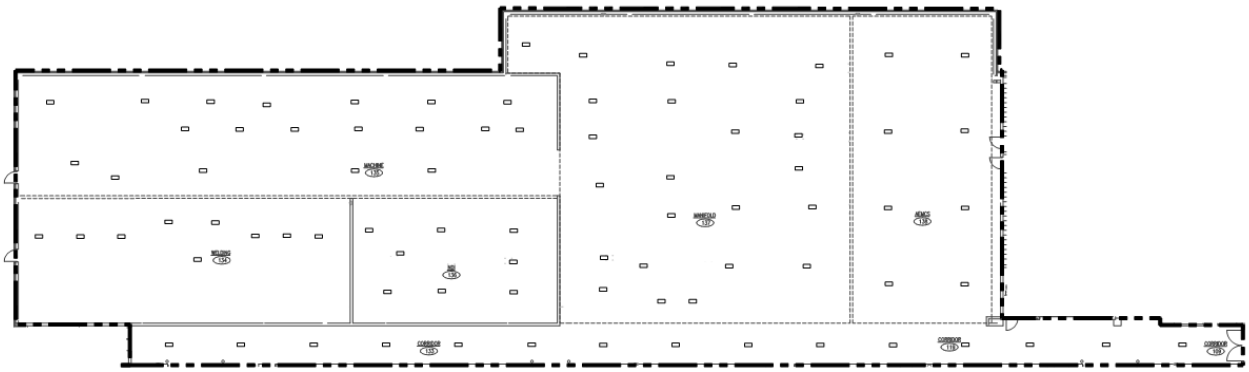


Figure 14. High-Bay Area Lighting Layout.

- <u>Office Area Lighting System – Phase 1</u>

Figure 15. Office Area Phase 1 Pendant Luminaire

- The pendant layout was initially coordinated with the furniture, but the site requested a more "standard" array layout which did not coordinate with the furniture. This un-coordinated layout resulted in shadowing and reduced uniformity. Figure 16 shows the two different design layouts: the proposed design (left) and the actual installed design (right). Table 3 shows the estimated difference in light levels between the proposed pendant deign and the actual.
- The existing lighting in the office area was first replaced with Finelite HP2 series direct/indirect pendant mounted luminaires. Additional information, and detail about the Phase 1 luminaires is documented in APPENDIX B: HARDWARE INVENTORY

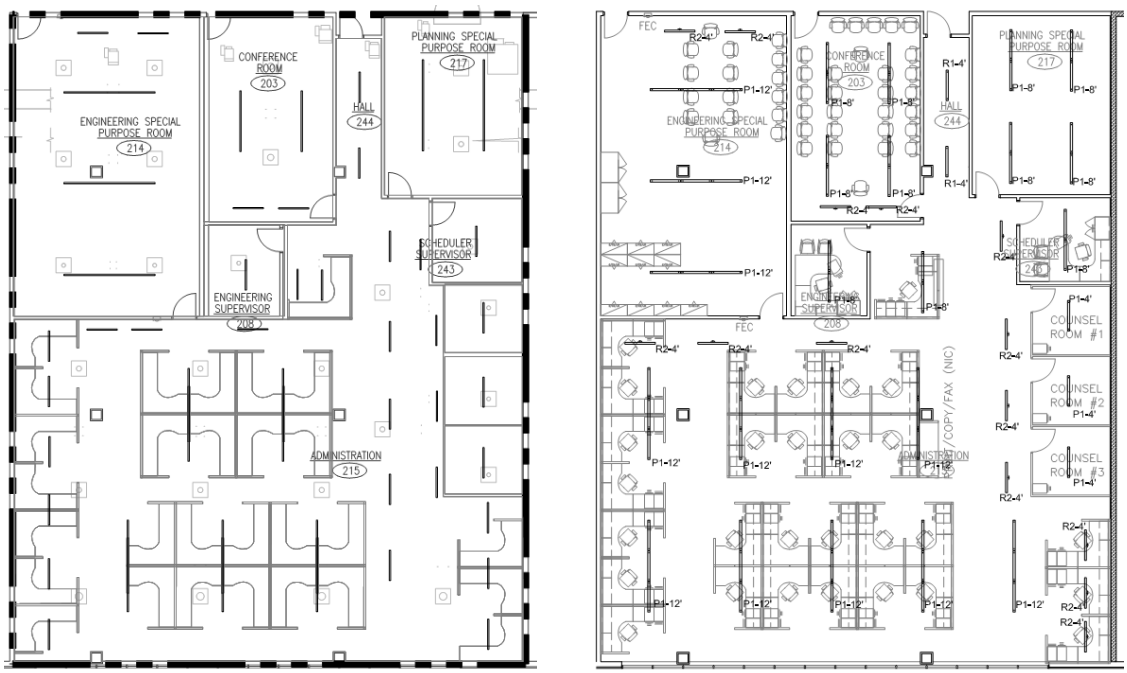


Figure 16. Office Area Pendant Lighting Layout during Phase 1.

Proposed design (right) and actual installed design (left)

Table 3. Office Area Pendant Light Levels Estimated on Desks with the Proposed Design versus the Actual Installed Design.

	Proposed Design			Installed Design		
	Avg (fc)	Max/Min	Avg/Min	Avg (fc)	Max/Min	Avg/Min
Desk 1	22	1.6	1.3	12	2.4	1.6
Desk 2	25	1.9	1.4	34	2.9	1.9
Desk 3	26	2.1	1.6	28	2.1	1.6
Desk 4	25	2.2	1.6	13	1.7	1.3
Desk 5	23	1.6	1.3	32	3.0	2.0
Desk 6	26	1.6	1.3	32	2.6	1.8
Desk 7	27	2.0	1.6	21	2.5	1.9
Desk 8	26	4.0	1.7	40	1.9	1.5
Desk 9	25	3.1	1.8	18	2.4	1.6
Desk 10	27	3.1	1.7	39	2.2	1.6
Desk 11	25	3.2	1.8	19	2.8	1.7
Desk 12	27	3.0	1.7	38	2.1	1.6
Desk 13	26	3.1	1.8	43	2.1	1.6
Desk 14	27	2.6	1.6	21	2.0	1.5
Desk 15	27	3.1	1.8	41	2.4	1.8
Desk 16	27	3.2	1.9	21	2.5	1.6
Desk 17	28	2.9	1.8	39	2.2	1.7
Desk 18	26	3.1	1.8	45	2.0	1.5
Desk 19	27	2.6	1.6	28	2.0	1.5
Desk 20	28	3.3	1.9	43	2.2	1.6
Desk 21	27	2.5	1.6	32	2.1	1.5
Desk 22	26	2.6	1.6	45	2.0	1.6
Desk 23	26	3.1	1.8	27	2.0	1.5
Desk 24	27	2.8	1.6	44	2.1	1.6
Desk 25	25	3.0	1.8	32	2.1	1.6
Desk 26	24	1.8	1.4	38	2.8	2.1
Desk 27	26	1.9	1.4	20	2.3	1.8
Desk 28	27	2.0	1.4	23	3.0	2.3
Desk 29	25	1.6	1.3	19	2.7	2.0

- Office Area Lighting System – Phase 2

  - The luminaire installed for Phase 2 was the ILP Value Lance 2'x4' LED retrofit kit for recessed lighting. This retrofit kit directly replaced the original fluorescent light with an LED source. Additional information and detail about the Phase 2 retrofit kit luminaires is documented in APPENDIX B: HARDWARE INVENTORY

Figure 17. Office area Phase 2 Troffer Luminaire.

  - The lighting layout for the Phase 2 installation is shown in Figure 18.

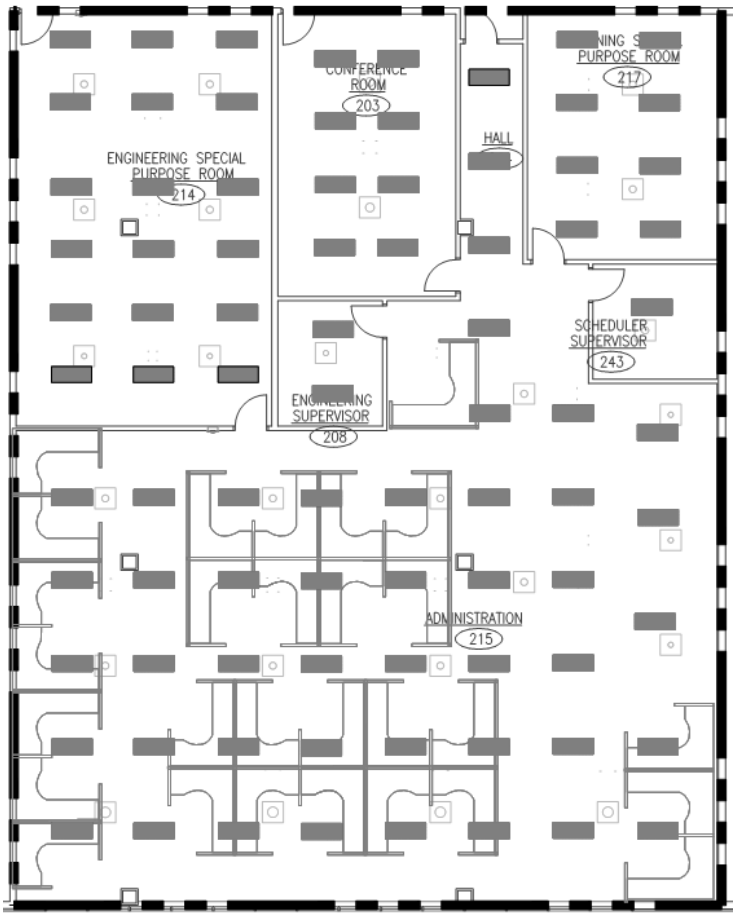


Figure 18. Office Area Troffer Lighting Layout Phase 2.

- System Controls: System controls and control schematics were previously provided in this section. If necessary, the systems could be manually overridden at the Management GUI.

5.3 OPERATIONAL TESTING

- Operational Testing of Cost and Performance: Baseline data collection was performed prior to any system retrofit activities. After systems were retrofitted, they were commissioned to make sure that they functioned as intended and that the data being measured and recorded was accurate and complete. Once systems were properly commissioned, data collection continued throughout the remainder of the demonstration period. Collected data was downloaded regularly from the Honeywell EBI system and the Enlighted Energy Manager and delivered to the project team for evaluation and analysis. Any discrepancies or anomalies were identified, and corrective actions taken as necessary.

  Operational Testing of Lighting:

  - High-Bay Area
    - On May 29th, 2018 the original HID lighting in the high-bay area was measured by Clanton & Assoc. The measurements taken were horizontal illuminance on the work plane (30" Above Finished Floor (AFF)), vertical illuminance at the eye, and luminance of building surfaces including walls, ceiling, floor, luminaires and work surfaces. A description of the locations of measurements can be found below.
    - On October 24th, 2018 the upgraded LED lighting in the high-bay area was measured in the same locations and protocol as the original lighting.
  - Office Area
    - On May 29th, 2018 the original fluorescent lighting in the Administrative area was measured by Clanton & Assoc. The measurements taken were horizontal illuminance on each desk, vertical illuminance at the eye, and luminance of building surfaces including walls, ceiling, floor, luminaires and work surfaces. A description of the locations of measurements can be found below.
    - On October 24th, 2018 the Phase 1 LED lighting in the Administrative area was measured in the same locations and protocol as the original lighting. Light levels were measured with and without daylight contribution from the windows.
    - On May 1st, 2019 the Phase 2 LED lighting in the Administrative area was measured in the same locations and protocol as the original lighting. Light levels were measured with and without daylight contribution from the windows.

- Modeling and Simulation: The office and high-bay areas were modeled in AGi32 and calculated using various luminaires to determine the appropriate lighting layouts and lumen outputs to meet criteria. The original layout was also calculated to determine original light levels in each space.

- Actual Timeline: Major demonstration activities are shown in the table below.

Table 4. Project Timeline.

Activity	Start	Finish	Duration	Usable Data Duration
Baseline lighting circuit monitoring (Dent Instruments)	9/20/2017	9/16/2018	12 months	307 days
User/occupant surveys (Baseline)	11/13/2017	12/21/2017	5 weeks	
Lighting quality measurements (Preliminary)	12/5/2017	12/5/2017	1 day	
Lighting quality measurements (Baseline)	5/30/2018	5/30/2018	1 day	
Replace original high-bay area HID lighting with LED fixtures	9/17/2018	10/4/2018	3 weeks	
Replace original office area lighting with LED pendant-type fixtures	9/17/2018	10/4/2018	3 weeks	
Install lighting and plug-load controls	9/17/2018	10/4/2018	3 weeks	
Lighting quality measurements (Post Install/Phase 1)	10/24/2019	10/24/2019	1 day	
User/occupant surveys (Phase 1)	1/18/2019	1/31/2019	2 weeks	
Baseline plug-load circuit monitoring (EEM)	12/13/2018	3/5/2019	3 months	83 days
Install HVAC energy monitoring controls	7/1/2018	12/13/2018	5 months	
Monitor high-bay area demo lighting energy	10/25/2018	9/2/2019	10 months	313 days
Monitor HVAC energy high-bay and admin areas / (Valid HVAC data period)	12/13/2018 5/7/2019	8/31/2019 8/31/2019	8 months/ (4 months)	Baseline: 52 days Demo: 103 days
Monitor plug-load demo energy data (EEM)	3/6/2019	8/31/2019	6 months	181 days
Monitor Office area lighting energy Phase 1 (pendants)	10/25/2018	3/24/2019	5 months	151 days
Replace office area pendant-type fixtures with LED troffer retrofit kits	3/25/2019	3/28/2019	1 week	
Monitor Office area lighting energy Phase 2 (troffer retrofits)	3/29/2019	9/2/2019	5 months	158 days
User/occupant surveys (Phase 2)	4/29/2019	5/29/2019	1 month	
Lighting quality measurements (Post Install/Phase 2)	5/1/2019	5/1/2019	1 day	

5.4 SAMPLING PROTOCOL

The sampling protocol is described below.

- Data Collector(s):
  - **PO1: Lighting Energy Use:** Lighting circuit energy data (baseline and demonstration period) was recorded in the Dent Instruments devices. Data was downloaded regularly for analysis by Honeywell personnel.

    Occupancy data, as well as lighting energy usage from each fixture, was transmitted from the light fixtures to the Enlighted Energy Manager system, where it was integrated and stored. Data was downloaded regularly for analysis by Honeywell personnel.

- **PO2: HVAC Energy Use**: HVAC energy data was stored in the Honeywell EBI system and forwarded to the project team by the Honeywell onsite personnel at regular intervals.
- **PO3: Instrumented Plug-load usage**: Baseline plug-load circuit energy data was recorded in the Enlighted Energy Manager. Data was downloaded regularly for analysis by Honeywell personnel.
- **PO4: Lighting Quality**:

  Lighting was measured using two different metrics: 1) illuminance (the density of light falling onto a surface measured in footcandles) and 2) luminance (the light source or surface brightness that people perceive measured in candela per square meter [cd/m^2]). Light levels on work surfaces and vertical light at the eye were measured in footcandles using an illuminance spectrometer. This measuring device not only recorded the illuminance, but also the color temperature and the CRI. Surface brightness of walls, floors, ceiling, screens, luminaires and work surfaces was measured in luminance to record brightness and uniformity in each space. Multiple luminance measurements were taken on each surface to gain an accurate understanding of the surface brightness and how uniformly the surfaces were lighted. The illuminance measurements were taken at specific locations in each space. The locations of illuminance measurements in each space is shown in Figure 19 and Figure 20.

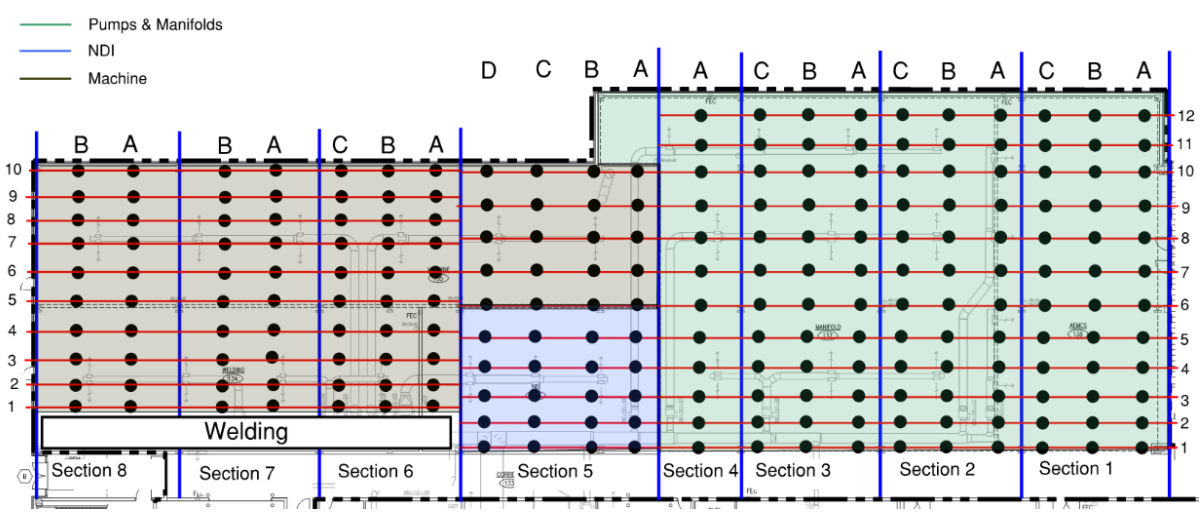


Figure 19. High-Bay Area Illuminance Measurement Locations.

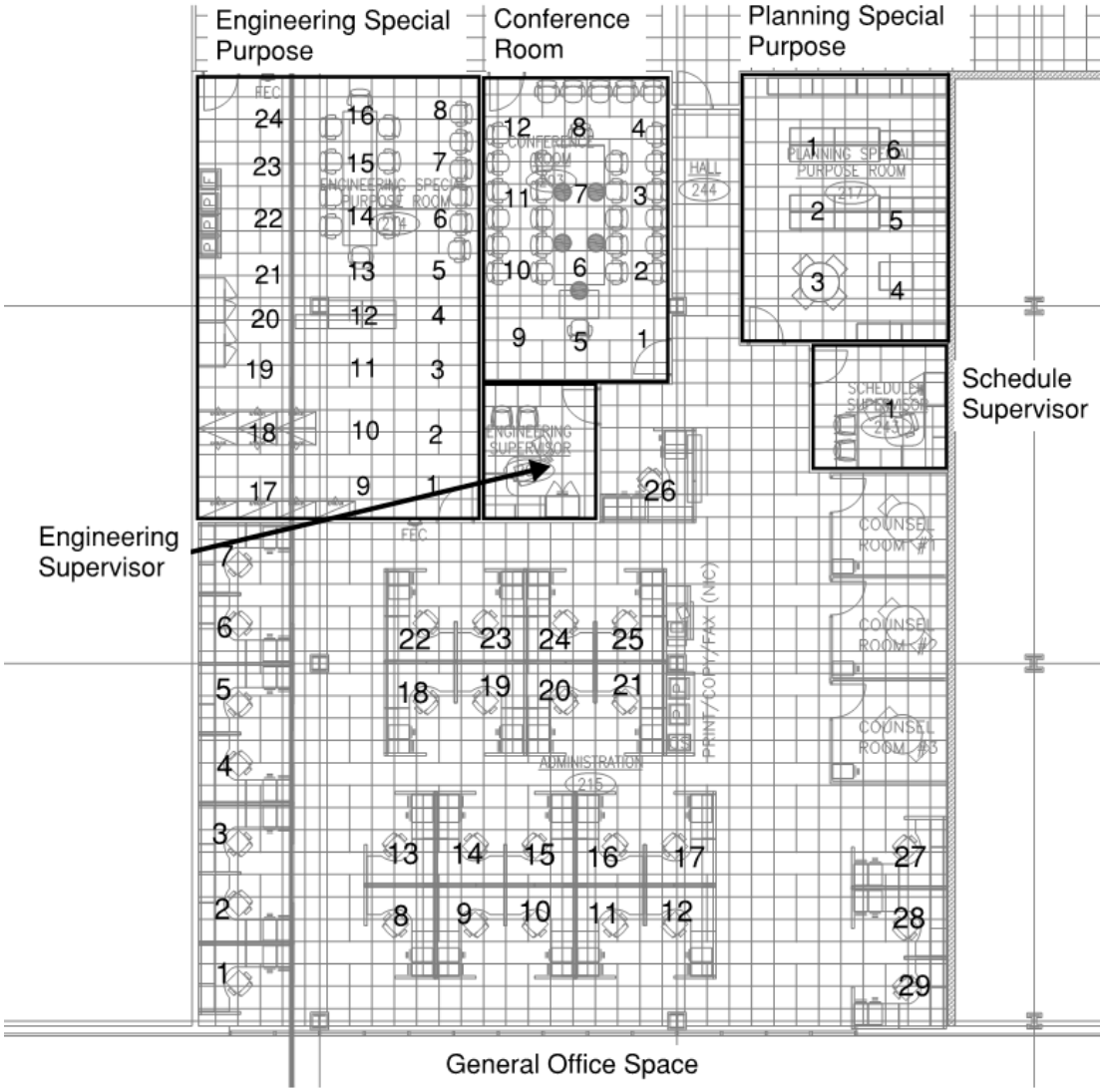


Figure 20. Office Area Illuminance Measurement Locations.

Occupants in the office area were surveyed 3 times to get a subjective evaluation of the various lighting strategies. They were surveyed on the original fluorescent lighting, the Phase 1 LED pendant lighting, and the Phase 2 LED troffer lighting. The survey on the original lighting had 25 responses, the Phase 1 lighting survey had 17 responses, and the Phase 2 lighting survey had 19 responses.

In the high-bay area, workers were surveyed twice, once on the original HID lighting and again after the new LED high-bay lights were installed. The original lighting survey had 9 responses, and the new LED lighting survey had 14 responses.

- <u>Data Recording:</u>
  - Lighting circuit energy data was automatically sampled at 15-minute intervals and recorded in the Dent Instruments devices.

- Smart sensor data (occupancy, space temperature, lighting levels, plug-load energy) was automatically sampled at 5-minute intervals, integrated, and stored in the Enlighted Energy Manager system. Data was regularly downloaded for analysis by Honeywell personnel.
- HVAC energy data was automatically sampled at 6-minute intervals, stored in the Honeywell EBI system, and regularly forwarded to the project team by the Honeywell onsite personnel.
- Worker surveys were manually completed by the workers, received by first level supervisors, and forwarded by management personnel to the Honeywell project team after administration of each survey.

- Data Description:
  - Lighting circuit energy data:
    - Amperage data
    - Voltage data
    - Power factor data
    - Approximate samples: 37,900 per circuit (at 15-minute intervals)
  - Smart sensor data:
    - Occupied/unoccupied data
      - Approximate samples: 105,100 per sensor (at 5-minute intervals)
    - Space temperature data
      - Approximate samples: 105,100 per sensor (at 5-minute intervals)
    - Lighting level
      - Approximate samples: 105,100 per sensor (at 5-minute intervals)
    - Lighting energy
      - Approximate samples: 105,100 per sensor (at 5-minute intervals)
  - Plug-load data:
    - Energy consumption data
      - Approximate samples: 105,100 per device (at 5-minute intervals)
  - HVAC energy data:
    - Temperature data
    - Air flow rate data
    - Approximate samples: 87,600 per point (at 6-minute intervals)
  - Worker surveys: Various responses to survey questions
    - Approximate samples: Unknown – dependent on workers' responsiveness

- Data Storage and Backup:
  - Lighting circuit energy data: Data was stored in the individual Dent Instruments power loggers. Units had battery backup to reduce risk of data loss.
  - Smart sensor data: Data was stored in the Enlighted Energy Manager system.

- HVAC energy data: Data was stored in the Honeywell EBI building automation system.
- Worker surveys: Data was stored on paper survey forms that were scanned and transmitted to the Honeywell project team.

- Data Collection Diagram: Our data collection protocol is described above.
- Non-standard Data: Not applicable.
- Survey Questionnaires: The adapted Light Right survey is included in Appendix E.

5.5 SAMPLING RESULTS

- Equipment Calibration:
  - Lighting circuit energy data: The Dent Instruments power loggers are factory calibrated and require no further calibration.
  - Smart sensor data: The smart sensors require no calibration.
  - Plug-load data: The plug-load controllers require no calibration.
  - HVAC energy data:
    - Temperature data: The HVAC equipment requires no calibration.
    - Air flow rate data: The HVAC equipment requires no calibration.

- Quality Assurance Sampling: The HVAC data was stored in the Honeywell EBI system. Primarily lighting energy data (sampled at 15-minute intervals) was stored in the Dent data logger instruments. The occupancy data, plug-load energy data, and secondary lighting energy data (sampled at 5-minute intervals) was stored in the Enlighted Energy Manager System. Data was downloaded regularly from all three data collection systems (Honeywell EBI, Dent loggers, and Enlighted System) and delivered to the project team, who evaluated the data as soon as it was received. This allowed us to quickly identify any anomalies, discuss the problem with the system operators and take any corrective actions that may be necessary. Furthermore, initially, during the first month, at the start of the demonstration, we monitored the data weekly to validate the data and ensure the system was operational and functioning as expected.

5.5.1 PO1: Lighting Energy Usage

5.5.1.1 Baseline lighting energy consumption

This section summarizes energy consumption of the baseline (non-LED) lighting over the baseline period (307 days total: 11/14/2017 to 9/16/2018), before installation of the Enlighted lighting demo system.

Daily energy consumption of the baseline (non-LED) lights is plotted for the high-bay area in Figure 21 (blue dots) and for the office area in Figure 22 (red dots). Solid lines indicate mean daily values, which were 269 kWh per day for high-bay lights and 57 kWh per day for office lights.

Table 5, column 1 lists the energy consumption of the baseline lighting over the baseline period. Column 2 lists the mean daily energy consumption of baseline lighting, and column 3 lists the projected yearly energy consumption of baseline lights. Baseline energy consumption results are listed separately for the office area (row 2), the high-bay area (row 3), and the total (office + high-bay) in row 4.

Monthly energy consumption of the high-bay and office lights during the baseline period is listed in Table 6 and plotted in Figure 23.

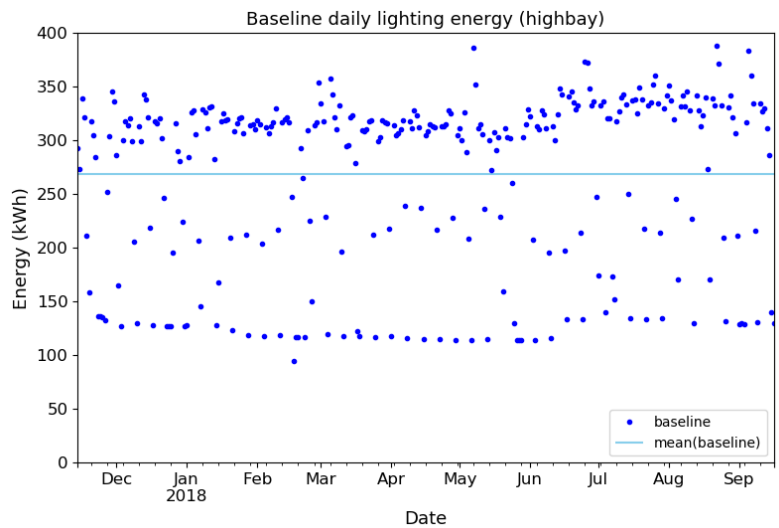


Figure 21. Daily Energy Consumption of Lights in High-bay Area during Baseline Period.

The solid line shows the mean daily consumption over the baseline period.

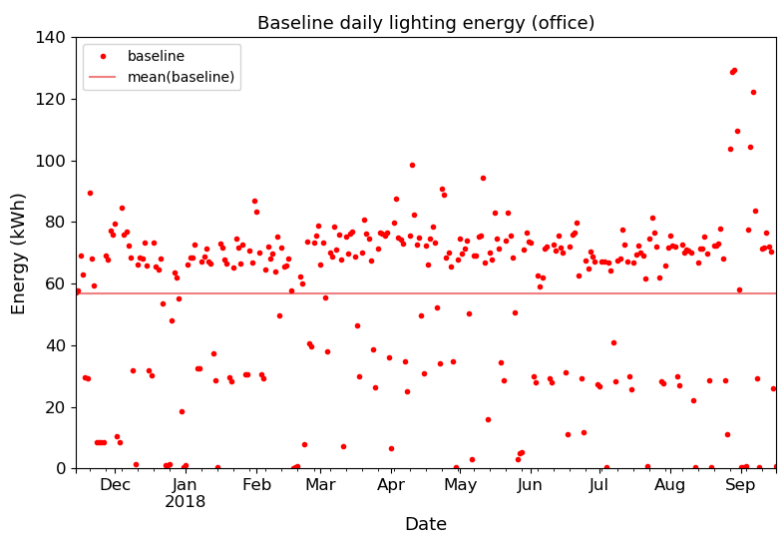


Figure 22. Daily Energy Consumption of Lights in Office Area during Baseline Period.

The solid line shows the mean daily consumption over the baseline period.

Table 5. Summary of Energy Consumption of Office and High-bay Lights During the Baseline Period (11/14/2017 to 9/16/2018).

Total energy consumption over the baseline period is shown in column 2. Mean daily consumption over the baseline period is shown in column 3. Column 4 lists projected yearly energy consumption of baseline lights.

	Energy consumption over baseline period (kWh)	Mean daily energy consumption over baseline period (kWh)	Projected baseline yearly energy consumption (kWh)
Office	17,460	57	20,770
High-bay	82,510	269	98,160
Total (office + high-bay)	99,970	326	118,930

Table 6. Summary of Monthly Energy Consumption of High-bay and Office Lights During the Baseline Period (307 days total: 11/14/2017 to 9/16/2018).

Month	High-bay lighting energy consumption (kWh)	Office lighting energy consumption (kWh)	Total (high-bay + office) lighting energy consumption (kWh)
2017-11	4,283	847	5,130
2017-12	7,747	1,490	9,237
2018-01	8,392	1,723	10,115
2018-02	7,068	1,520	8,588
2018-03	8,402	1,963	10,365
2018-04	8,102	1,880	9,982
2018-05	8,030	1,826	9,856
2018-06	8,551	1,693	10,244
2018-07	8,774	1,741	10,515
2018-08	9,171	1,971	11,142
2018-09	3,990	807	4,797

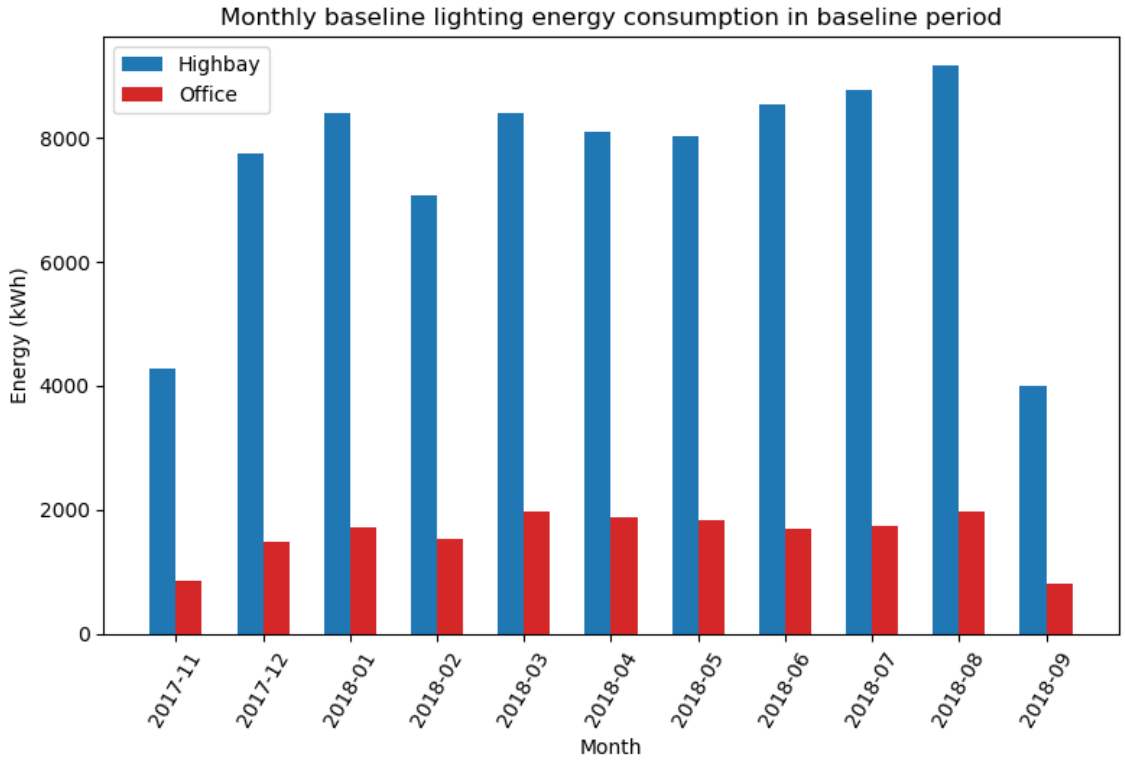


Figure 23. Plot of Monthly Energy Consumption of High-bay (Blue) and Office Lights (Red) During the Baseline Period (11/14/2017 to 9/16/2018).

Energy consumption and savings of the demo system

This section summarizes the energy consumption of the demo lighting system. It also lists the energy savings achieved relative to baseline energy consumption.

The primary source of lighting energy consumption measurements were the Dent data loggers. However, two incidents of data loss occurred in the high-bay area, due to logger hardware failures. Measurements from the Enlighted system (which was our backup measurement system) were used to fill in the missing Dent data. Figure 24 compares daily high-bay lighting energy consumption as recorded by the Dent loggers and the Enlighted system over a 3-month period where both measurements were available. The relationship is linear. A least-squares linear regression is indicated. Figure 25 plots the same relationship using data from several months later, to validate the linear relationship is stable over time. Missing Dent measurements of high-bay lighting data were filled in by taking daily lighting energy consumption measurements from the Enlighted system and correcting them with the linear equation indicated in Figure 24, so they would be consistent with Dent measurements. (See Section 1.1.1.1.1 for details.)

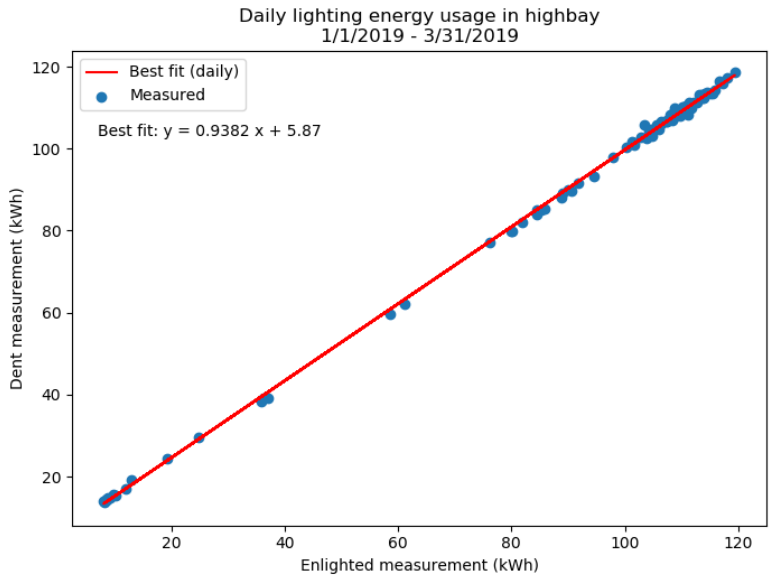


Figure 24. Comparison of Daily Lighting Energy Consumption in High-bay as Measured by Dent Loggers vs the Enlighted System, During the Period 1/1/2019 to 3/31/2019.

Best-fit line shown in red. This plot shows that one can reliably predict Dent measurements from Enlighted measurements using a linear model.

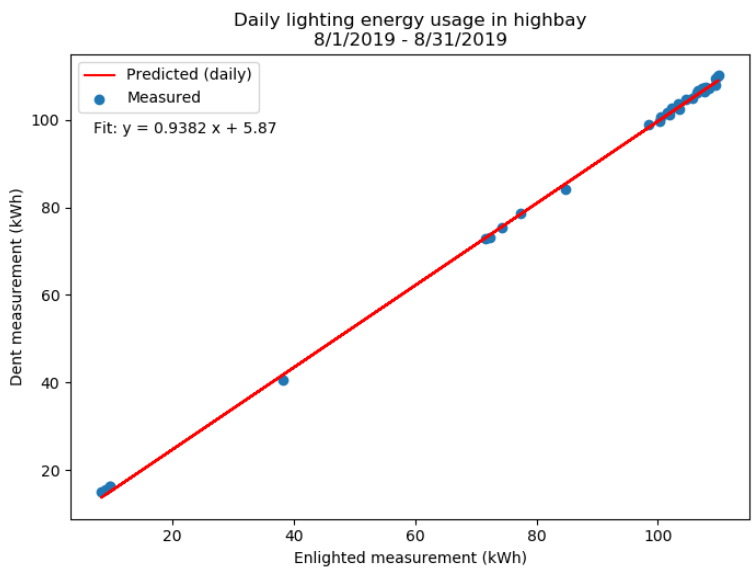


Figure 25. Validation of Best-fit Line from Figure 24 Over Date Range 8/1/2019 to 8/31/2019.

This shows that the linear relationship determined in Figure 24 (over a date range 1/1/2019-3/31/2019) continued to be valid months later (8/1/2019-8/31/2019).

Daily energy consumption of the demo system in the high-bay area is shown in red dots in Figure 26, and mean daily energy consumption is shown as a solid red line. For ease of comparison, daily energy consumption of the baseline lights is shown in blue in the same figure. Table 7 summarizes several aspects of the demo system's energy consumption in the high-bay area, including: mean daily energy consumption (column 1), total consumption over the high-bay demo period 10/25/2018 to 9/2/2019 (column 2), the projected energy consumption that baseline lighting would have used over the demo period (if the demo system were not installed) – column 3, the energy saved by the high-bay demo relative to the high-bay baseline (column 4), and high-bay energy savings as a percent of the baseline (column 5). Table 8 lists projected yearly energy consumption of the high-bay demo lights (column 1) and projected yearly savings (column 2).

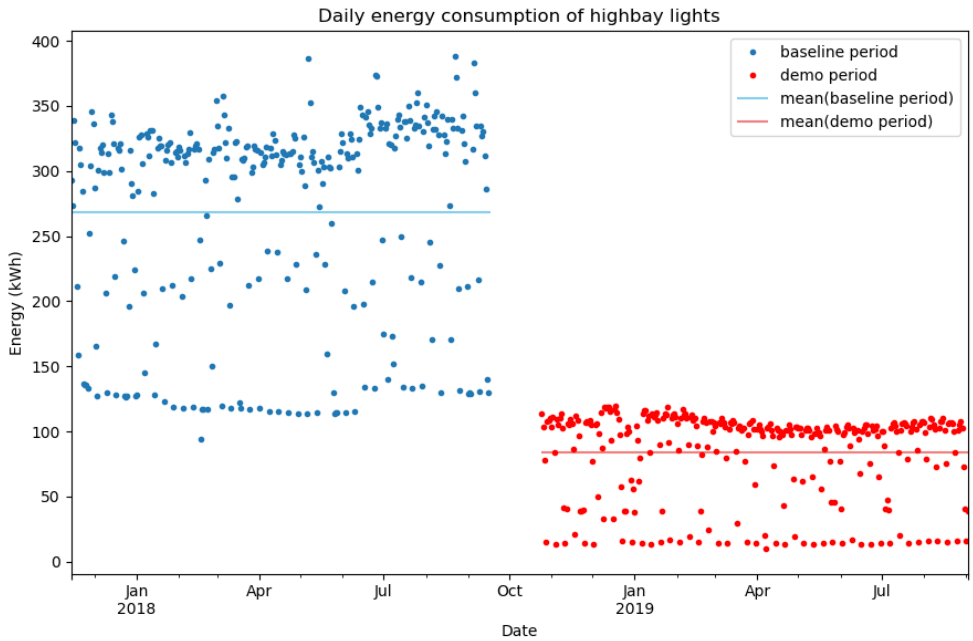


Figure 26. Daily Energy Consumption of High-bay Lights (Measured by Dent Loggers).

Blue dots indicate the baseline period (non-LED lighting) and red dots indicate the demo period (Enlighted LED lighting). Solid lines indicate the mean daily value per period. Note the significant energy reduction achieved by the demo system relative to the baseline lights.

Table 7. Summary of Energy Consumption and Savings of High-bay Demo System During the High-bay Demo Period (10/25/2018 to 9/2/2019).

High-bay demo system's mean daily energy consumption over demo period (kWh)	High-bay demo system's total lighting energy consumption over demo period (kWh)	Baseline lighting energy consumption for high-bay over demo period (kWh)	Energy saved by high-bay lighting demo system over demo period (kWh)	High-bay lighting energy savings as a percent of baseline (%)
84	26,390	84,120	57,730	**69**

Table 8. Projected Yearly Energy Consumption and Savings of High-bay Demo System.

Projected yearly energy consumption of high-bay demo (kWh)	Projected yearly energy savings of high-bay demo (kWh)
30,790	67,370

Table 9 lists the monthly energy consumption (column 2) and savings (column 4) of the demo system in the high-bay, as well as baseline energy consumption (column 3). Monthly consumption and baseline consumption are also plotted in Figure 27.

Table 9. Monthly Totals of High-bay Lighting Energy Consumption and Savings During the High-bay Demo Period (10/25/2018 to 9/2/2019).

Month	High-bay lighting Baseline energy consumption (kWh)	High-bay lighting Demo energy consumption (kWh)	High-bay lighting Demo energy savings (kWh)
2018-10	1,881	637	1,244
2018-11	8,063	2,469	5,594
2018-12	8,332	2,547	5,785
2019-01	8,332	2,773	5,559
2019-02	7,525	2,514	5,011
2019-03	8,332	2,677	5,655
2019-04	8,063	2,484	5,579
2019-05	8,332	2,488	5,844
2019-06	8,063	2,438	5,625
2019-07	8,332	2,613	5,719
2019-08	8,332	2,695	5,637
2019-09	537	55	482

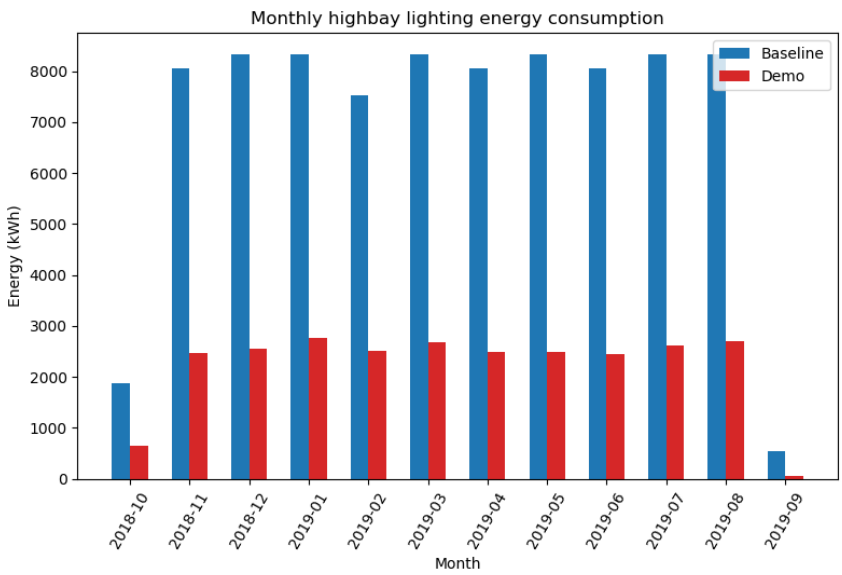


Figure 27. Plot of Monthly Energy Consumption of High-bay Lighting During the Demo (Red) vs Baseline (Blue) (High-bay Demo Period: 10/25/2018 to 9/2/2019).

Figure 28 graphs daily lighting energy consumption in the office area. Green dots indicate the pendant lighting demo, red dots the troffer lighting demo, and blue dots are baseline (non-LED) lighting. Solid lines indicate mean daily energy consumption over each period. Table 10 summarizes pendant lighting energy consumption and energy savings over the pendant demo period (10/25/2018 to 3/24/2019). Table 11 lists projected yearly energy consumption and savings of the pendant lighting.

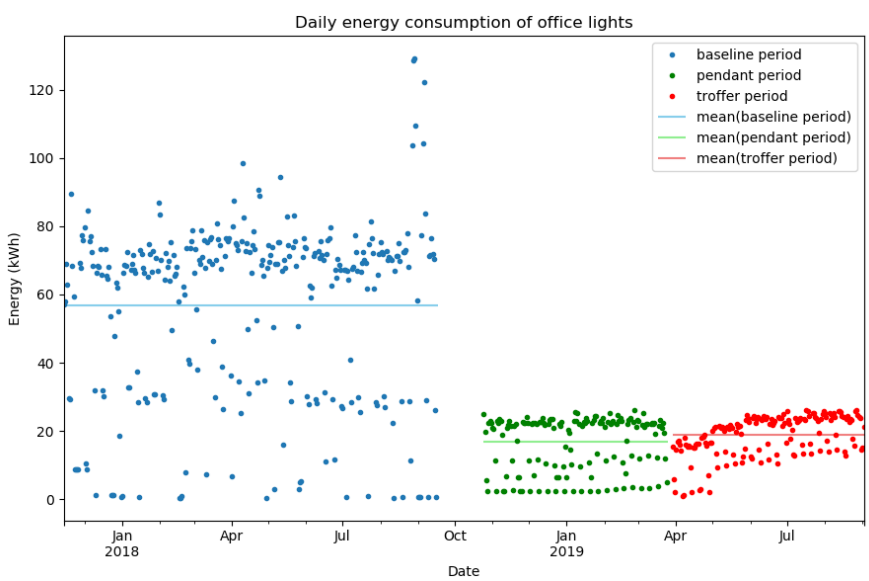


Figure 28. Daily Energy Consumption of Office Lights.

Blue dots indicate the baseline period (fluorescent lights), green dots indicate the pendant LED lighting solution, and red dots indicate the troffer LED lighting solution. Solid lines indicate the mean daily value per period. Note the significant energy savings reduction achieved by the demo systems relative to the baseline fluorescent lights.

Table 10. Summary of Energy Consumption and Savings of Pendant Lights During the Pendant Demo Period (10/25/2018 to 3/24/2019).

Pendant lighting mean daily energy consumption over pendant demo period (kWh)	Pendant lighting energy consumption over pendant demo period (kWh)	Baseline office lighting energy consumption over pendant demo period (kWh)	Energy saved by pendant lights over pendant demo period (kWh)	Pendant lighting energy savings as a percent of baseline (%)
17	2,520	8,589	6,068	**71**

Table 11. Projected Yearly Energy Consumption and Savings of Pendant Lights.

Projected yearly energy consumption of pendant lights (kWh)	Projected yearly energy savings of pendant lights (kWh)
6,096	14,680

Table 12 lists monthly energy consumption (column 2) and savings (column 4) of pendant lights compared to baseline consumption (column 3) over the pendant demo period. Monthly consumption and baseline consumption are also plotted in Figure 29.

Table 12. Monthly Totals of Pendant Lighting Demo Energy Consumption and Savings during the pendant Demo Period (10/25/2018 to 3/24/2019).

Month	Office lighting Baseline energy consumption (kWh)	Pendant lighting Demo energy consumption (kWh)	Pendant lighting Demo energy savings (kWh)
2018-10	398	120	278
2018-11	1,706	469	1,237
2018-12	1,763	480	1,283
2019-01	1,763	538	1,225
2019-02	1,592	499	1,094
2019-03	1,365	414	951

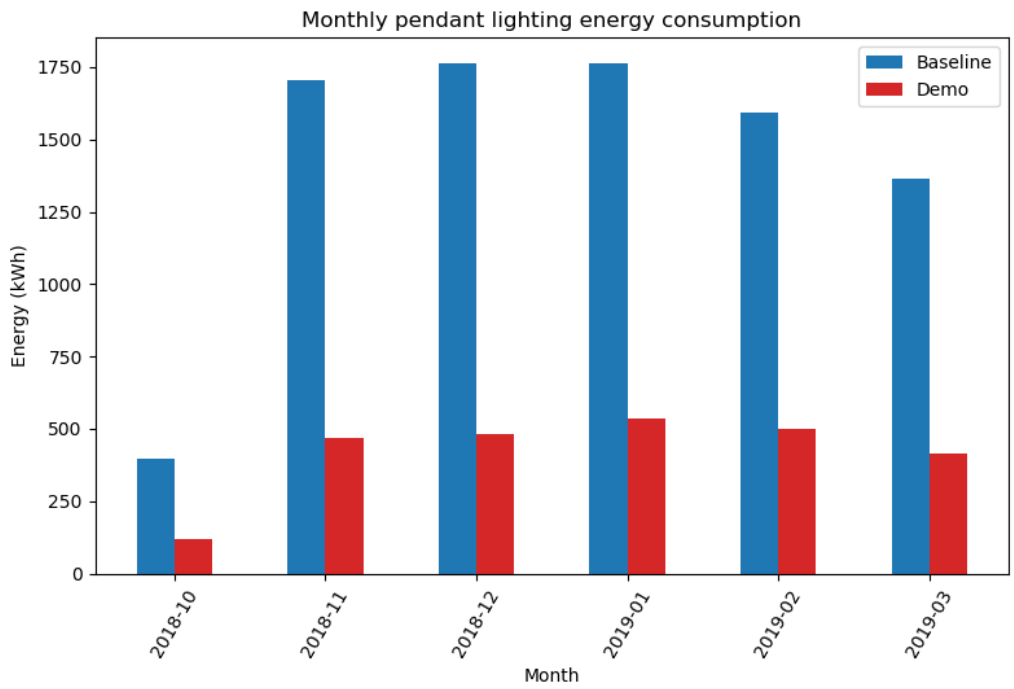


Figure 29. Plot of monthly Energy Consumption of Pendant Lighting During the Demo (Red) vs Baseline (Blue).

(Office area pendant demo period: 10/25/2018 to 3/24/2019).

Table 13 summarizes troffer lighting energy consumption and energy savings over the troffer demo period (3/29/2019 to 9/2/2019). Table 14 lists projected yearly energy savings and consumption of the troffer lighting. Table 15 lists monthly energy consumption (column 2) and savings (column 4) of troffer lights compared to baseline consumption (column 3) over the troffer demo period. Monthly consumption and baseline consumption are plotted in Figure 30.

Finally, Table 16 lists projected yearly energy consumption and energy savings of the entire demo system (high-bay + office). Results are listed separately for (high-bay + pendant lights) and (high-bay + troffer lights).

Table 13. Summary of Energy Consumption and Savings of Troffer Lights During the Troffer Demo Period (3/29/2019 to 9/2/2019).

Troffer lighting mean daily energy consumption over troffer demo period (kWh)	Troffer lighting energy consumption over troffer demo period (kWh)	Baseline office lighting energy consumption over troffer demo period (kWh)	Energy saved by troffer lights over troffer demo period (kWh)	Troffer lighting energy savings as a percent of baseline (%)
19	2,971	8,987	6,016	**67**

Table 14. Projected Yearly Energy Consumption and Savings of Troffer Lights.

Projected yearly energy consumption of troffer lights (kWh)	Projected yearly energy savings of troffer lights (kWh)
6,867	13,910

Table 15. Monthly Totals of Troffer Lighting Demo Energy Consumption and Savings During the Troffer Demo Period (3/29/2019 to 9/2/2019).

Month	Office Baseline energy consumption (kWh)	Troffer lighting demo energy consumption (kWh)	Troffer lighting energy savings (kWh)
2019-03	171	23	147
2019-04	1,706	386	1,320
2019-05	1,763	577	1,186
2019-06	1,706	607	1,100
2019-07	1,763	662	1,101
2019-08	1,763	679	1,085
2019-09	114	36	77

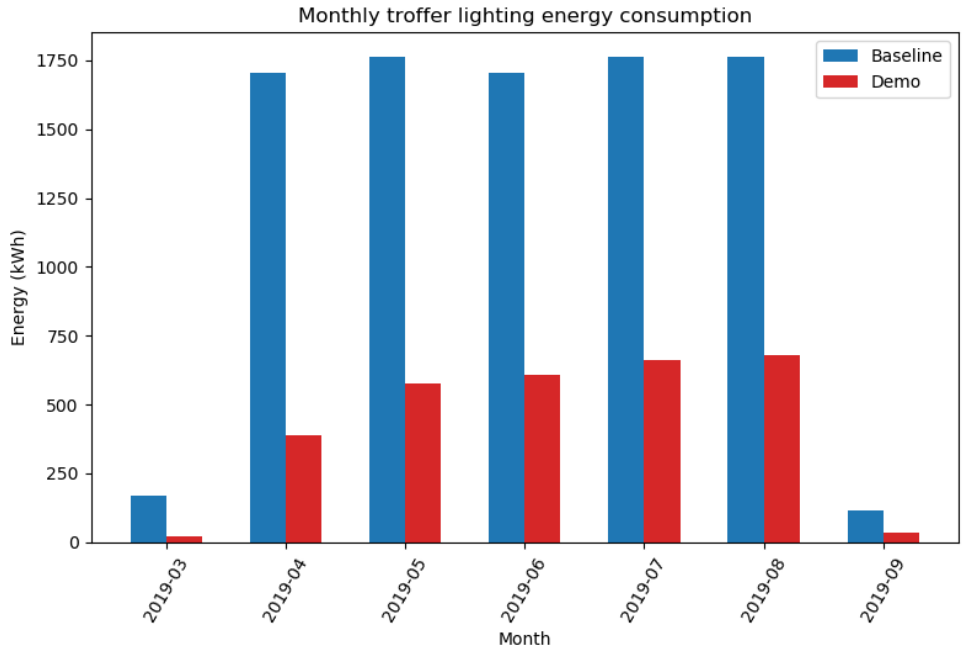


Figure 30. Plot of Monthly Energy Consumption of Troffer Lighting During the Demo (red) vs baseline (blue)

(Office area troffer demo period: 3/29/2019 to 9/2/2019).

Table 16. Projected Yearly Lighting Energy Consumption and Savings of the High-bay and Office Lighting.

Listed separately for pendants and troffer office lights.

	Projected yearly usage (kWh)	Projected yearly savings (kWh)	Projected yearly savings as percentage of baseline (%)
Total (high-bay + pendants)	36,890	82,050	69
Total (high-bay + troffers)	37,660	81,280	68

5.5.1.2 Energy savings breakdown analysis:

This section quantifies the contributions to the energy savings of the lighting demo from different sources, such as savings from occupancy control of lights and from daylight harvesting. In this section, we compare the energy consumption and savings to the hypothetical energy consumption that would occur if the LED lights in the demo system were run 24 hours per day, without occupancy control or daylight harvesting. We term this the *always-on baseline,* as it is the energy consumption that would occur if the lights were always on, without dimming. (This is different from baselines discussed in previous sections.) Energy savings from occupancy and daylight harvesting are expressed relative to this always-on baseline. We separately analyzed the high-bay demo system as well as the office area pendant and troffer systems.

Figure 31 plots the power over time of one high-bay sensor, as reported by the Enlighted system at a 5-minute frequency. The red line is the 99th quantile of power measurements, which we used as a robust estimate of peak energy consumption of the light fixture. Similar estimates are computed for each fixture and summed to estimate the always-on baseline of the demo system. (See Section 1.1.1.1.3 for details.)

Figure 32 plots energy use and savings of the high-bay lighting demo system over a 2-week period, broken down into consumption (red bars) and savings from occupancy control (blue bars). The top graph expresses energy in kWh, while the bottom graph expresses energy as a percent of the always-on baseline. Table 17 summarizes high-bay energy consumption (column 2) and occupancy savings (column 4), as well as the always-on baseline (column 3): row 2 lists the mean daily values over the high-bay demo period, row 3 lists the totals over the high-bay demo period, and row 4 lists the projected yearly totals. Table 18 lists the high-bay lighting energy consumption and occupancy savings as percentages of the always-on baseline.

Figure 33 illustrates a correlation between energy savings from daylight harvesting in the office area (blue curve, left axis), and sky clarity (expressed as the mean percentage of the sky unobstructed by clouds, between 7am and 5pm) – red curve, right axis. This illustrates daylight harvesting achieved greater energy savings on days with clearer skies, as expected.

Figure 34 plots energy use and savings of the pendant lighting system over a 2-week period, broken down into consumption (red bars), daylight harvesting savings (green bars), and occupancy savings. The top graph expresses energy in kWh, while the bottom expresses energy as a percent of the always-on baseline. Table 19 summarizes pendant energy consumption (column 2) and occupancy savings (column 4), as well as the always-on baseline (column 3):

row 2 lists the mean daily values over the pendant demo period, row 3 lists totals over the pendant demo period, and row 4 lists the projected yearly totals. Table 20 lists the pendant lighting energy consumption, daylight harvesting savings, and occupancy control savings as percentages of the always-on baseline.

Figure 35 shows the same quantities as in Figure 34, but only lights immediately adjacent to exterior-facing windows are included. Similarly, Table 21 and Table 22 report the same quantities as Table 19 and Table 20, but only lights along windows are included in the calculation. As expected, savings from daylight harvesting is greater (as a percent of the always-on baseline) for lights along the windows than for the office as a whole.

Figure 36 breaks down energy use and savings of the troffer lights over a two-week period (similar to Figure 34 for pedants), and Table 23 and

Table 24 summarize results over the troffer demo system (similar to Table 19 and Table 20 for pendants). Figure 37, Table 25, and Table 26 repeat the analysis but only include troffer lights immediately adjacent to exterior windows. As expected, troffer lights along the windows achieve a relatively larger savings from daylight harvesting.

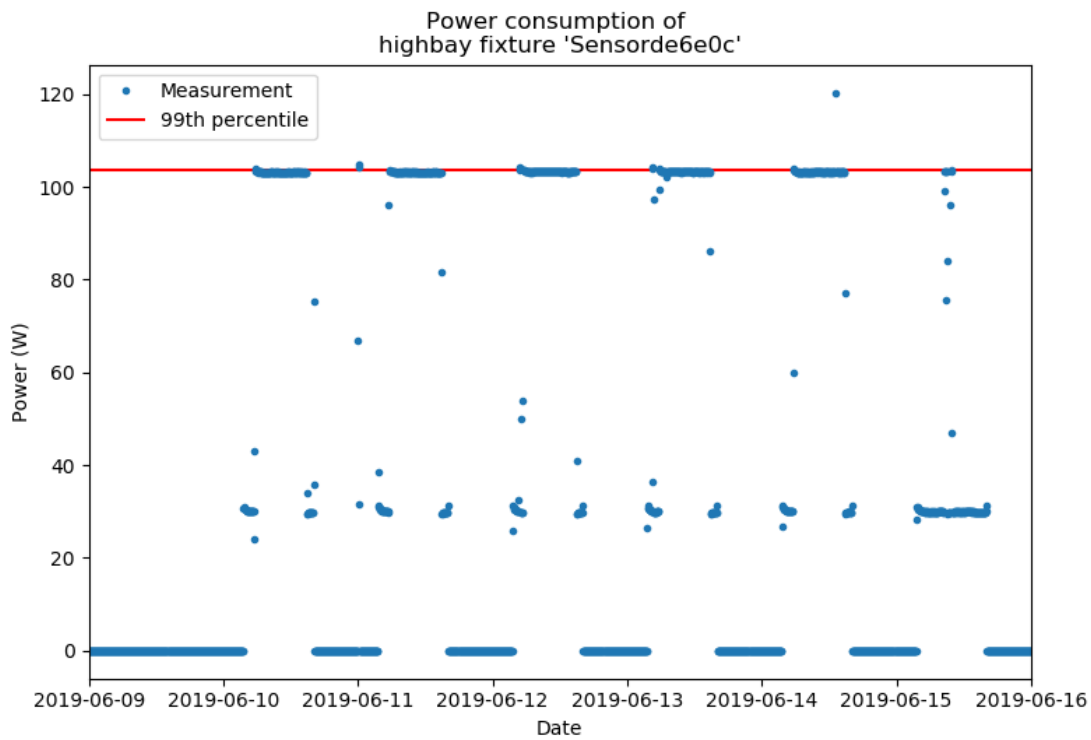


Figure 31. Blue Dots Show Power Usage of One High-bay Fixture (over 5 min. intervals) as Measured by the Enlighted System.

The red line is the 99th percentile of power measurements. Note there is one outlier reading near 120W on 6/14/2019.

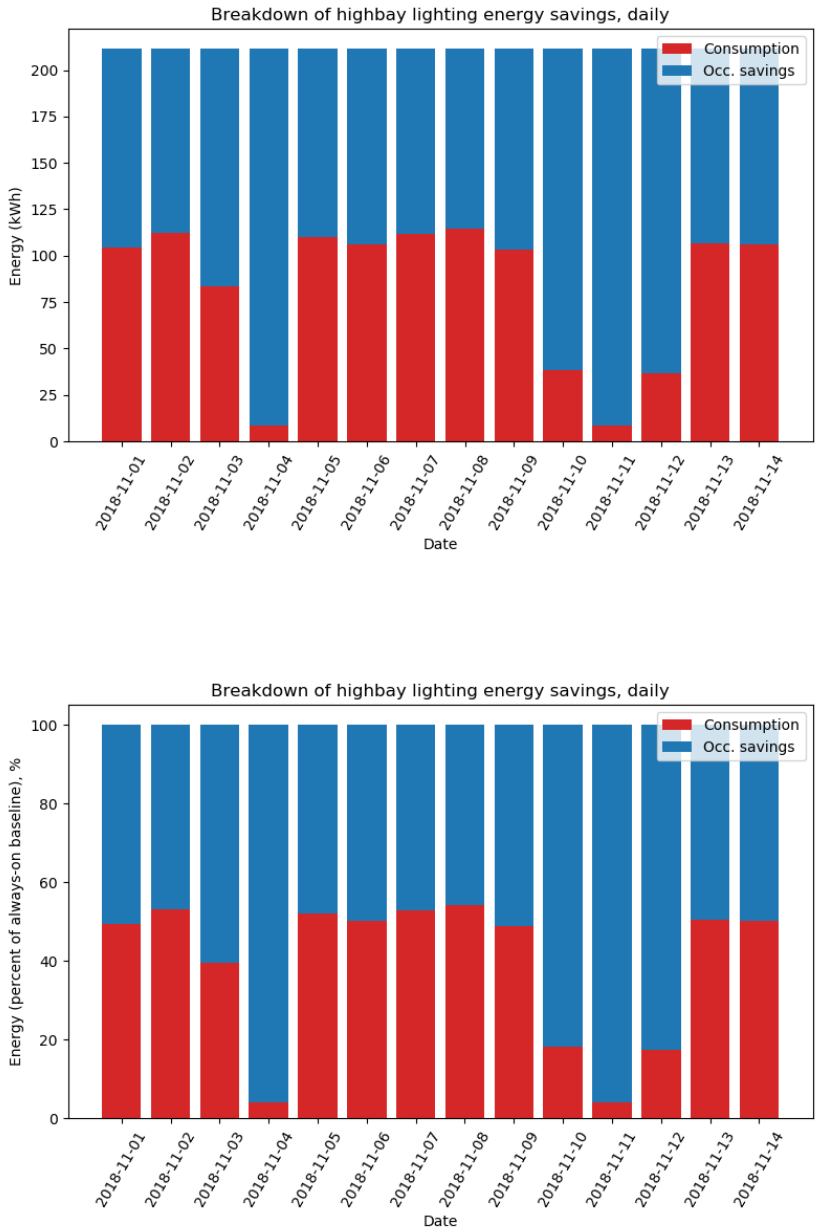


Figure 32. A Breakdown of High-bay Lighting Energy Consumption and Savings.

Red bars indicate energy consumption. Blue bars indicate savings due to occupancy. Top figure: energy in kWh. Bottom figure: energy as a percent, relative to the always-on baseline (assuming LED lights ran 24 hours per day).

Table 17. Energy Consumption (Column 2) and Occupancy-based Savings (Column 4) of the High-bay Demo System during the High-bay Demo Period.

Energy consumption is measured by Enlighted system. (This explains the small differences compared to values in Table 2, which was based on Dent logger measurements.)

	High-bay lighting energy consumption (kWh) (as measured by the Enlighted system)	High-bay lighting always-on baseline energy consumption (kWh)	High-bay lighting occupancy-based savings (kWh), relative to always-on baseline
Mean daily value	**83**	**212**	**128**
Total over high-bay demo period	**26,060**	**66,210**	**40,150**
Projected yearly total	**30,400**	**77,260**	**46,850**

Table 18. High-bay Lighting Energy Consumption and Occupancy-based Savings.

(Totals over entire high-bay demo period, listed as a percentage of the always-on baseline energy usage.)

High-bay lighting energy consumption as % of always-on baseline	High-bay lighting occupancy-based savings as % of always-on baseline
39	61

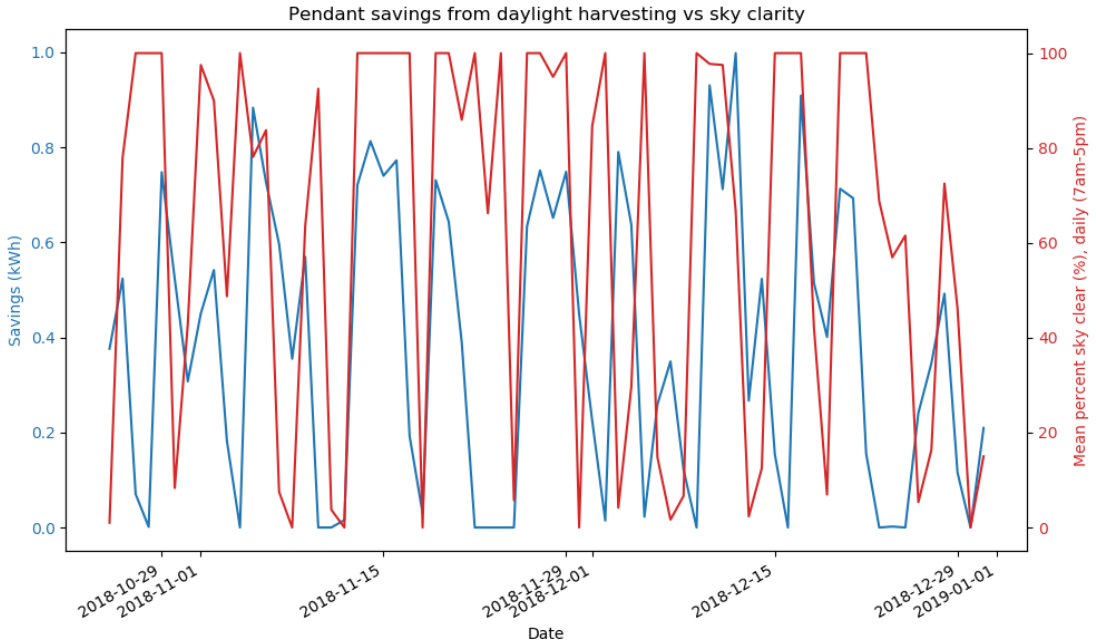


Figure 33. Graphing the Correlation Between Daily Energy Savings from Daylight Harvesting (Blue Line, Left Axis) of Office Pendant Lights, vs Mean Percentage of the Sky That Is Clear Between 7am and 5pm (Red Line, Right Axis).

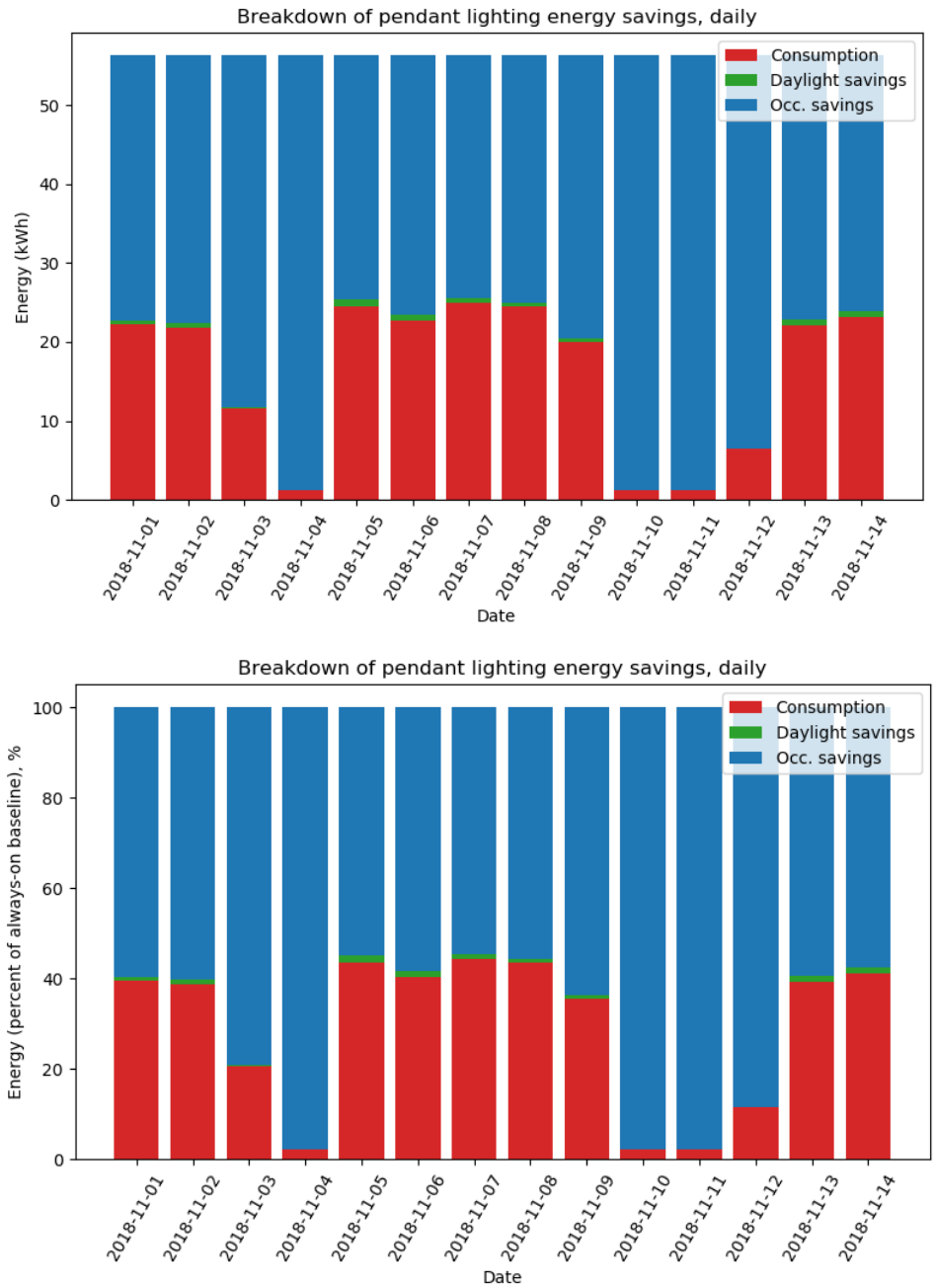


Figure 34. A Breakdown of Office Pendant Lighting Energy Consumption and Savings. Red Bars Indicate Energy Consumption.

Green bars indicate savings due to daylight harvesting. Blue bars indicate savings due to occupancy. Top figure: energy in kWh. Bottom figure: energy as a percent, relative to the always-on baseline (assuming LED lights ran 24 hours per day).

Table 19. Energy Consumption (Column 2) and Energy Savings from Daylight Harvesting (Column 4) and Occupancy (Column 5) of the Pendant Demo System during the Pendant Demo Period.

Energy consumption is measured by Enlighted system. (This explains the small differences compared to values in Table 5, which was based on Dent logger measurements.)

	Pendant lighting energy consumption (kWh)	Pendant lighting always-on baseline energy consumption (kWh)	Pendant lighting savings from daylight harvesting (kWh)	Pendant lighting occupancy-based savings (kWh), relative to always-on baseline
Mean daily value	18	56	0.47	38
Total over pendant demo period	2,643	8,513	71	5,800
Projected yearly total	6,392	20,590	171	14,040

Table 20. Pendant Lighting Energy Consumption and Occupancy-based Savings, as a Percent of the Always-on Baseline Energy Usage.

Pendant lighting energy consumption as % of always-on baseline	Pendant daylight harvesting savings as % of always-on baseline	Pendant lighting occupancy-based savings as % of always-on baseline
31	0.83	68

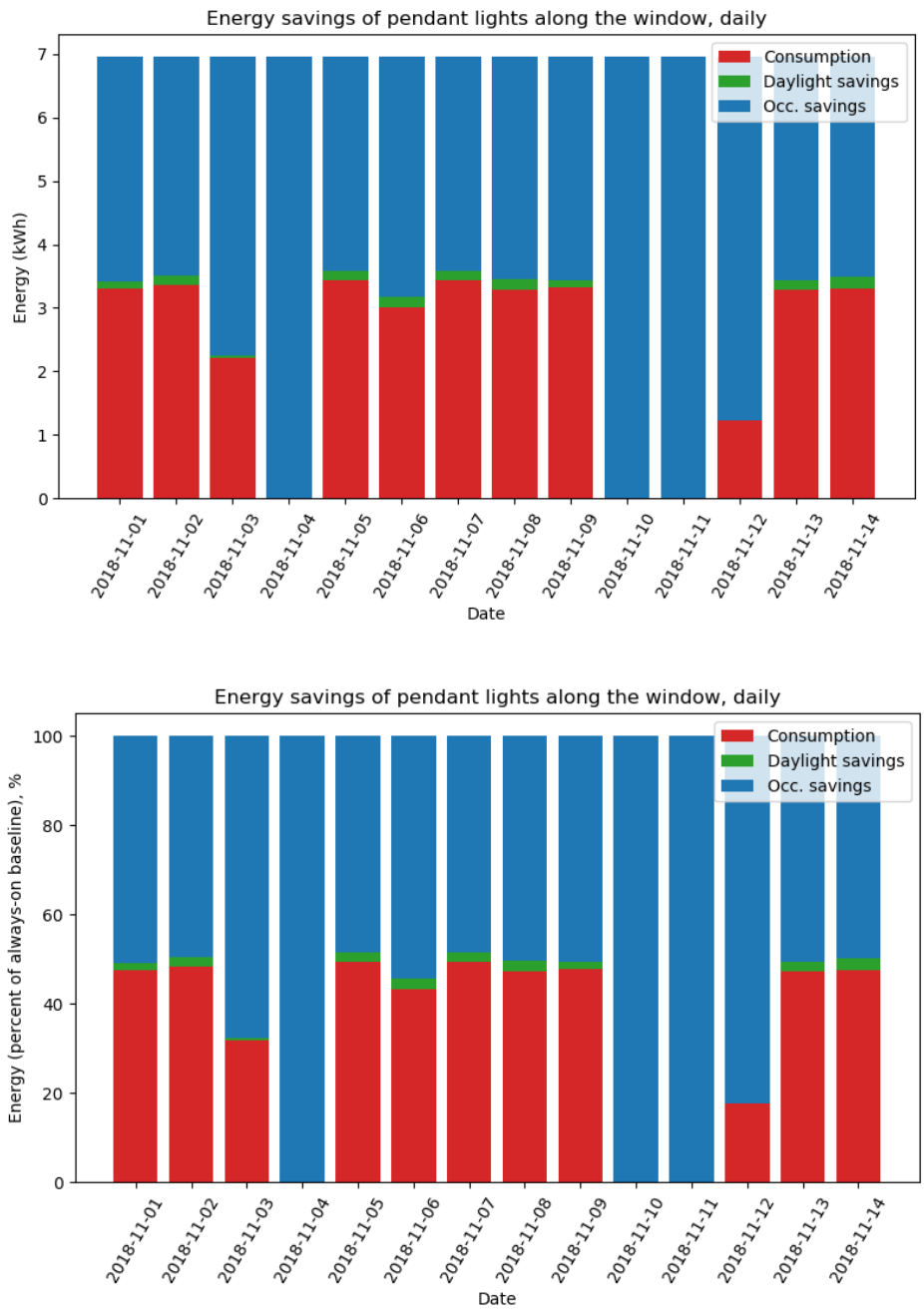


Figure 35. This Is a Breakdown of Office Pendant Lighting Energy Consumption and Usage, Similar to Figure 34, but These Plots Only Include Fixtures Immediately Adjacent to Windows, Whereas Figure 34 Includes all Fixtures in the Office Area.

Note that the savings from daylight harvesting (as a percentage) are larger in these plots than in Figure 34. This confirms savings from daylight harvesting were greater for fixtures next to windows.

Table 21. This Summarizes Energy Savings and Consumption of Pendant fixtures, Similar to Table 14, But This Table Only Includes Fixtures Immediately Adjacent to the Windows.

	Pendant lighting energy consumption (kWh)	Pendant lighting always-on baseline energy consumption (kWh)	Pendant lighting savings from daylight harvesting (kWh)	Pendant lighting occupancy-based savings (kWh), relative to always-on baseline
Mean daily value	2.5	6.9	0.14	4.4
Total over pendant demo period	371	1,051	21	659
Projected yearly total	898	2,542	50	1,595

Table 22. This Summarizes Pendant Lighting Energy Consumption and Occupancy-based Savings As A Percent of the Always-on Baseline Energy Usage, Similar to Table 15, But This Table Only Includes Fixtures Immediately Adjacent To The Windows.

Pendant lighting energy consumption as % of always-on baseline	Pendant daylight harvesting savings as % of always-on baseline	Pendant lighting occupancy-based savings as % of always-on baseline
35	2	63

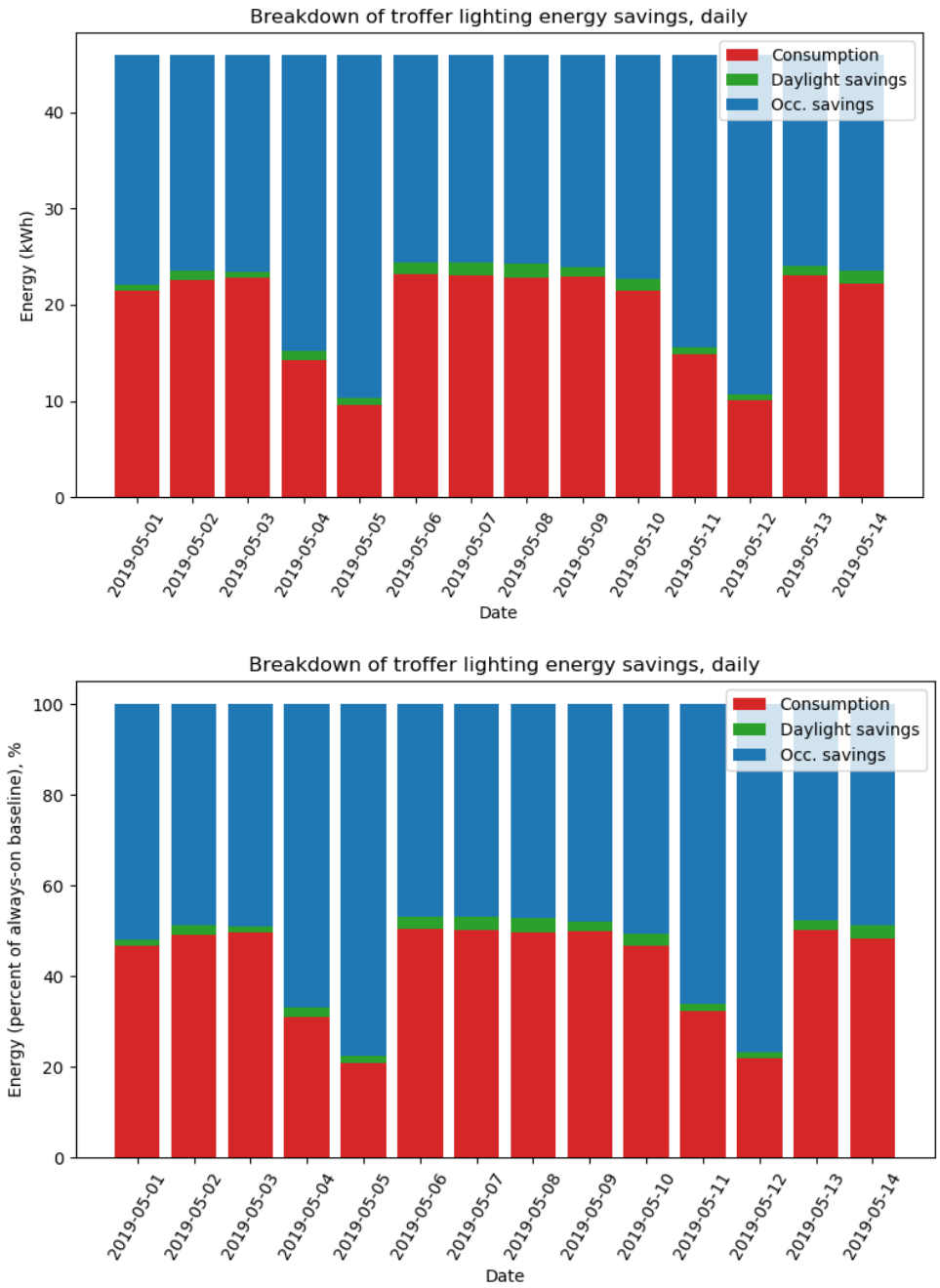


Figure 36. A Breakdown of Office Troffer Lighting Energy Consumption and Savings.

Red bars indicate energy consumption. Green bars indicate savings due to daylight harvesting. Blue bars indicate savings due to occupancy. Top figure: energy in kWh. Bottom figure: energy as a percent, relative to the always-on baseline (assuming LED lights ran 24 hours per day).

Table 23. Energy Consumption (Column 2) and Energy Savings from Daylight Barvesting (Column 4) and Occupancy (Column 5) of the Troffer Demo System During the Troffer Demo Period.

Energy consumption is measured by Enlighted system. (This explains the small differences compared to values in Table 8, which was based on Dent logger measurements.)

	Troffer lighting energy consumption (kWh)	Troffer lighting always-on baseline energy consumption (kWh)	Troffer lighting savings from daylight harvesting (kWh)	Troffer lighting occupancy-based savings (kWh), relative to always-on baseline
Mean daily value	20	46	1.12	24.59
Total over troffer demo period	3,200	7,262	177	3,885
Projected yearly total	7,398	16,790	409	8,981

Table 24. Troffer Lighting Energy Consumption and Occupancy-based Savings, as a Percent of the Always-on Baseline Energy Esage.

Troffer lighting energy consumption as % of always-on baseline	Troffer daylight harvesting savings as % of always-on baseline	Troffer lighting occupancy-based savings as % of always-on baseline
44	2	54

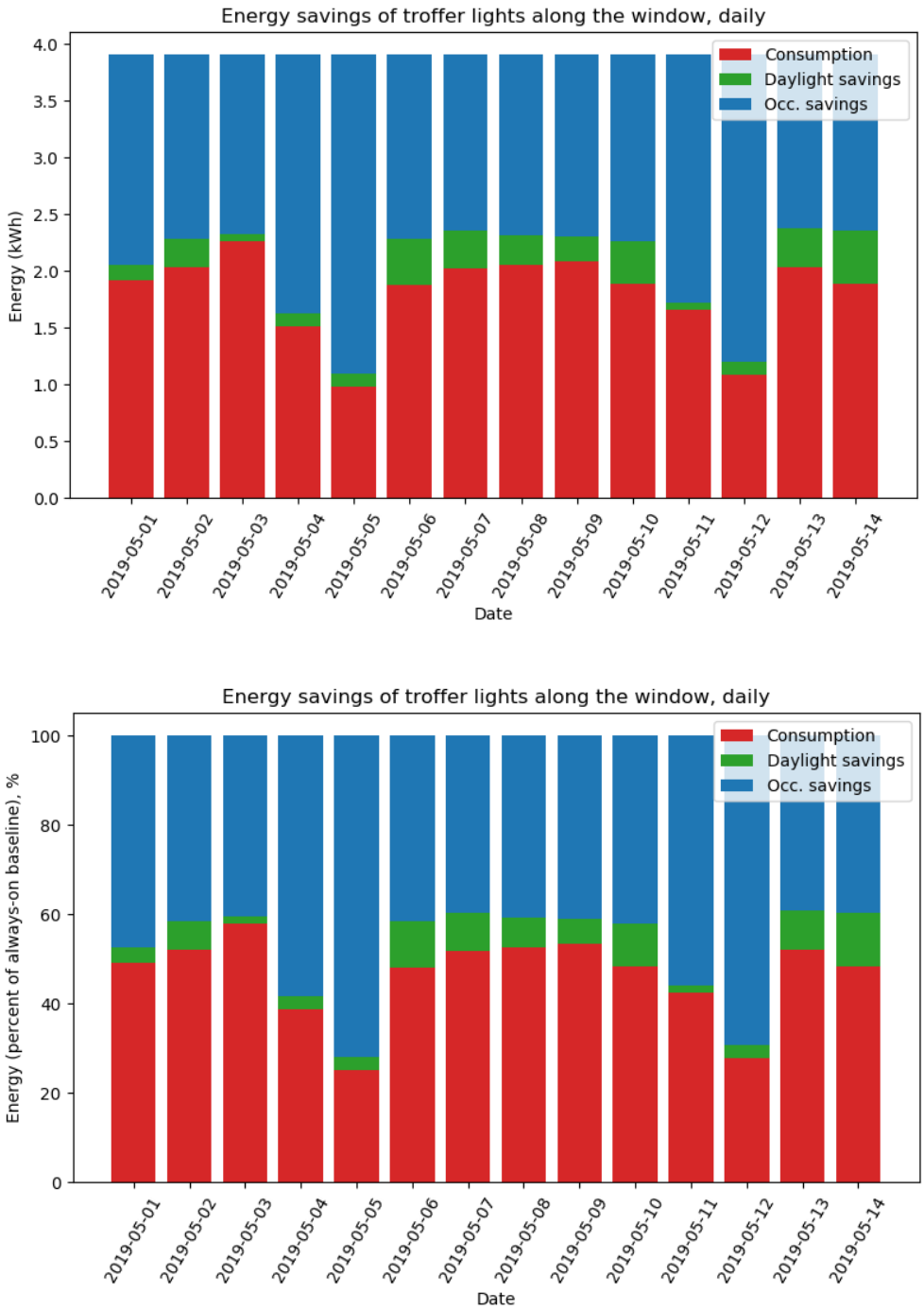


Figure 37. This Is A Breakdown of Office Troffer Lighting Energy Consumption and Usage, Similar to Figure 36, But These Plots Only Include Fixtures Immediately Adjacent to Windows, Whereas Figure 36 Includes All Fixtures In the Office Area.

Note that the savings from daylight harvesting (as a percentage) are larger in these plots than in Figure 36. This confirms savings from daylight harvesting were greater for fixtures next to windows.

Table 25. This Summarizes Energy Savings and Consumption of Troffer Fixtures, Similar to Table 18, But This Table Only Includes Fixtures Immediately Adjacent to the Windows.

	Troffer lighting energy consumption (kWh)	Troffer lighting always-on baseline energy consumption (kWh)	Troffer lighting savings from daylight harvesting (kWh)	Troffer lighting occupancy-based savings (kWh), relative to always-on baseline
Mean daily value	1.6	3.9	0.24	2
Total over troffer demo period	252	617	38	326
Projected yearly total	584	1,427	88	755

Table 26. This Summarizes Troffer Lighting Energy Consumption and Occupancy-based Savings as A Percent of the Always-on Baseline Energy Usage, Similar to Table 19, But This Table Only Includes Fixtures Immediately Adjacent to the Windows.

Troffer lighting energy consumption as % of always-on baseline	Troffer daylight harvesting savings as % of always-on baseline	Troffer lighting occupancy-based savings as % of always-on baseline
41	6	53

5.5.2 PO2: HVAC Energy Usage

This section summarizes HVAC energy usage data. Section 5.5.2.1 contains information about the efficiencies of the chillers and boilers in Building 3907. Section 5.5.2.2 summarizes measured energy consumption at the AHUs, and Section 5.5.2.3 summarizes the impact of weather on AHU energy consumption. Sections 5.5.2.4 and 5.5.2.5 summarize energy consumption of the high-bay and office areas. Finally, 5.5.2.6 lists projected yearly HVAC energy consumption and savings.

5.5.2.1 Efficiency of boilers and chillers

In this section, we list the efficiencies of the boilers and chillers that serve the office and high-bay areas. Efficiencies are needed to compute energy consumed (e.g. by the boiler or chiller) based on energy consumption measured by BTU meters at the air handling units.

The efficiencies listed in this section were taken from the design drawings of Building 3907. For both chillers and boilers, we define *efficiency* as (output energy)/(input energy).

Building 3907 has three natural gas-powered boilers. All three are the same model (BMK 2) made by AERCO. According to the building design drawings, the efficiency of each boiler is 0.86, meaning 86% of the energy released by burning natural gas is transferred into heating water. (The rest is lost, e.g., in vented combustion exhaust.)

Building 3907 has two centrifugal York chillers, both model YKM2M4K1-CBG. According to the building design drawings, each chiller has a coefficient of performance (COP) of 5.784, meaning for each unit of electrical energy consumed, 5.784 units of thermal cooling energy is delivered. The efficiencies are summarized in Table 27.

Table 27. Efficiency of the Boilers and Chillers in Building 3907.

Chiller efficiency (coefficient of performance)	5.784
Boiler efficiency	0.86

5.5.2.2 Energy consumption of Air Handling Units (AHUs)

In this section, we report HVAC energy consumption measured at the air handling units. Two air handling units serviced the two demo areas: AHU 101 served the high-bay area and AHU 202 served the office area. However, neither AHU exclusively served the demo areas. Rather, each AHU supplied airflow to areas outside of the demonstration zones, in addition to supplying the demo zones. In this section, for completeness, we report raw energy consumption data measured at each AHU. In subsequent sections, we report energy data specific to the demo areas only.

Figure 38 shows the daily chilled water load for AHU 101, which is the thermal cooling energy delivered to AHU 101 via cold water pipe from the chillers. Quantities were measured by a BTU meter installed at AHU 101. (Note that the cooling load is measured for the entire AHU, and AHU 101 serves both the high-bay demonstration area and other rooms outside of the demo area. Hence, the energy consumption shown is greater than the energy use by the high-bay demo area alone.) Energy is reported in kBTU. Red dots show energy consumption on days when the occupancy-based HVAC control feature was enabled. Blue dots (baseline) show energy consumption on days when occupancy-based HVAC control was disabled. Note that occupancy control reduced energy consumption. Chilled water loads are plotted starting March 6, 2019, because there was a programming error in the controller which communicated BTU meter data to the EBI server. This caused incorrect values for BTU meter data to be reported before March 6.

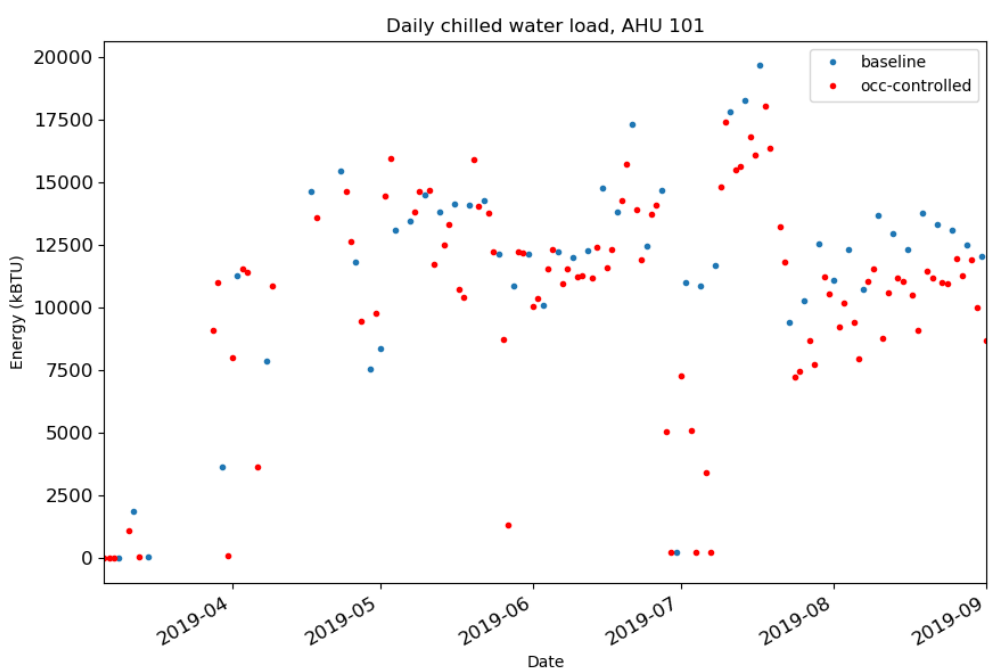


Figure 38. This Plots the Amount of Cooling Energy Consumed by AHU 101 Per Day, Which Is Measured by a BTU Meter on the Chilled Water Coil at the Air Handler.

Figure 39 plots the daily energy consumption of the supply fan on AHU 101, as measured by an electricity meter connected to the supply fan. (Note that the supply fan delivered air to both the high-bay demo area and rooms outside of the demo.) Note that AHU 101 has no return fan. Red dots show energy consumption on days when the occupancy-based HVAC control feature was enabled. Blue dots (baseline) show energy consumption on days when occupancy-based HVAC control was disabled. We are not completely clear what caused the dramatic drop in fan energy consumption in late July, but technicians on site told us that maintenance was performed on AHU 101 around this time, including replacement of the air filter. We note that airflow did not significantly decrease after later July, so the maintenance evidently made the supply fan more efficient.

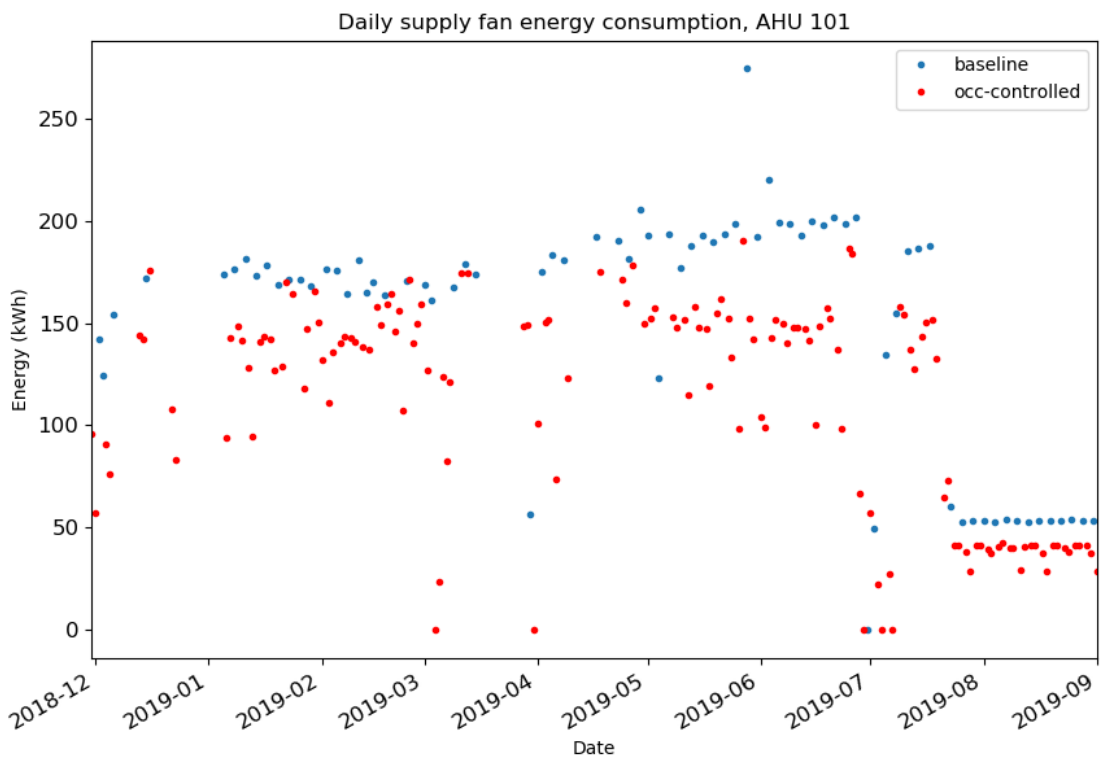


Figure 39. Daily Energy Consumption of the Supply Fan in AHU 101.

This is measured via an electricity meter connected to the supply fan.

Figure 40 plots the daily chilled water load (the amount of cooling energy consumed) by AHU 202, as measured by a BTU meter installed at AHU 202. (Note that the cooling load is measured for the entire AHU, and AHU 202 serves both the office demonstration area and other rooms outside of the demo area. Hence, the energy consumption shown is greater than the energy use by the office demo area alone.) Reported in kBTU. Red dots are days when occupancy-based HVAC control was enabled, and blue dots (baseline) are days when occupancy-based HVAC control was disabled.

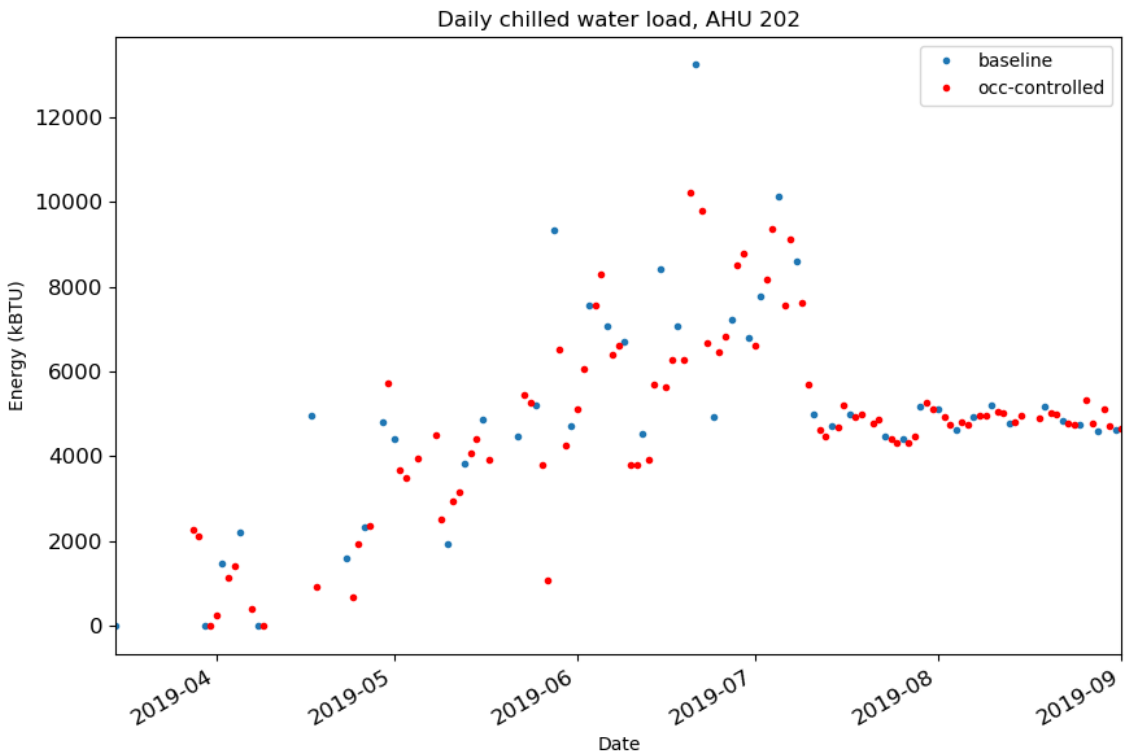


Figure 40. This Plots the Amount of Cooling Energy Consumed by AHU 202 Per Day, Which Is Measured by a BTU Meter on the Chilled Water Coil at the Air Handler.

Figure 41 shows the daily energy consumption of the supply fan on AHU 202, as measured by an electricity meter connected to the supply fan. (Note that the supply fan delivered air to both the office demo area and rooms outside of the demo area.) Red dots are days when occupancy-based HVAC control was enabled, and blue dots (baseline) are days when occupancy-based HVAC control was disabled. There is a large decrease in supply fan energy consumption in early July. This coincides with replacement of AHU 202's return fan and an increase in the return fan's speed by technicians on site, as well as other AHU maintenance. We believe the increased speed of the return fan caused it to do more work blowing air, which in turn caused the supply fan to do less work, which may in part explain the decrease in supply fan energy consumption in July. We are uncertain why the occupancy savings of the supply fan decreased starting in July, but we note that occupancy savings of the return fan was larger in that period.

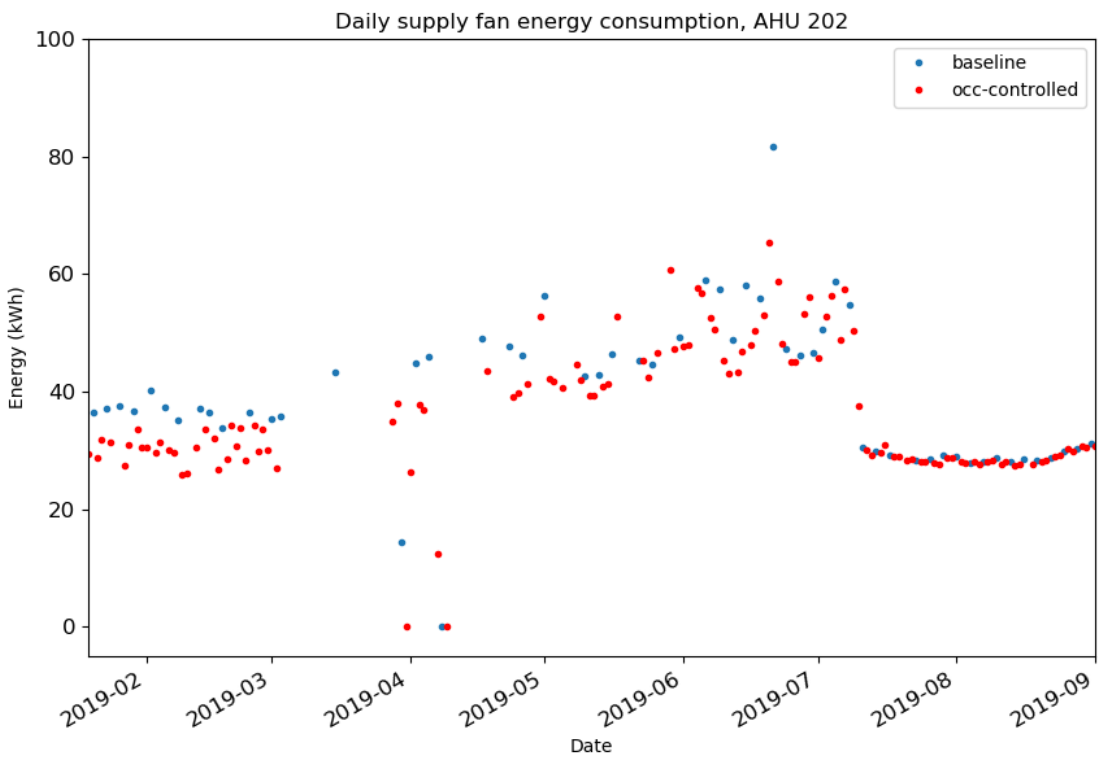


Figure 41. Daily Energy Consumption of the Supply Fan in AHU 202.

This is measured via an electricity meter connected to the supply fan.

Figure 42 plots the daily energy consumption of the return fan on AHU 202, as measured by an electricity meter connected to the fan. (Note that the return fan delivered air to both the office demo area and rooms outside of the demo area.) The return fan **broke in April**, which explains the long period of minimal energy consumption. In early July, the return fan was **replaced**, and technicians on-site placed the fan into manual override mode increased its speed. This explains the greater energy consumption after July compared to February and March. Red dots are days when occupancy-based HVAC control was enabled, and blue dots (baseline) are days when occupancy-based HVAC control was disabled.

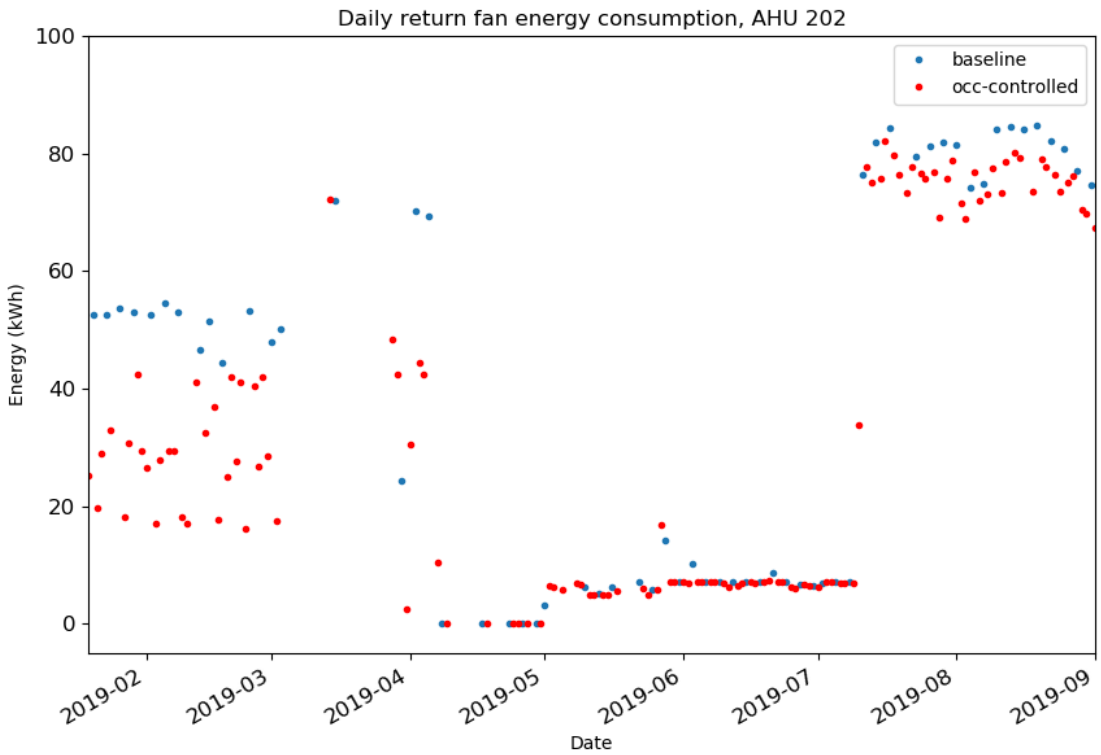


Figure 42. Daily Energy Consumption of the Return Fan in AHU 202.

This is measured via an electricity meter connected to the return fan.

Figure 43 compares the AHU 101 chilled water load measured by BTU meter (our primary measurement method) to chilled water energy consumption calculated using a physics formula and measurements of airflow and enthalpy (our backup method). The backup method is expected to be less accurate due to limited accuracy of airflow measurements. This figure is included as a consistency check between methods. The blue curve shows daily chilled water load of AHU 101 (in units of kBTU), as measured by the BTU meter on the chilled water coil. The red curve computes the same quantity (total AHU 101 chilled water load) using a physics formula and measurements of AHU 101's total airflow, supply air enthalpy, and mixed air enthalpy. The shapes of the curves are quite consistent in June, which is a good check that the BTU meter measurements are reasonable. We note that airflow meters were not as precisely calibrated for AHU 101 as for 202 (which were calibrated with a station hood). Also, we suspect enthalpy measurements in AHU 101 may have been off. Together, these may explain the disagreements between the curves.

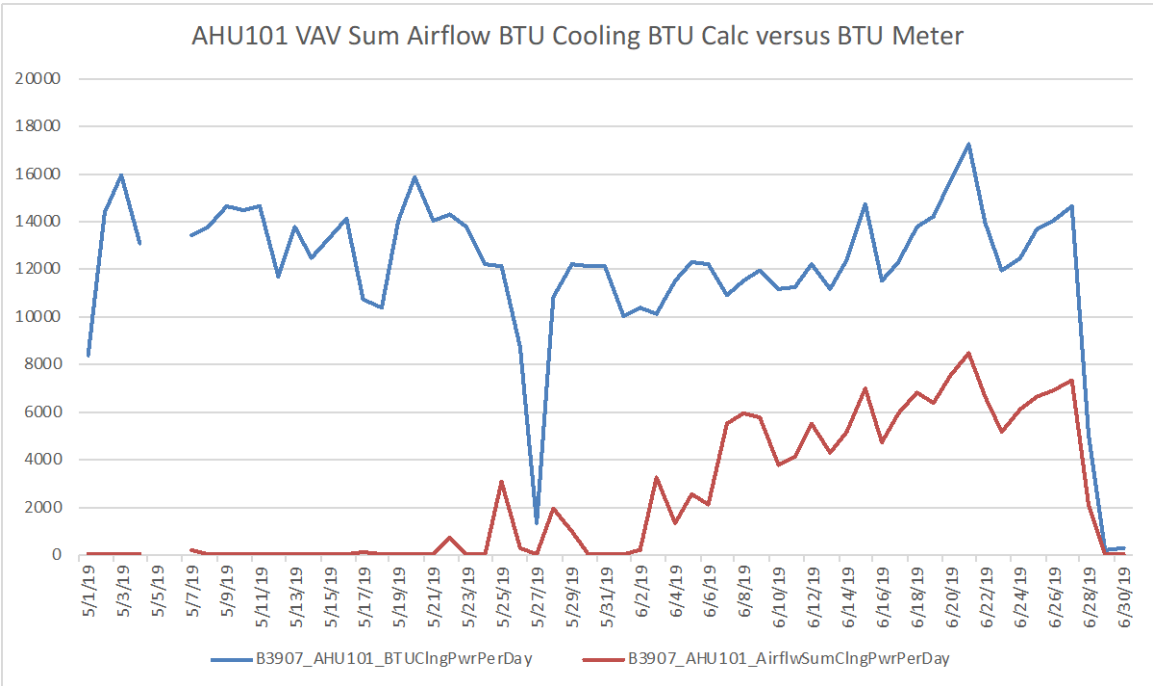


Figure 43. Comparison of Our Primary Measurement of AHU 101's Chilled Water Load (Blue Curve), Made by a BTU meter on the AHU's Chilled Water Coil, Against Our Secondary Measurement (Red).

The secondary measurement used airflow and enthalpy measurements to compute the chilled water load with a physics formula. Shown in units of kBTU.

Figure 44 compares the AHU 202 chilled water load measured by BTU meter (our primary measurement method) to chilled water energy consumption calculated using a physics formula and measurements of airflow and enthalpy (our backup method). The backup method is included to verify the BTU meter's measurements. The green curve shows daily chilled water load of AHU 202 (in units of kBTU), as measured by the BTU meter on the chilled water coil. The red and blue curves compute the same quantity (total chilled water load) using a physics formula and measurements of AHU 202 total airflow, supply air enthalpy, and mixed air enthalpy. Note the blue curve was computed using airflow station measurements at the AHU, while for the red curve the total airflow was computed by summing airflows through all connected VAVs. The three curves have excellent agreement, which is a good consistency check that the BTU meter's measurements were accurate. We note that for AHU 202, the airflow measurements were precisely calibrated with a station hood, which may explain why AHU 202's measurements are more consistent than AHU 101.

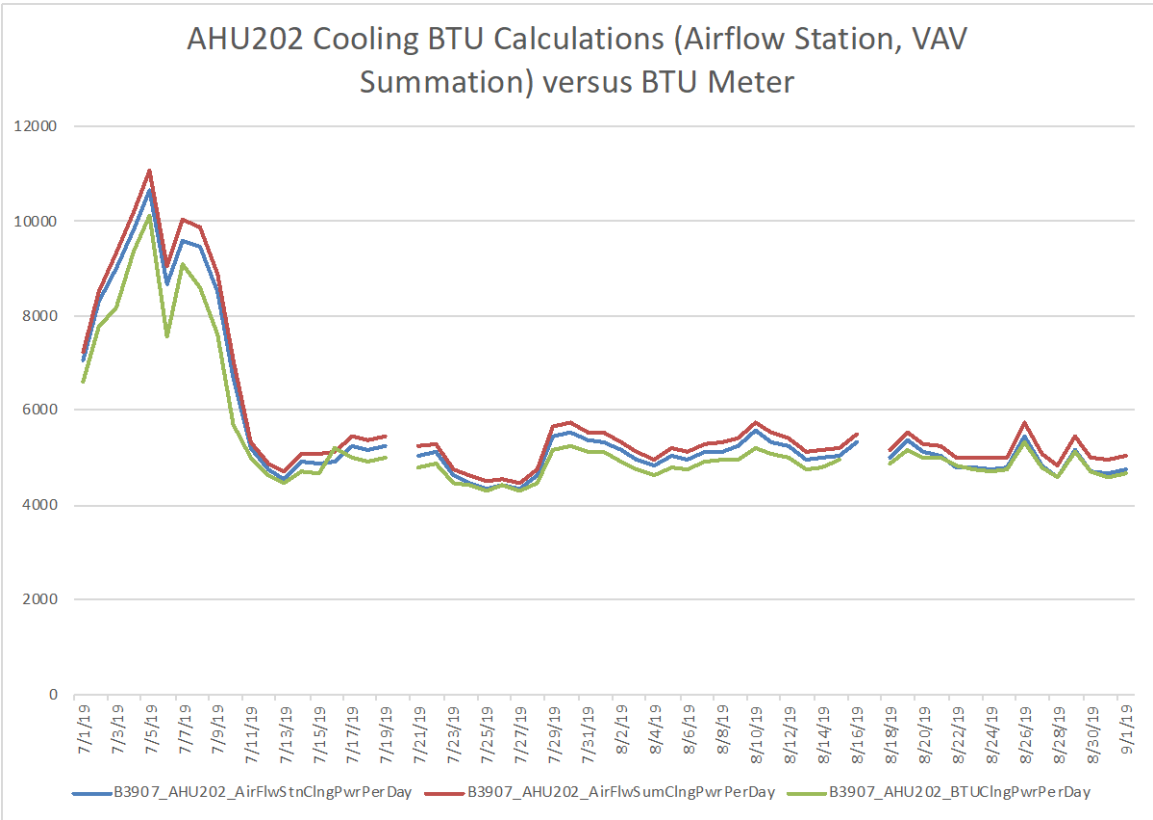


Figure 44. Comparison of Several Measurements of AHU 101's Chilled Water Load.

The green curve shows measurements by a BTU meter on the AHU's chilled water coil (our primary measurement). The red and blue curves are backup measurements, computed with a physics formula using measurements of airflow and enthalpy. Shown in units of kBTU. Blue curve used airflow station measurements at the AHU, red curve computed total airflow by summing airflows through all connected VAVs.

5.5.2.3 Influence of weather on AHU energy consumption

In this section, we show the influence of weather on AHU energy consumption. We plot daily energy consumption (from the graphs in the previous section) vs the *degree days*, which quantify outside weather conditions for each day. Degree days are computed as $(T_{mean} - 65F)$, where T_{mean} is the mean value of the daily high and low temperature. In the graphs in this section, blue dots show energy consumption on baseline days (without occupancy-based control), and red dots show energy consumption on occupancy-controlled days.

In general, we find weather had little correlation to energy consumption. We believe this may be explained by the various mechanical issues with the HVAC components of AHU 101 and 202, such as broken fans, stuck valves, and equipment in manual override mode. In the plots in this section, we include data from Mar. 6, 2019 – Sept. 1, 2019.

Figure 45 shows the daily chilled water load consumed by AHU 101 vs degree days. From the figure, it appears there was little correlation between cooling energy and outside temperature. It is clear from the figure that occupancy control reduced energy consumption.

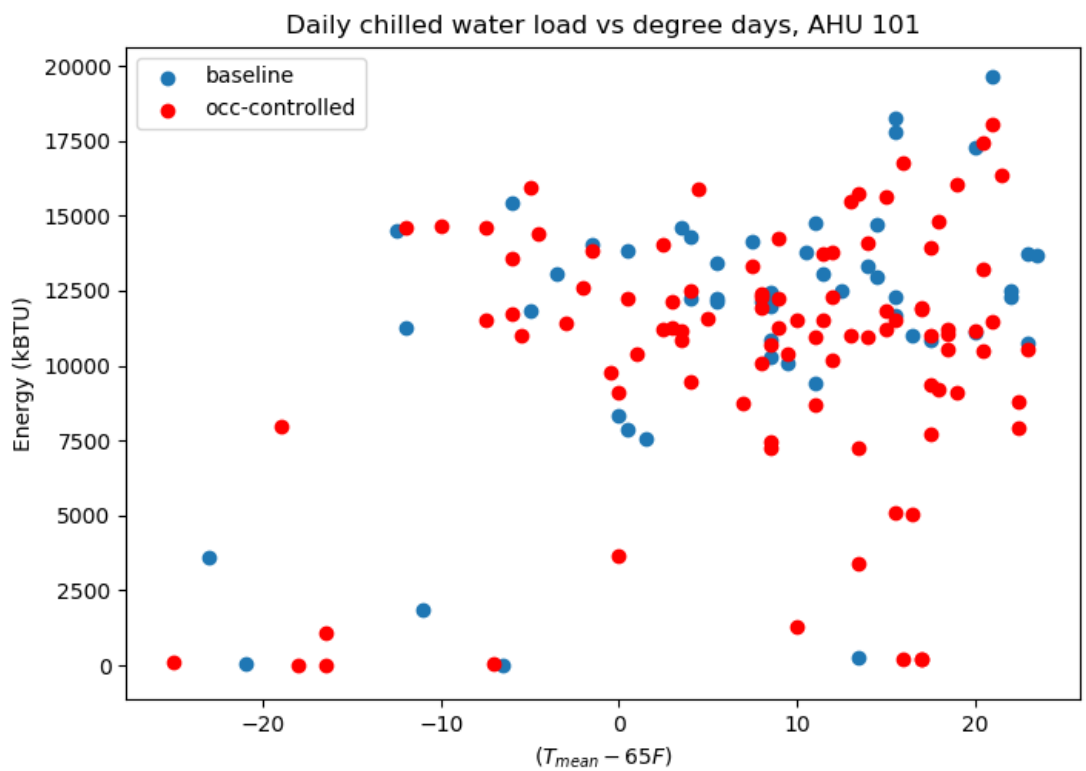


Figure 45. Daily Chilled Water Load of AHU 101 vs Degree Days $(T_{mean} - 65F)$, Which Quantifies Daily Outside Weather Temperatures.

Figure 46 shows the daily energy consumption of the supply fan in AHU 101 vs degree days. From the figure, it appears there was little correlation between cooling energy and outside temperature. It is clear from the figure that occupancy control reduced energy consumption.

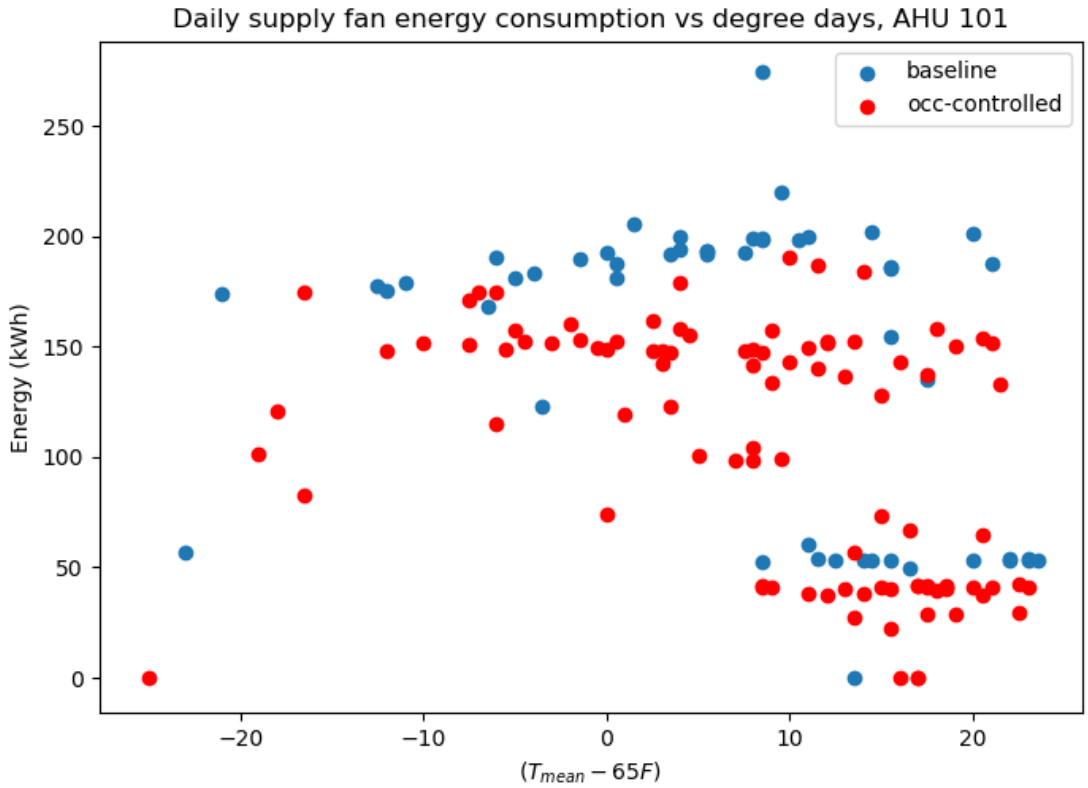


Figure 46. Daily Energy Consumption of the Supply Fan in AHU 101, vs Degree Days ($T_{mean} - 65F$), Which Quantifies Daily Outside Weather Temperatures.

Figure 47 shows the daily chilled water load consumed by AHU 202 vs degree days. From the figure, it appears there was a modest correlation between cooling energy consumption and degree days. It is clear that occupancy control reduced energy consumption.

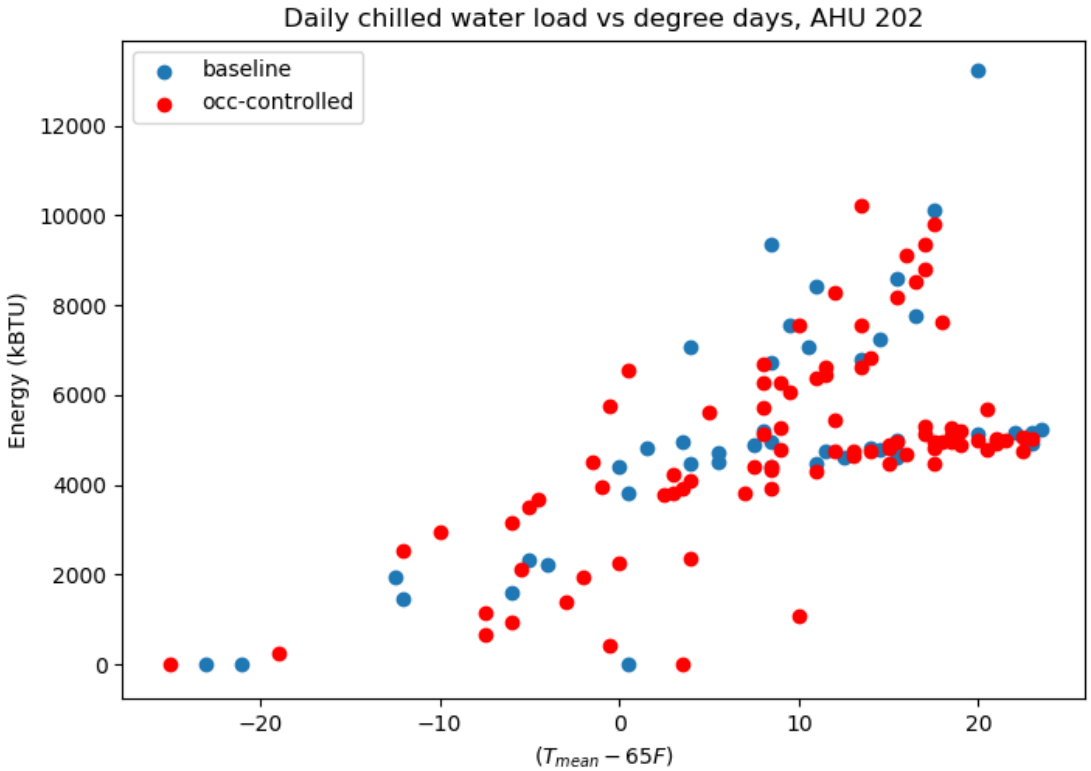


Figure 47. Daily Chilled Water Load of AHU 202 vs Degree Days ($T_{mean} - 65F$), Which Quantifies Daily Outside Weather Temperatures.

Figure 48 shows the daily energy consumption of the supply fan in AHU 202 vs degree days. From the figure, it appears there was little correlation between cooling energy and outside temperature. It appears that occupancy control reduced energy consumption.

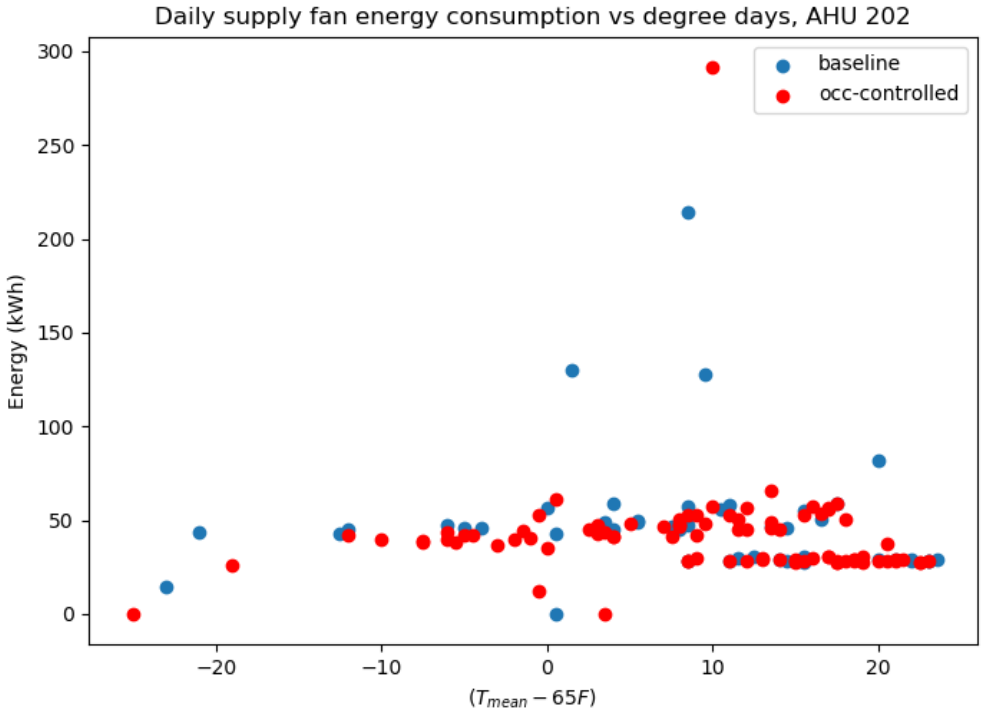


Figure 48. Daily Energy Consumption of the Supply Fan in AHU 202, vs Degree Days ($T_{mean} - 65F$), which Quantifies Daily Outside Weather Temperatures.

Figure 49 shows the daily energy consumption of the return fan in AHU 202 vs degree days. From the figure, it appears there was little correlation between cooling energy and outside temperature. It appears that occupancy control reduced energy consumption.

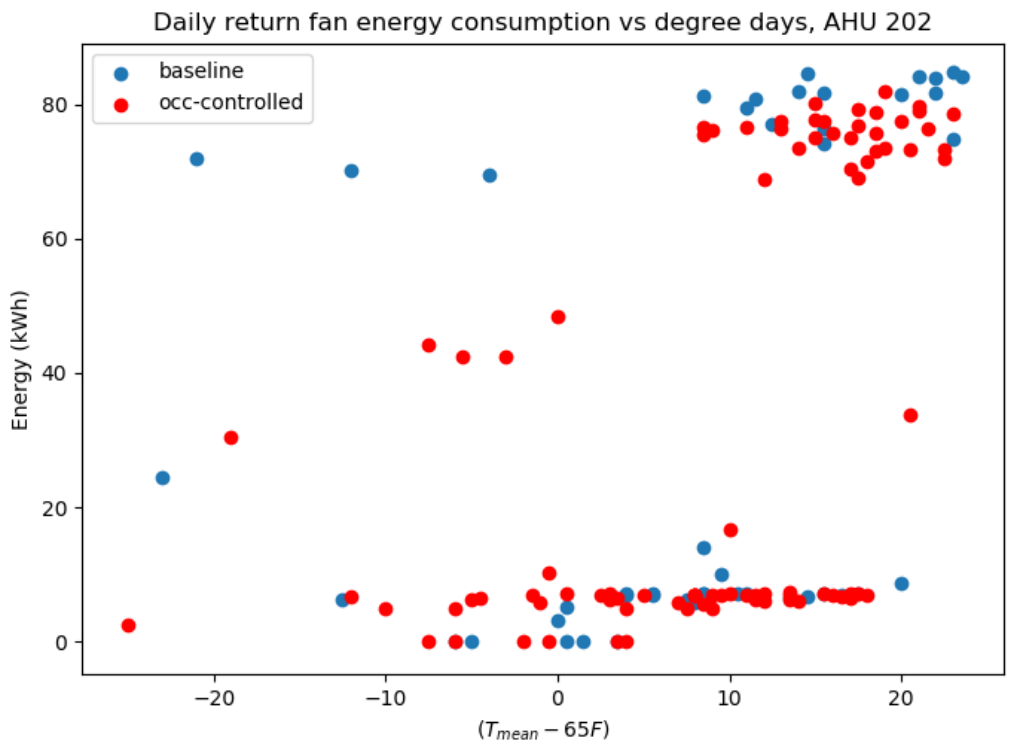


Figure 49. Daily Energy Consumption of the Return Fan in AHU 202, vs Degree Days ($T_{mean} - 65F$), Which Quantifies Daily Outside Weather Temperatures.

5.5.2.4 HVAC energy consumption and savings of high-bay area

This section summarizes the energy consumption by HVAC components for heating and cooling the high-bay area (only). For details of how various quantities were computed, see the analysis in Section 6.2.1. We note that we experienced severe, repeated network disruptions due to an overloaded BACnet network and EBI point server. This caused repeated lockups of controllers and significant loss of data before May 7, 2019. Hence, in the following HVAC sections, we **only include data from May 7, 2019 to Sept. 1, 2019,** when the HVAC system and HVAC data collection worked reliably.

Figure 50 shows the fraction of AHU 101's total daily airflow that was delivered to the high-bay demo area. This airflow fraction is used when calculating the energy consumption of the high-bay area (only) based on measured AHU 101 energy consumption. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled.

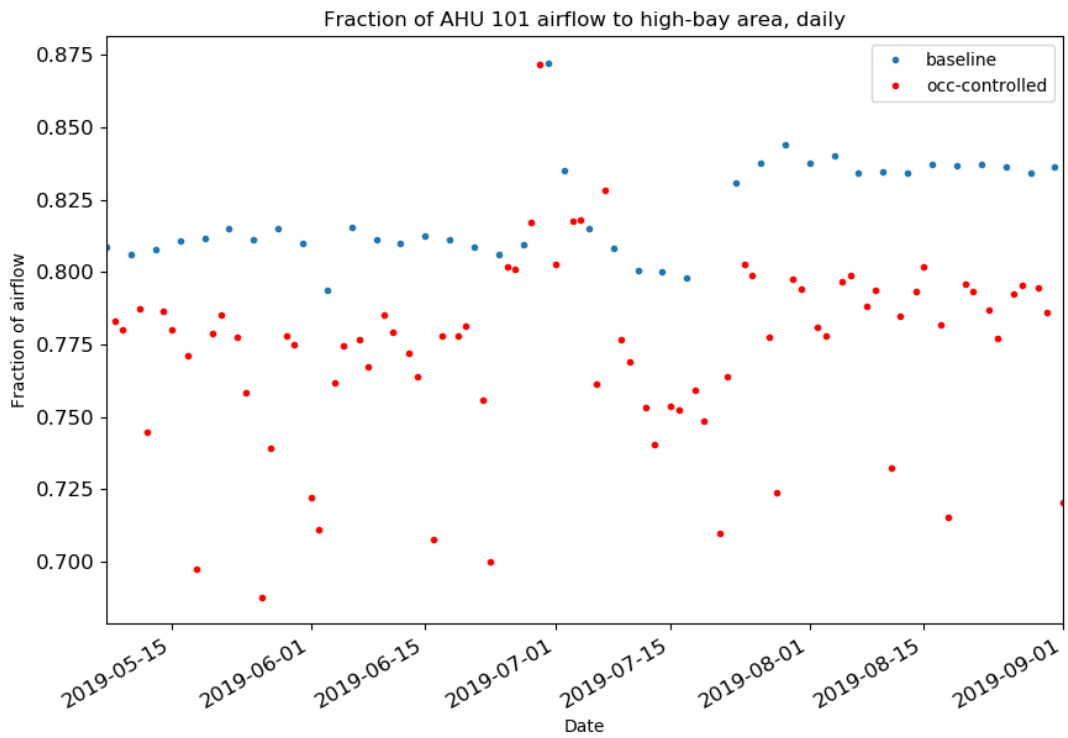


Figure 50. Fraction of AHU 101's Total Daily Airflow That Was Delivered to the High-Bay Demo Area.

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled.

Figure 51 shows the daily supply fan energy consumption for the high-bay demo area (only). It is computed by scaling the energy consumption of AHU 101's supply fan by the fraction of AHU 101's air that went to the demo area. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings due to occupancy control are shown in Figure 52.)

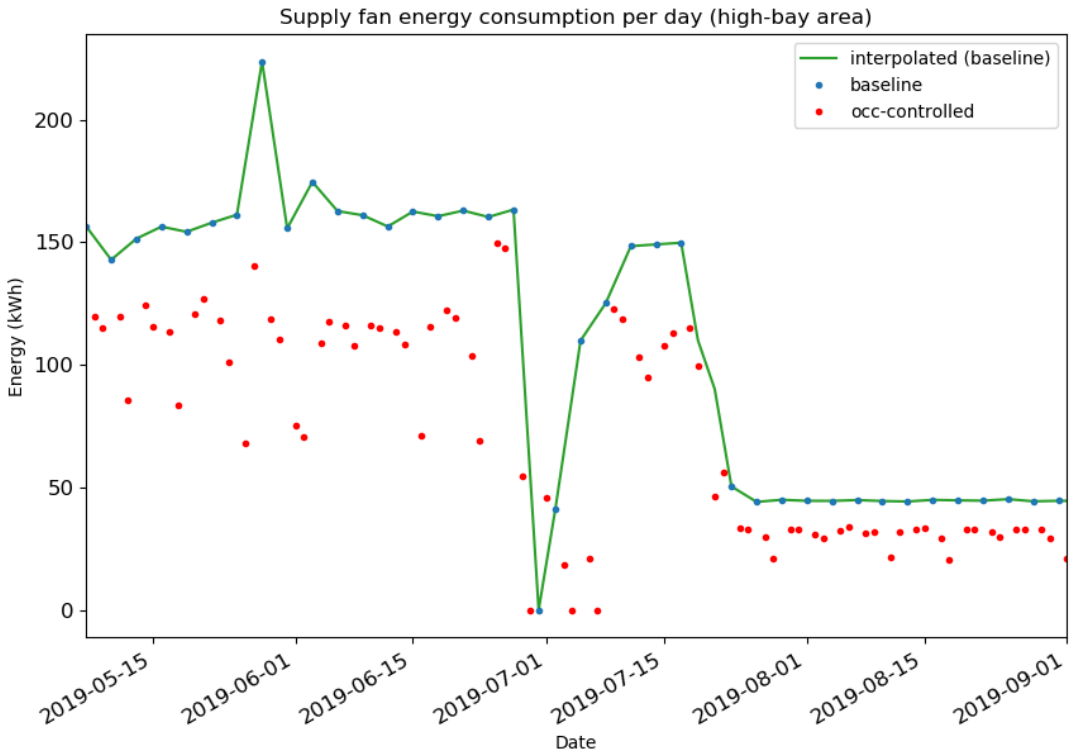


Figure 51. Calculated Daily Supply Fan Energy Consumption for the High-bay Demo Area (Only).

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 52 shows the daily supply fan energy savings for the high-bay area with occupancy control enabled. The daily savings are computed by subtracting occupancy-controlled consumption in Figure 51 (red dots) from the interpolated baseline (green line). Only two of every three days have occupancy control enabled (due to the 2+1 schedule), so only two of every three days have a computed energy savings. The red line in Figure 52 shows the mean daily energy savings, which was 37.39 kWh.

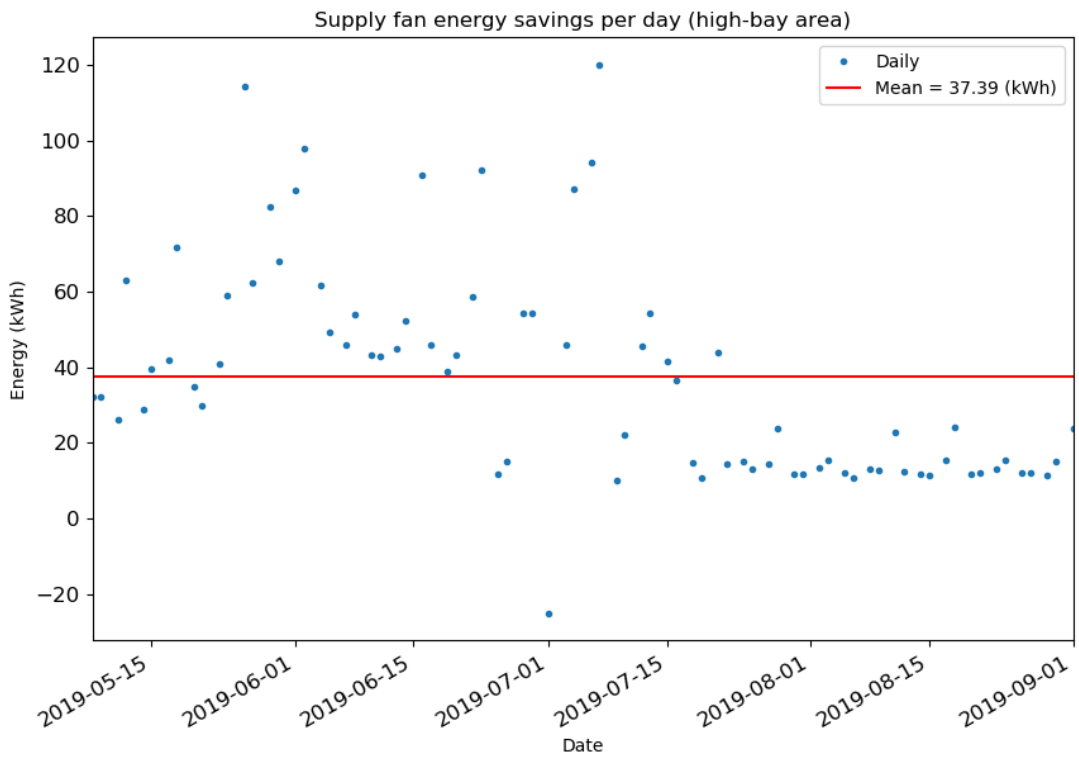


Figure 52. This Shows the Computed Daily Supply Fan Energy Savings for the High-bay Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Figure 53 shows the daily electricity energy used to chill water for the high-bay demo area. It is computed by scaling the chilled water load measured at AHU 101 by the fraction of air that went to the demo area. Chiller efficiency is also incorporated into the calculation. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings from occupancy control are shown in Figure 54.)

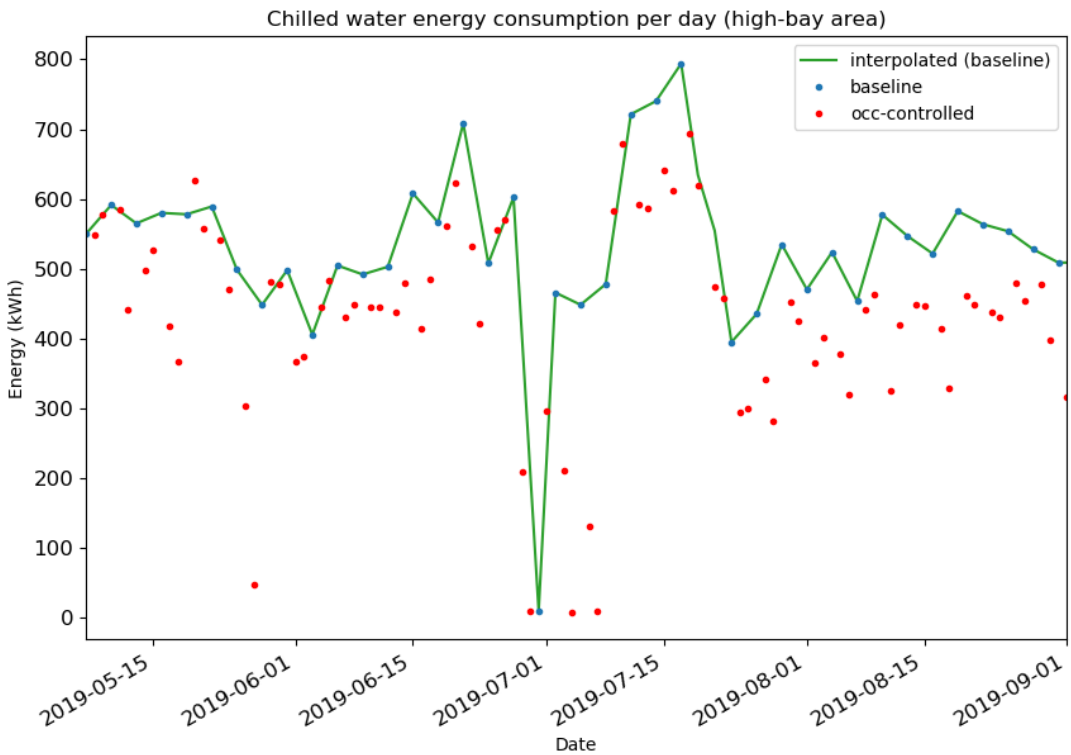


Figure 53. Calculated Daily Electrical Energy Used to Chill Water for the High-bay Demo Area (Only).

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 54 shows the daily chilled water energy savings for the high-bay area with occupancy-based HVAC control.

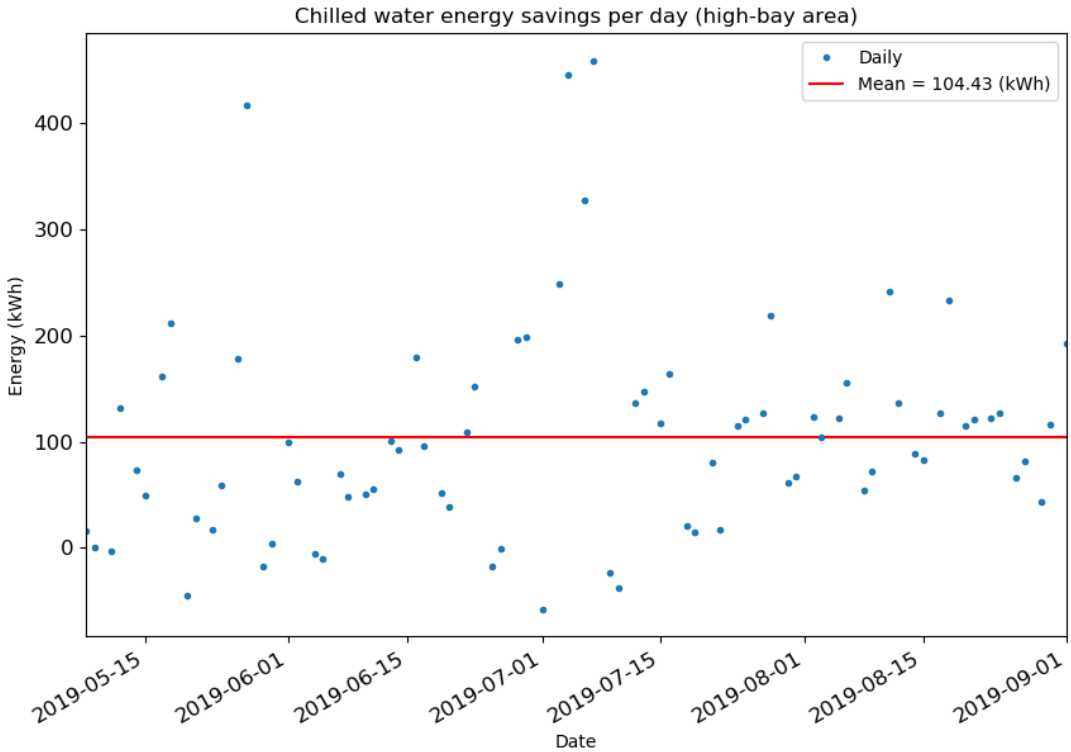


Figure 54. This Shows the Computed Daily Chilled Water Energy Savings for the High-bay Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Figure 55 shows the daily energy consumed by natural gas boilers to supply hot water to VAV reheat elements serving the high-bay demo area. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings due to occupancy control are shown in Figure 56.)

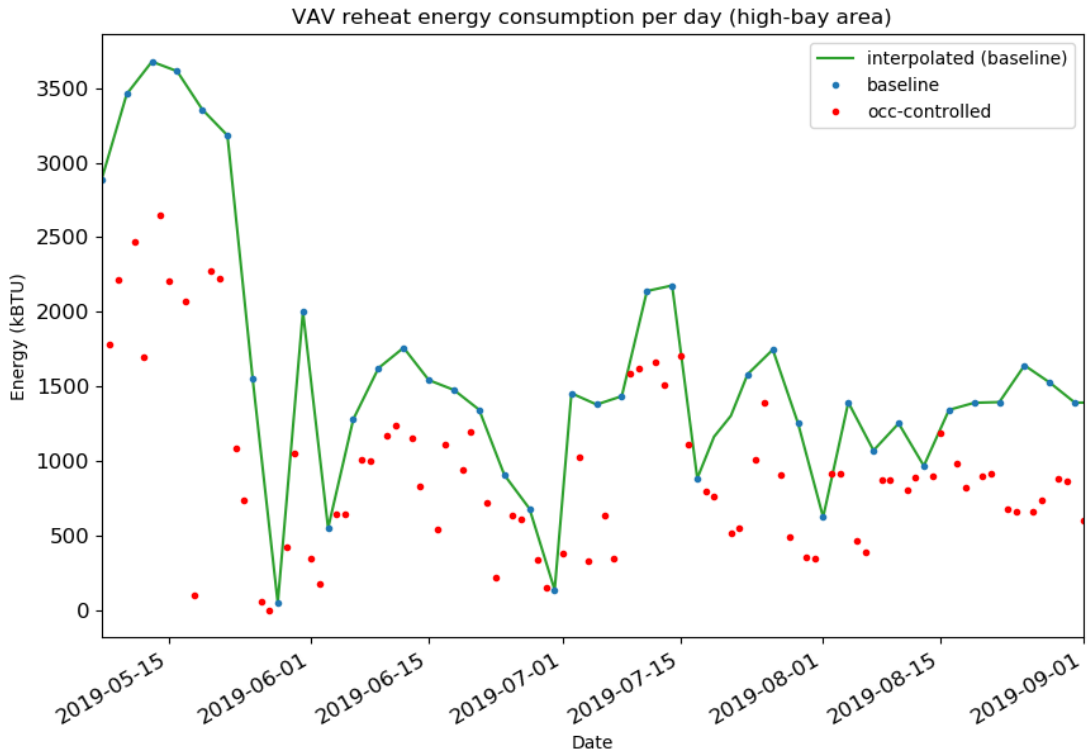


Figure 55. Calculated Daily Energy Used for VAV Reheat in the High-bay Demo Area (Only).

Red dots are days with occupancy-based HVAC control enabled and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 56 shows the daily VAV reheat energy savings for the high-bay area with occupancy control enabled. The daily savings are computed by subtracting occupancy-controlled consumption in Figure 55 (red dots) from the interpolated baseline (green line). The red line in Figure 56 shows the mean daily energy savings, which was 659 kBTU.

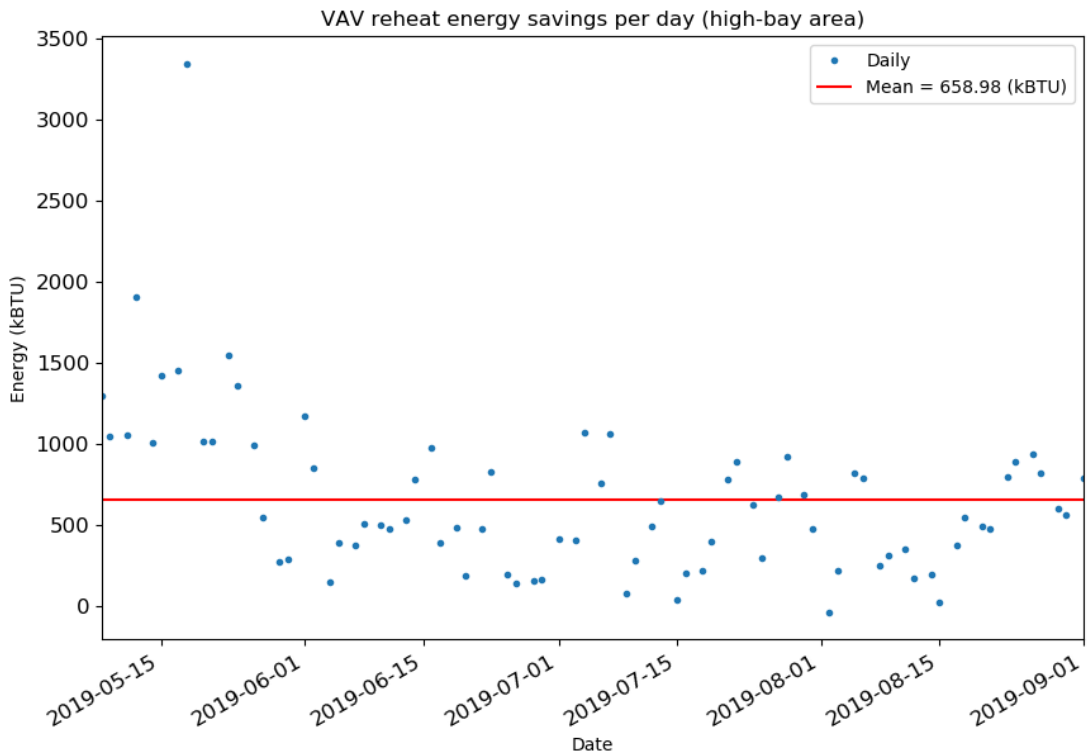


Figure 56. This Shows the Computed Daily VAV Reheat Energy Savings for the High-bay Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Table 28 summarizes the mean daily HVAC energy consumption in the high-bay area (only), across the baseline period when occupancy-based HVAC control was disabled. (The baseline period was every third day in the period May 7, 2019 – Sept 1, 2019). High-bay energy consumption is listed separately for the supply fan, VAV reheat, and chilled water (supplied by the chillers). The final row shows the total mean daily baseline HVAC energy consumption of the high-bay from all sources (converted to common units of kWh using the conversion factor: 0.293 kWh per kBTU).

Table 28. High-bay Mean Daily HVAC Energy Consumption (Baseline).

	Baseline energy consumption
Supply fan	110 kWh
VAV reheat (energy from boilers)	474 kWh (1618 kBTU)
Chilled water (energy from chillers)	530 kWh
HVAC total	1,114 kWh

Table 29 summarizes the mean daily HVAC energy consumption and savings of the high-bay when occupancy control was enabled. (Occupancy control was enabled two out of three days, repeating, from May 7, 2019 – Sept 1, 2019.) Column 2 lists mean daily high-bay HVAC energy consumption, by source, with occupancy-based HVAC control. Column 3 lists the mean daily energy savings achieved by occupancy control. Column 4 lists the savings as a percentage of the baseline consumption. Energy is listed separately for the supply fan, VAV reheat, and chilled water (supplied by chillers). The final row shows the total HVAC energy (converted to common units of kWh). Note total high-bay HVAC energy savings was **30% of the baseline**, which **exceeded our performance objective of 20% energy savings**.

Table 29. High-bay Mean Daily HVAC Energy Consumption and Savings (Occupancy-Controlled).

	Occ-controlled consumption	**Savings**	**Savings (% of baseline)**
Supply fan	73 kWh	37 kWh	34%
VAV reheat (energy from boilers)	277 kWh (944 kBTU)	193 kWh (659 kBTU)	41%
Chilled water (energy from chillers)	431 kWh	104 kWh	20%
HVAC total	780 kWh	335 kWh	**30%**

5.5.2.5 HVAC energy consumption and savings of office area

This section summarizes the energy consumption by HVAC components for heating and cooling the office area (only). For details of how various quantities were computed, see the analysis in Section 6.2.1. We note that we experienced severe, repeated network disruptions due to an overloaded BACnet network and EBI point server. This caused repeated lockups of controllers and significant loss of data before May 7, 2019. Hence, in the following HVAC sections, we **only include data from May 7, 2019 to Sept. 1, 2019,** when the HVAC system worked reliably.

Figure 57 shows the fraction of AHU 202's total daily airflow that was delivered to the office demo area. This airflow fraction is used when calculating the energy consumption of the office area (only) based on measured AHU 202 energy consumption. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled.

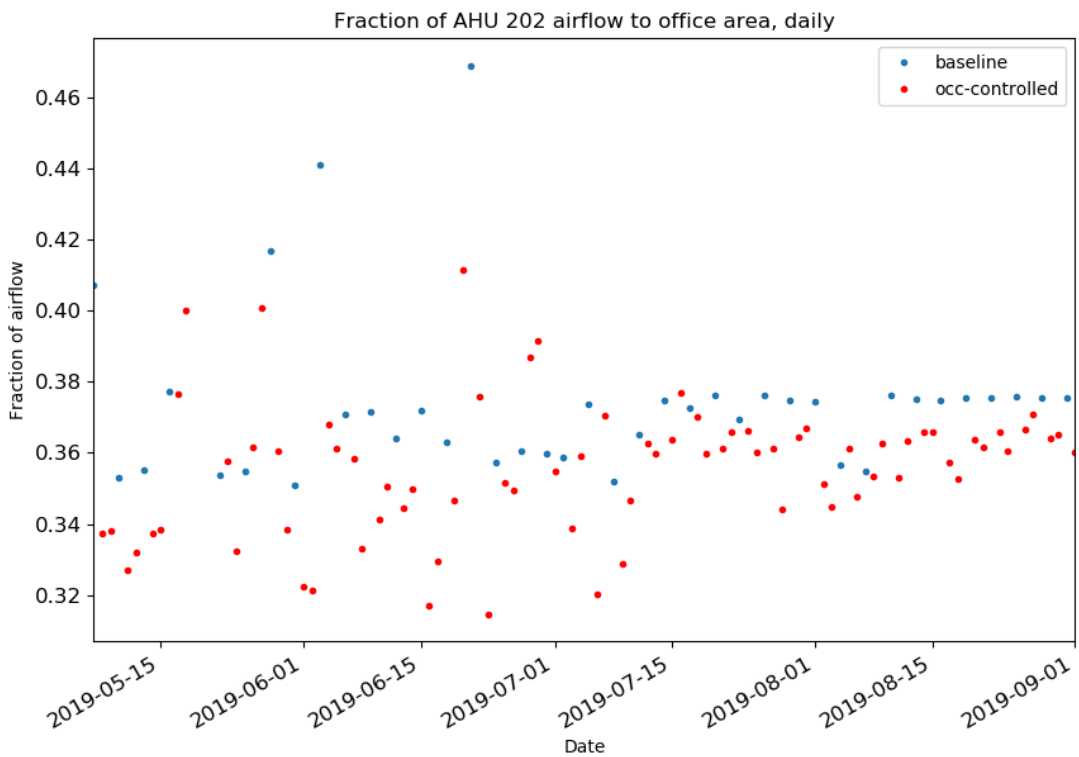


Figure 57. Fraction of AHU 202's Total Daily Airflow that Was Delivered to the Office Area.

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled.

Figure 58 shows the daily supply fan energy consumption for the office demo area (only). It is computed by scaling the energy consumption of AHU 202's supply fan by the fraction of AHU 202's air that went to the demo area. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings due to occupancy control are shown in Figure 59.)

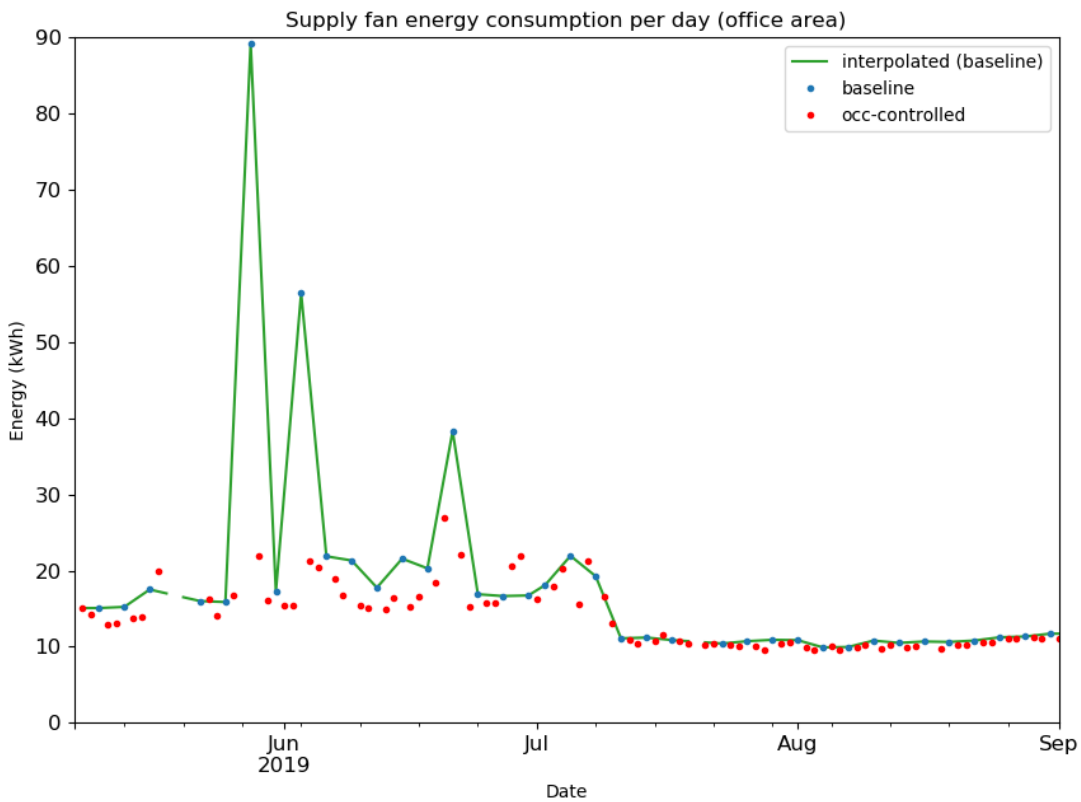


Figure 58. Calculated Daily Supply Fan Electricity Energy Consumption of the Office Area (Only).

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 59 shows the daily supply fan energy savings for the office area with occupancy control enabled. The daily savings are computed by subtracting occupancy-controlled consumption in Figure 58 (red dots) from the interpolated baseline (green line). Only two of every three days have occupancy control enabled (due to the 2+1 schedule), so only two of every three days have a computed energy savings. The red line in Figure 59 shows the mean daily energy savings, which was 3.46 kWh.

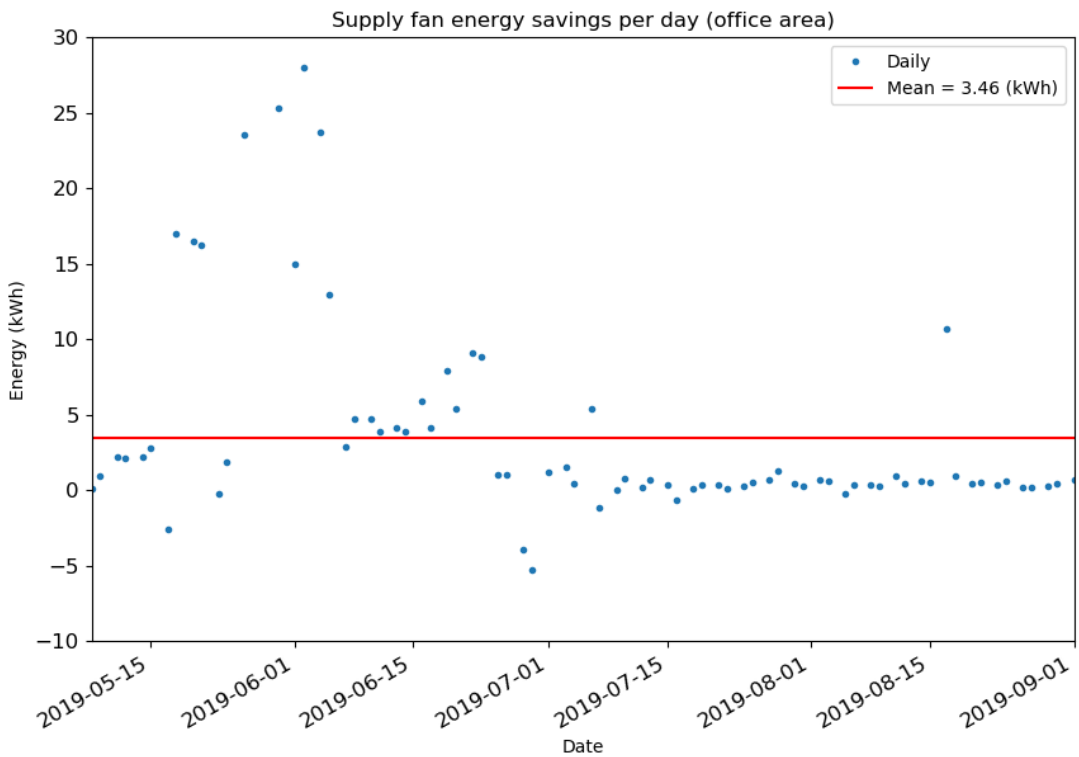


Figure 59. This Shows the Computed Daily Supply Fan Energy Savings for the Office Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Figure 60 shows the daily return fan energy consumption for the office demo area (only). Note the return fan **broke in April and was repaired in July**, which explains the jump in energy consumption.

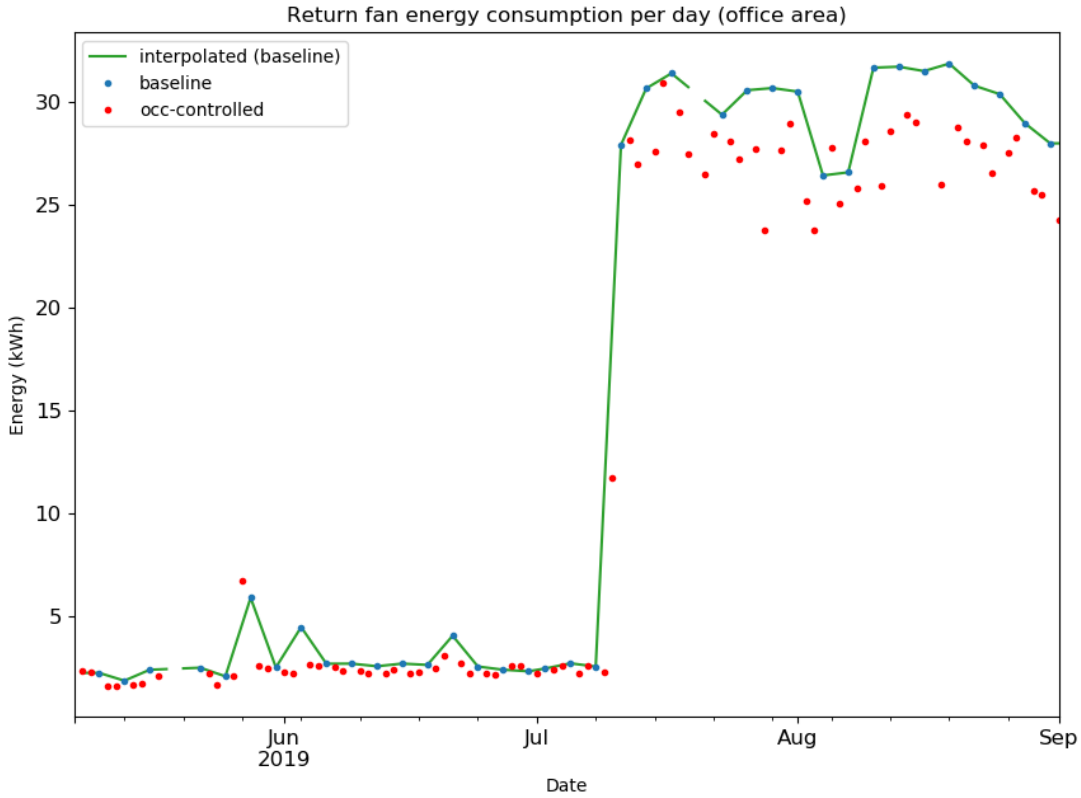


Figure 60. Calculated Daily Return Fan Electricity Energy Consumption of the Office Area (Only).

Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 61 shows the daily return fan energy savings for the office area with occupancy control enabled. The daily savings are computed by subtracting occupancy-controlled consumption in Figure 60 (red dots) from the interpolated baseline (green line). Only two of every three days have occupancy control enabled (due to the 2+1 schedule), so only two of every three days have a computed energy savings. The red line in Figure 61 shows the mean daily energy savings, which was 2.11 kWh.

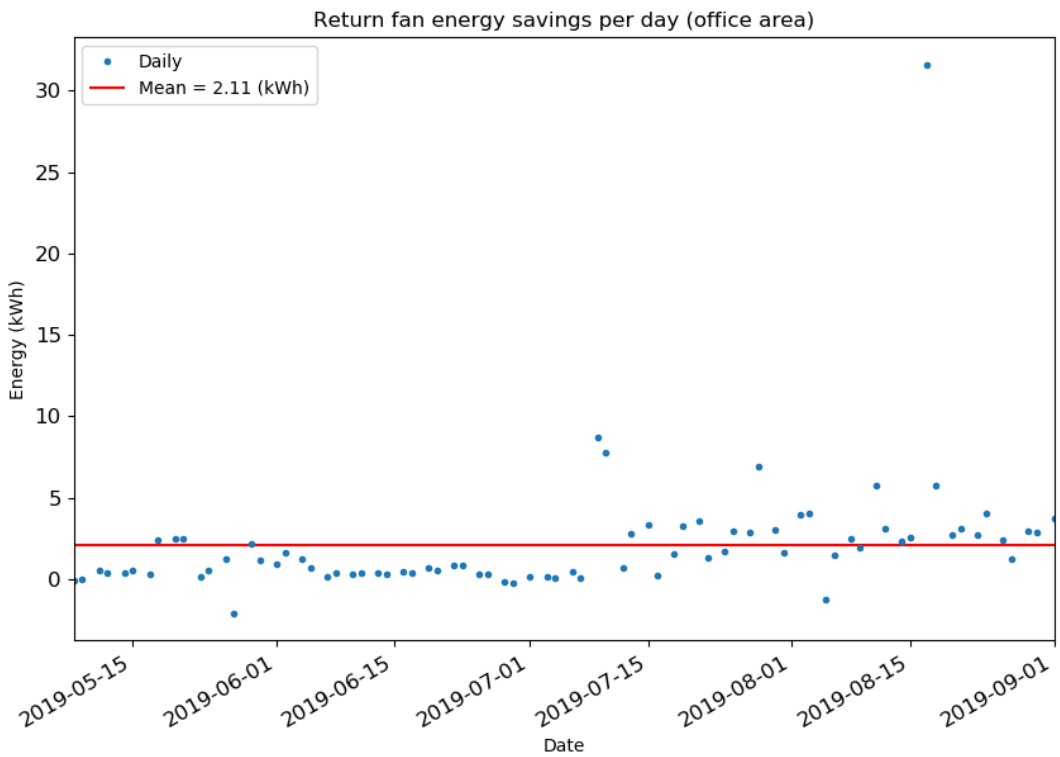


Figure 61. This Shows the Computed Daily Return Fan Energy Savings for the Office Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Figure 62 shows the daily electricity energy used to chill water for the office demo area. It is computed by scaling the chilled water load measured at AHU 202 by the fraction of air that went to the demo area. Chiller efficiency is also incorporated into the calculation. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings due to occupancy control are shown in Figure 63.)

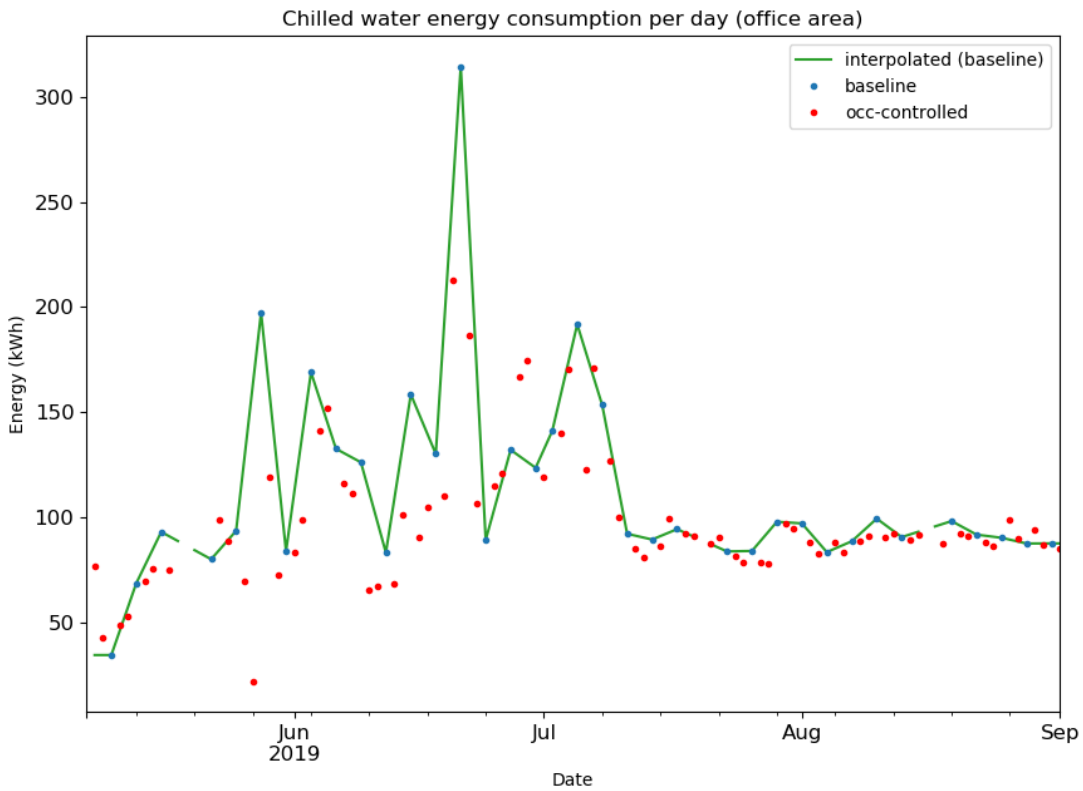


Figure 62. Calculated Daily Electrical Energy Used to Chill Water for the Office Area (Only).

Red dots are days with occupancy-based HVAC control enabled, blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline.

Figure 63 shows the daily chilled water energy savings for the office area with occupancy-based HVAC control.

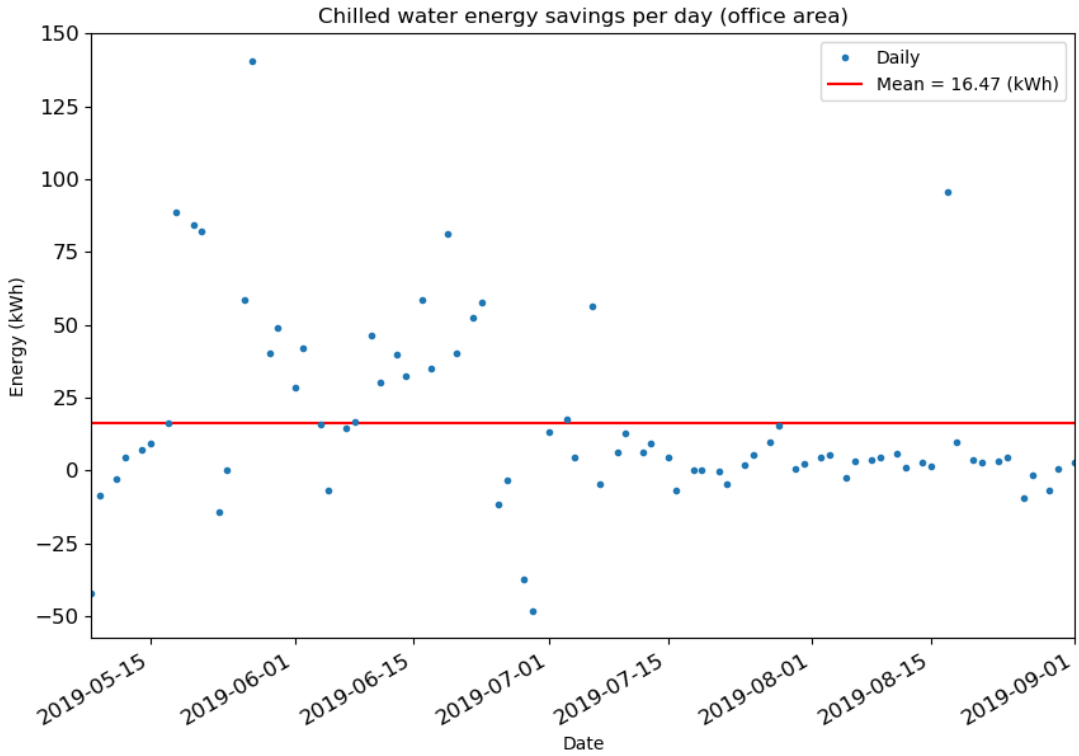


Figure 63. This Shows the Computed Daily Chilled Water Energy Savings for the Office Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Figure 64 shows the daily energy consumed by natural gas boilers to supply hot water to VAV reheat elements serving the office area. Red dots are days with occupancy-based HVAC control enabled, and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days and is used to estimate energy savings of occupancy control. (Daily energy savings due to occupancy control are shown in Figure 65.) Note that AHU 202's return fan was manually adjusted by technicians at the site to increase space cooling in July. The changes caused too much cool air to be delivered to the office area. As a result, VAV reheat activated to increase the temperature of air delivered into the office. This explains the significant increase in reheat energy in the period from late July – September.

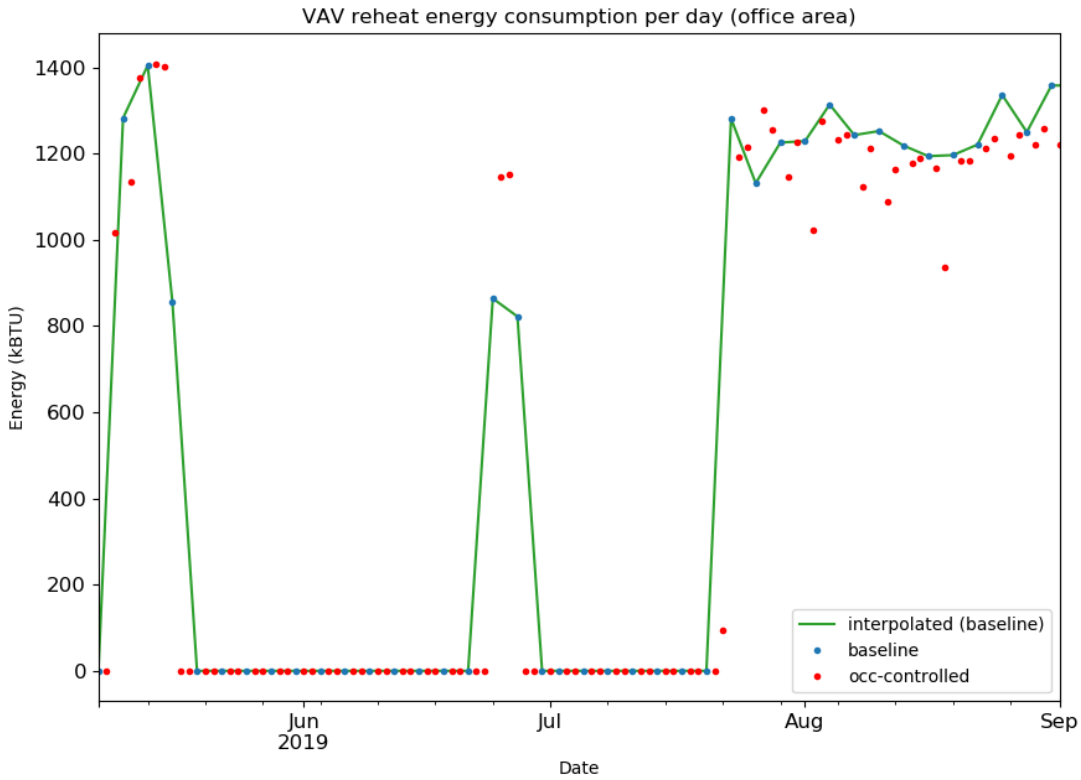


Figure 64. Calculated Daily Energy Used by VAV Reheat in the Office Area (Only).

Red dots are days with occupancy-based HVAC control enabled and blue dots (baseline) have occupancy-control disabled. The green line interpolates between baseline days.

Figure 65 shows the daily VAV reheat energy savings for the office area with occupancy control enabled. The daily savings are computed by subtracting occupancy-controlled consumption in Figure 64 (red dots) from the interpolated baseline (green line). The red line in Figure 65 shows the mean daily energy savings, which was 58 kBTU.

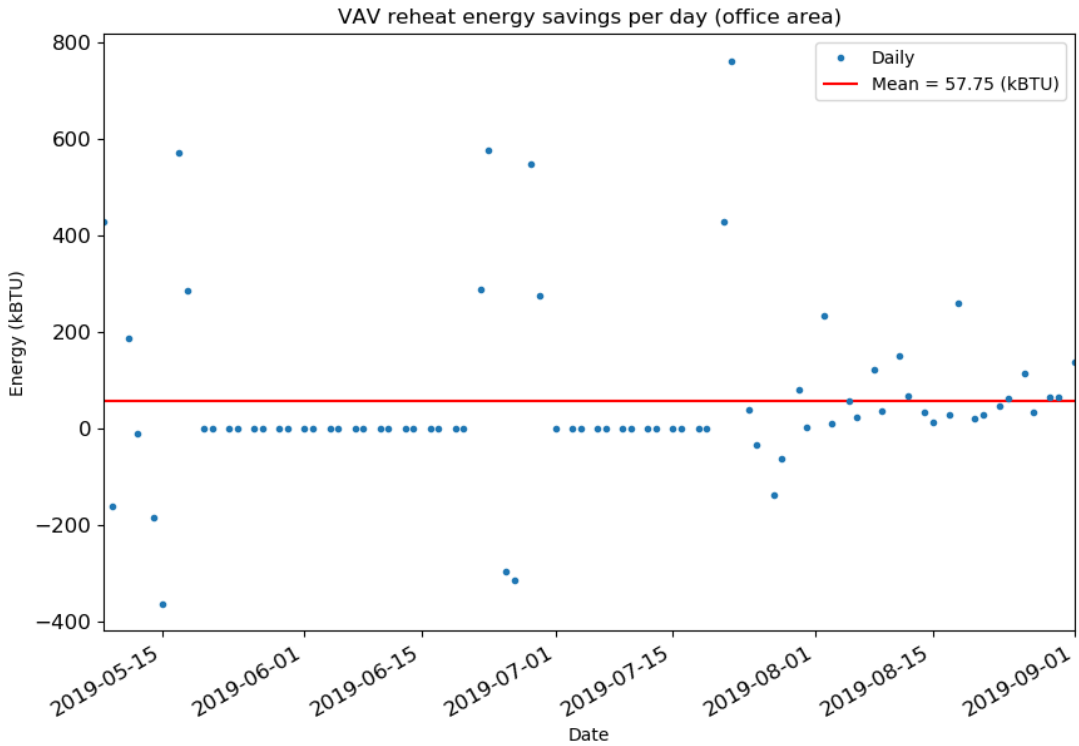


Figure 65. This Shows the Computed Daily VAV Reheat Energy Savings for the Office Area with Occupancy-based HVAC Control (Blue Dots).

The mean daily energy savings is shown in red.

Table 30 summarizes the mean daily HVAC energy consumption in the office area (only), across the baseline period when occupancy-based HVAC control was disabled. (The baseline period was every third day in the period May 7, 2019 – Sept 1, 2019). Office HVAC energy consumption is listed separately for the supply and return fan, VAV reheat, and chilled water (supplied by the chillers). The final row shows the total mean daily baseline HVAC energy consumption of the office (converted to common units of kWh using the conversion factor: 0.293 kWh per kBTU).

Table 30. Office Area Mean Daily HVAC Energy Consumption (Baseline).

	Baseline energy consumption
Supply fan	18 kWh
Return fan	15 kWh
VAV reheat (energy from boilers)	166 kWh (567 kBTU)
Chilled water (energy from chillers)	113 kWh
HVAC total	312 kWh

Table 31 summarizes the mean daily HVAC energy consumption and savings of the office area when occupancy control was enabled. (Occupancy control was enabled two out of three days, repeating, from May 7, 2019 – Sept 1, 2019.) Column 2 lists mean daily office HVAC energy consumption, by source, when occupancy-based HVAC control was enabled. Column 3 lists the mean daily energy savings achieved by occupancy control. Column 4 lists the savings as a percentage of the baseline consumption. Energy is listed separately for the supply fan, VAV reheat, and chilled water (supplied by chillers). The final row shows the total HVAC energy savings was **12% of the baseline**. This **did not achieve the performance objective of 20% energy savings**. We believe the failure to reach the performance objective in the office area was caused by overactive Enlighted occupancy sensors in the office area. As we discussed in Section 1.1.1.1.5, occupancy sensors in the office area were overly sensitive from May 1, 2019 to the end of the demo period which caused them to detect intermittent occupancy throughout overnight periods when the office was unoccupied. (This is discussed further in Section 6.5.2 and Section 8.1.4.) The false detection of occupancy reduced occupancy-based energy savings of the troffer lights (Phase 2) compared to the pendant lights (Phase 1). Similarly, false detection of occupancy would reduce HVAC energy savings, since HVAC setpoint setbacks are not applied when occupancy is detected.

Table 31. Office Area Occupancy-controlled HVAC Energy Consumption and Savings.

	Occ-controlled consumption	Savings	Savings (percent of baseline)
Supply fan	15 kWh	3 kWh	19%
Return fan	14 kWh	2 kWh	14%
VAV reheat	154 kWh (524 kBTU)	17 kWh (58 kBTU)	10%
Chiller	98 kWh	16 kWh	15%
HVAC total	281 kWh	39 kWh	**12%**

5.5.2.6 Projected yearly HVAC energy consumption

This section lists the estimated yearly energy consumption and savings for the HVAC system. It is extrapolated by taking the mean daily energy consumption and savings values from the prior section and multiplying them by 365.25 days per year. Table 32 lists estimated total HVAC yearly baseline energy consumption, occupancy-controlled energy consumption, and energy savings. Results are separately listed for the high-bay and office areas as well as the total (office + high-bay). Results are listed in common units of kWh.

Table 33 lists the projected yearly energy usage and savings for the whole area (high-bay + office), broken down by energy source. Natural gas consumption comes from boilers supplying the VAV reheat. Electricity consumption comes from return and supply fans as well as chillers. These results are needed for the economic analysis in Section 7.0.

Table 32. This Shows Projected Total Yearly HVAC Energy Usage, by Area.

The total includes all sources of energy consumption (supply and return fans, chilled water and VAV reheat), and is reported in common units of kWh. The final row shows total energy usage and saving (combined office + high-bay).

	Baseline energy consumption	Occ-controlled consumption	Savings	Savings (percent of baseline)
High-bay HVAC total	406,800 kWh	284,700 kWh	122,300 kWh	**30%**
Office HVAC total	114,100 kWh	102,600 kWh	14,230 kWh	**12%**
High-bay + office HVAC total	520,800 kWh	387,400 kWh	136,600 kWh	**26%**

Table 33. Projected Yearly HVAC Energy Usage and Savings for the Total Demo Area (office + high-bay), Broken Down by Energy Source.

The second row shows electricity energy consumption in kWh, and the third row shows natural gas energy consumption in millions of British thermal units (MMBtu).

	Baseline energy consumption	Occ-controlled consumption	Savings	Savings (percent of baseline)
Electricity	286,900 kWh	230,300 kWh	59,850 kWh	21%
Natural Gas	798 MMBtu	536 MMBtu	262 MMBtu	33%

5.5.3 PO3: Plug-Load Usage

There were 15 plug-load controllers installed in the 5,000 square foot office area. However, one plug-load controller was faulty and was excluded from the analysis. Hence the data analyzed consisted of 14 controlled outlets and 14 uncontrolled outlets. The baseline period was 83 days long, and the demo period was 181 days long. Daily energy consumption of controlled plugs is shown in Figure 66. Blue markers indicate measurements from the baseline period while red markers indicate measurements from the demo period. The solid blue and red lines indicate the mean daily energy consumption of controlled plugs during the baseline and demo periods, which were 0.18 kWh/day and 0.11 kWh/day, respectively. Figure 66 shows that occupancy control reduced energy consumption of controlled plugs during the demo period compared to the baseline period. A zoomed-in view of controlled plug energy consumption is shown in Figure 67. Note the repeating pattern of two adjacent red markers with reduced energy consumption: that is caused by occupancy control achieving greater energy savings over weekends (when the office space was lightly occupied). Figure 68 depicts daily energy consumption from uncontrolled plugs, with mean daily energy consumption values of 0.9 kWh/day for the baseline period, and 1.7 kWh/day for the demo period. And Figure 69 shows total plug energy consumption (controlled + uncontrolled), with mean daily energy consumption values for the baseline and demo periods of 1.1 kWh/day and 1.8 kWh/day respectively.

Plug energy consumption from the baseline period is summarized in Table 34. Plug data from the demo period is summarized in Table 35. Table 36 and Table 37 report the computed energy savings achieved by plug-load occupancy control. The total energy savings realized over the 181-day long demo period was 12 kWh. This was 4% of the total (controlled + uncontrolled) baseline plug energy consumption of 331 kWh over the demo period. This modest level of energy savings may be explained by the behavior of occupants in the office area: occupants predominantly plugged electrical appliances into uncontrolled plugs. This can be quantified using figures from Table 34: energy consumption from controlled plugs during the 83-day long baseline period (15 kWh) was 17% of the total plug consumption (87 kWh). And Table 35 shows energy consumption from controlled plugs during the demo period (20 kWh) was only 6.2% of the total energy consumption (319 kWh). Note that during the demo period, the energy consumption of uncontrolled plugs (299 kWh) was 90.3% of the baseline total consumption (331 kWh). Hence, even if (hypothetically) controlled plugs had used no energy during the demo period, they would have achieved a savings of at most 9.7% of the baseline, and the savings target of 20% reduction would not have been reached.

If we compare the energy savings achieved by controlled plugs in the demo period (12 kWh) vs the controlled plug baseline energy consumption in the demo period (32 kWh), the savings is 38% of the controlled plug baseline. Hence, we conclude that the primary limiting factor in realized energy savings was the limited use of controlled plugs by the office occupants.

We also graphed histograms of plug-load energy usage during the baseline and demo periods. These are shown for controlled plugs in Figure 70, for uncontrolled plugs in Figure 71, and total (controlled + uncontrolled plugs) in Figure 72.

Table 38 lists the estimated yearly energy consumption of plug-loads, had occupancy control never been enabled (column 1), vs the yearly consumption with occupancy-control of controlled plugs (column 2). The estimated yearly energy savings of occupancy control is given in column 3. For details of the computation and the analysis, see Section 6.3.5.

Finally, we also computed the percentage of daily energy consumption that occurred outside of business hours (before 6 am or after 5 pm). This quantity is less sensitive to changes in absolute daily energy consumption. Percentages are shown for controlled plugs in Figure 73, for uncontrolled plugs in Figure 74, and total in Figure 75. In Figure 73, note the significant decrease in the fraction of controlled plugs' energy usage occurring outside business hours during the demo period—this indicates savings from occupancy control. Mean values of the daily percentages are summarized for baseline and demo periods in Table 39. We find that for controlled plugs, the mean daily percentage of energy consumption occurring outside business hours dropped from 44% in the baseline period to 9% in the demo period. For uncontrolled plugs, the fractions were stable: 52% during the baseline period vs 48% during the demo period.

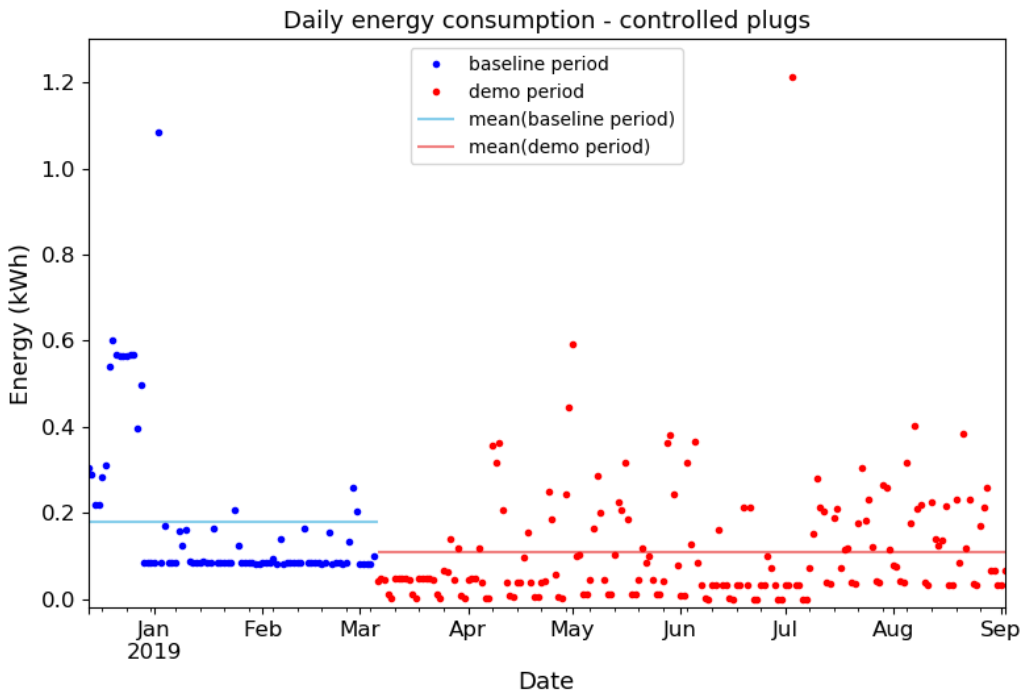


Figure 66. Daily Energy Consumption of Controlled Plugs During Baseline and Demo Periods.

Mean daily values of energy consumption: baseline: 0.18 kWh, demo: 0.11 kWh.

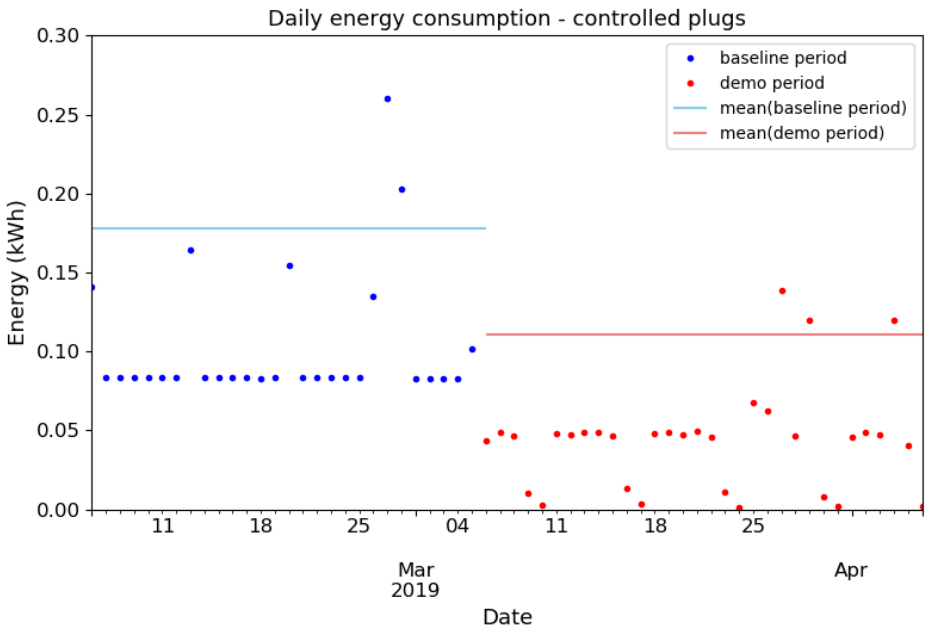


Figure 67. Zoomed-in View of Daily Energy Consumption of Controlled Plugs.

The repeating pattern of two red markers with minimal energy consumption indicates weekends (when the office was lightly occupied, and occupancy control achieved greater energy savings.)

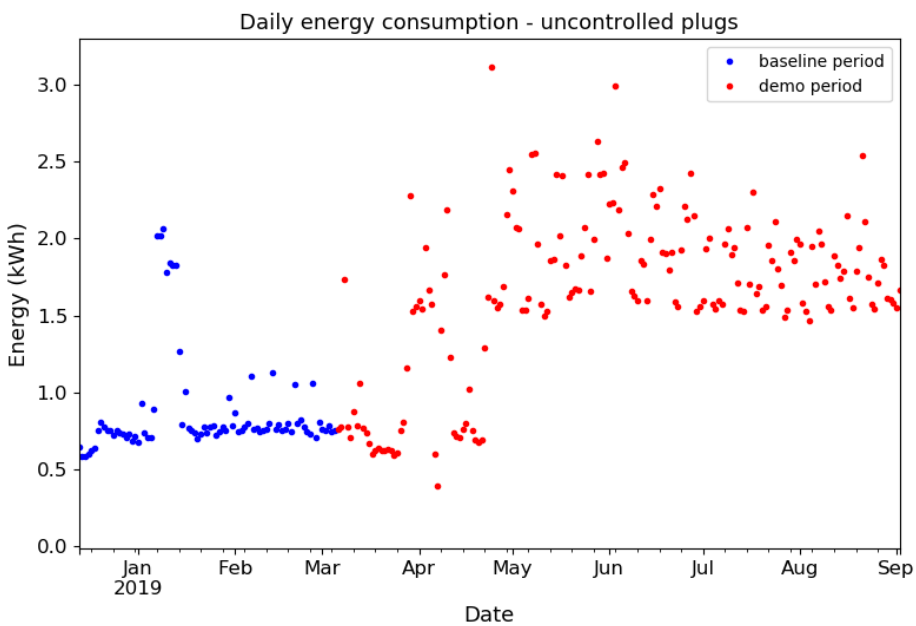


Figure 68. Daily Energy Consumption of Uncontrolled Plugs During Baseline and Demo Periods.

Mean daily values of energy consumption: baseline: 0.9 kWh, demo: 1.7 kWh.

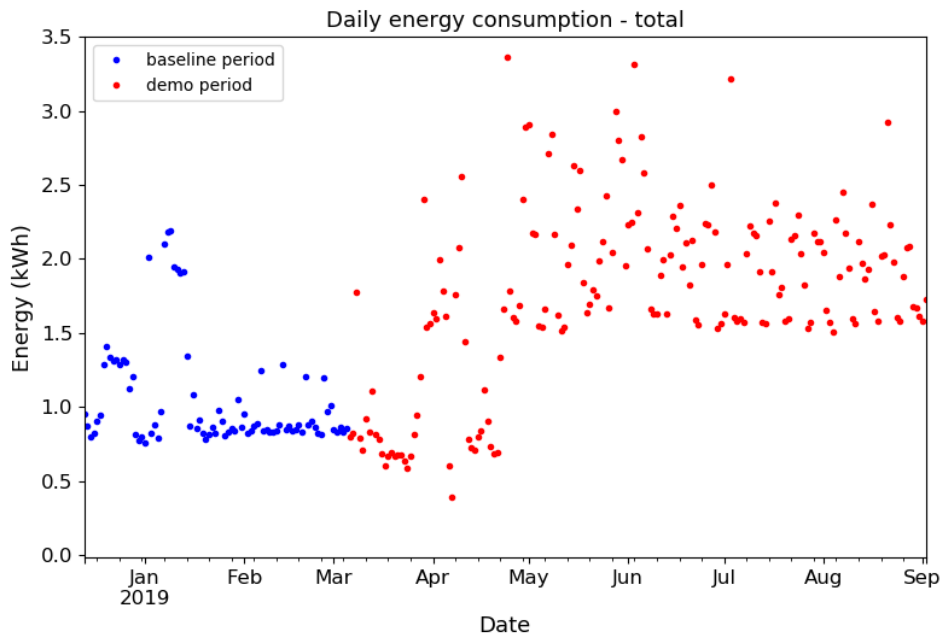


Figure 69. Total Daily Energy Consumption of All Plugs (Controlled + Uncontrolled) During Baseline and Demo Periods.

Mean daily values of energy consumption: baseline: 1.1 kWh, demo: 1.8 kWh.

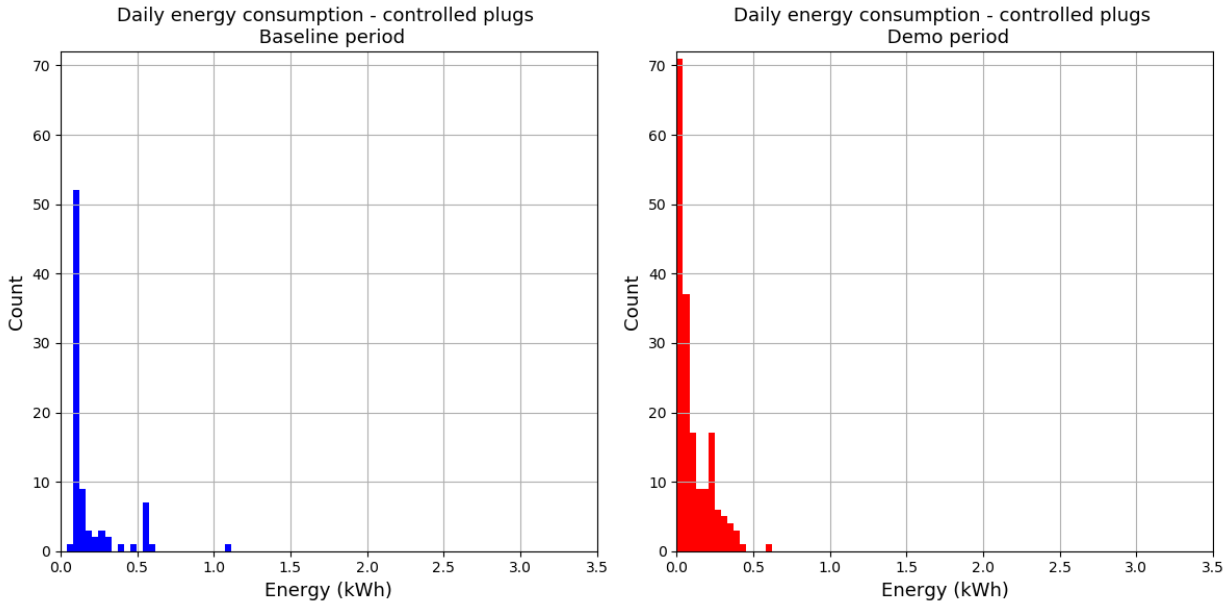


Figure 70. Histograms of Daily Energy Consumption of Controlled Plugs in Baseline and Demo Periods.

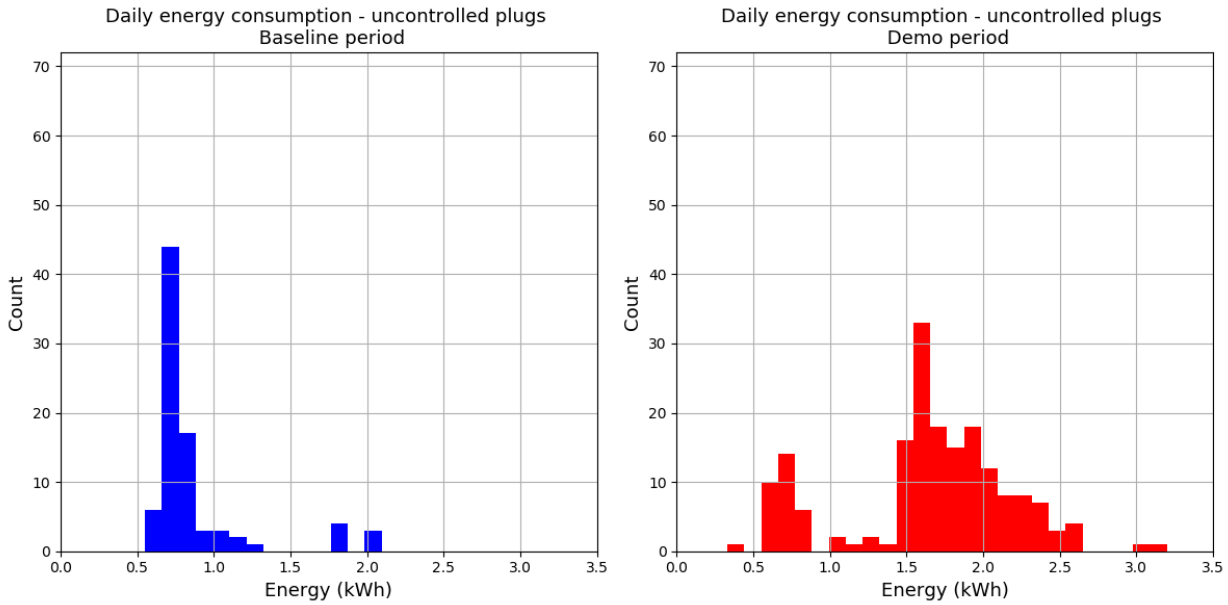


Figure 71. Histograms of Daily Energy Consumption of Uncontrolled Plugs in Baseline and Demo Periods.

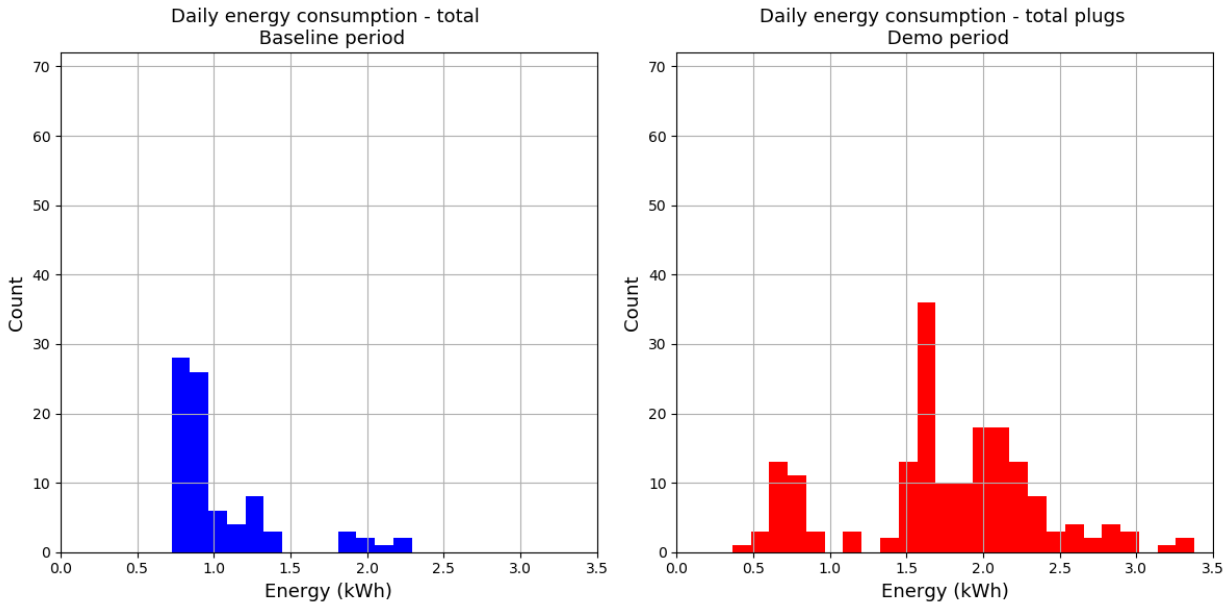


Figure 72. Histograms of Total Daily Energy Consumption (Controlled + Uncontrolled Plugs) in Baseline and Demo Periods.

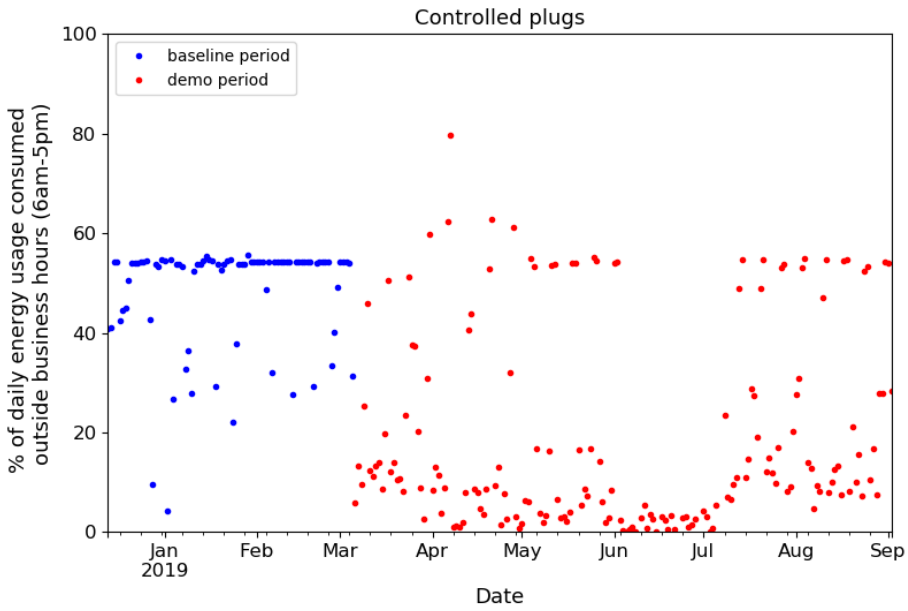


Figure 73. Percentage of Controlled plugs' Daily Energy Usage Occurring Outside of Business Hours (6 am - 5 pm).

Baseline and demo periods are shown in blue and red. Note the significant decrease during the demo period, indicating occupancy-based savings.

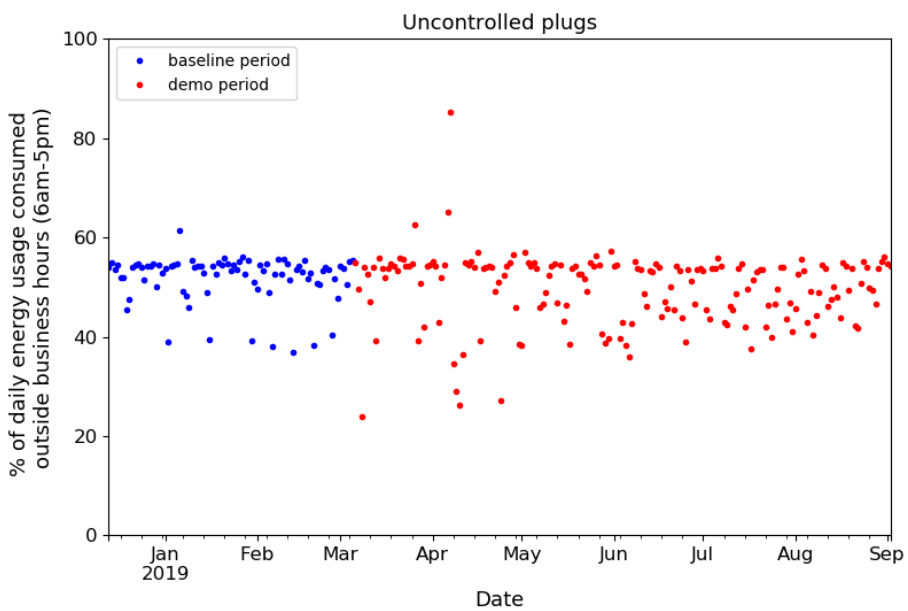


Figure 74. Percentage of Uncontrolled Plugs' Daily Energy Usage Occurring Outside of Business Hours (6 am - 5 pm).

Baseline and demo periods are shown in blue and red.

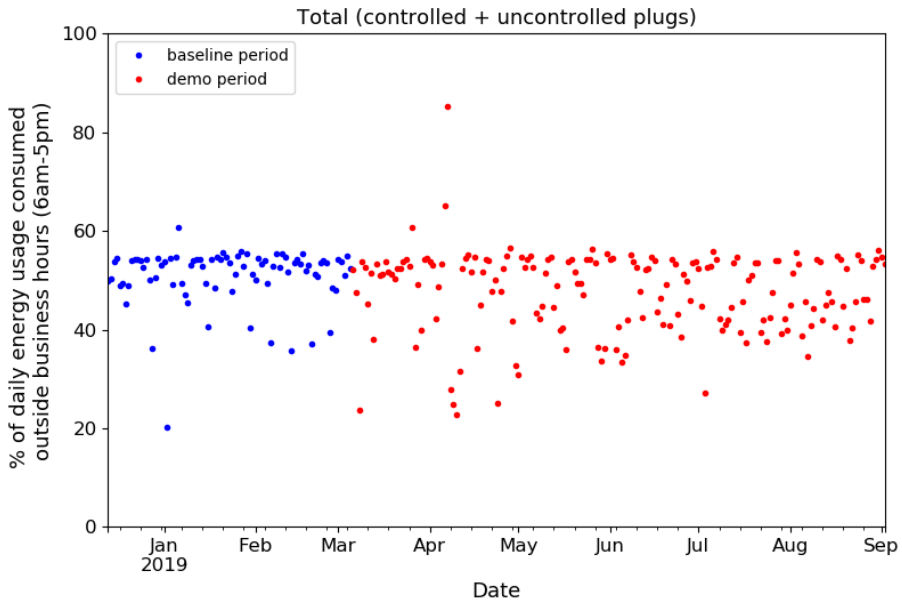


Figure 75. Percentage of Total Plug-load Daily Energy Usage Occurring Outside of Business Hours (6 am - 5 pm).

Baseline and demo periods are shown in blue and red.

Table 34. Energy Consumption of Controlled and Uncontrolled Plugs During the Baseline Period (83 Days Total: Dec. 13, 2018 - March 5, 2019), Grouped by Month.

Month	Controlled (kWh)	Uncontrolled (kWh)	Total (kWh)
2018-12	7.3	13.3	20.6
2019-01	4.1	32.5	36.7
2019-02	2.9	22.8	25.7
2019-03	0.4	3.8	4.2
Total	14.7	72.4	87.2

Table 35. Energy Consumption of Controlled and Uncontrolled Plugs During the Demo Period (181 days total: March 6, 2019 - Sept. 2, 2019), Grouped by Month.

Month	Controlled (kWh)	Uncontrolled (kWh)	Total (kWh)
2019-03	1.10	23.25	24.35
2019-04	3.25	40.47	43.72
2019-05	4.17	61.22	65.39
2019-06	2.03	60.24	62.27
2019-07	4.86	55.19	60.05
2019-08	4.46	55.04	59.50
2019-09	0.10	3.21	3.31
Total	19.97	298.62	318.59

Table 36. Baseline Energy Consumption of Controlled Plugs During the Demo Period is Shown in Column 2. Measured Energy Consumption of Controlled Plugs is Shown in Column 3. The Difference Between the Columns 2 and 3 Gives the Controlled Plug Energy Savings (Column 4). Column 5 Shows Controlled Plug Energy Savings as a Percentage of the Controlled Plug Baseline Consumption.

Month	Baseline_Controlled (kWh)	Demo Controlled (kWh)	Savings (kWh)	Savings as a percent of Baseline_Controlled (%)
2019-03	4.63	1.10	3.53	76
2019-04	5.34	3.25	2.09	39
2019-05	5.52	4.17	1.35	25
2019-06	5.34	2.03	3.31	62
2019-07	5.52	4.86	0.66	12
2019-08	5.52	4.46	1.06	19
2019-09	0.37	0.10	0.27	72
Total	32.24	19.97	**12.27**	**38**

Table 37. Plug-load Demo Savings: It Is Also Possible to Express Energy Savings of Controlled Plugs as a Percentage of the Total (Controlled + Uncontrolled Plug) Baseline Energy Consumption.

The baseline consumption of controlled plugs (column 2) is added to the energy consumption of uncontrolled plugs (column 3) to determine the total (controlled + uncontrolled) baseline in column 4. Energy savings of controlled plugs (column 5) is shown as a percentage of the total baseline energy in column 6.

Month	Baseline_Controlled (kWh)	Uncontrolled (kWh)	Baseline_Total (kWh)	Savings (kWh)	Savings as a percent of Baseline_Total (%)
2019-03	4.63	23.25	27.88	3.53	12.7
2019-04	5.34	40.47	45.81	2.09	4.6
2019-05	5.52	61.22	66.74	1.35	2.0
2019-06	5.34	60.24	65.58	3.31	5.0
2019-07	5.52	55.19	60.71	0.66	1.1
2019-08	5.52	55.04	60.56	1.06	1.8
2019-09	0.37	3.21	3.58	0.27	7.5
Total	32.24	298.62	330.86	**12.27**	**3.7**

Table 38. Estimated Yearly Energy Consumption of 14 Plug-loads without Any Occupancy Control (column 1), or with Occupancy Control of Controlled Plugs (column 2).

Estimated yearly energy savings from occupancy control in column 3. For details, see 1.1.2.

Total yearly plug-load consumption (no occupancy control)	Total yearly plug-load consumption (with occupancy control of controlled plugs)	Yearly plug-load energy savings from occupancy control of controlled plugs
553 kWh/year	528 kWh/year	**25 kWh/year**

Table 39. Mean Percentage of Daily Plug-load Energy Consumption Occurring Outside of Business Hours (6 am – 5 pm).

Shown separately for baseline and demo periods. Note the drop for controlled plugs from 44% (baseline period) to 9% (demo period), indicating energy savings from occupancy control.

	Controlled (%)	Uncontrolled (%)	Total (%)
Baseline period	44	52	50
Demo period	9	48	46

5.5.4 PO4: Lighting Quality

High-Bay Area - Original Baseline HID Lighting: The baseline measurements taken in the high-bay area of Building 3907 at Tinker AFB show that there was insufficient lighting. The original metal halide lamps, which have now been replaced, were deteriorated and multiple lamps in the high-bay area were burned out. The color rendering capabilities of the original luminaires was also low, particularly the luminaires ability to render the color red. The poor capability of the luminaires to render red colors reduces workers ability to identify colors properly, which can reduce productivity and cause fatigue in color critical tasks. The vertical illuminance is also far below the criteria for high-bay areas. Vertical illuminance aids in reading instruments, gauges and monitors on the large equipment that exists in the space. Lastly, the original direct lighting system was a major source of glare in the high-bay area and created large contrast between the luminaires and the ceiling. This large contrast may cause visual fatigue for those working in the area.

The walls and ceiling in the high-bay area do not have sufficient light, resulting in higher contrast between the surfaces and the luminaires. Dark ceilings and walls may result in a visually uncomfortable space.

Note: For all Illuminance and luminance measurements, six measurements were taken on each surface.

Table 40. High-Bay Area Horizontal Illuminance – Baseline HID Lighting.

	Measured Values				Calculated Values		
	Average (fc)	Max:Min	Avg:Min	% Off of Criteria	Average (fc)	Max:Min	Avg:Min
Criteria per UFC 3-530-01	50	-	<5:1		50	-	<5:1
Section 1	22	3.4	1.9	43%	40	6.3	4.2
Section 2	22	8.2	4.6	43%	49	9.4	4.8
Section 3	26	3.3	2.3	51%	61	9.7	5.2
Section 4	29	1.9	1.5	58%	56	9.0	4.6
Section 5	36	2.6	1.7	73%	60	10.1	5.2
Section 6	42	1.7	1.3	83%	56	265.3	140.7
Section 7	39	2.4	1.7	78%	64	265.8	159.2
Section 8	32	2.4	1.6	63%	39	267	130.9
Pumps & Manifolds	23	8.4	5.0	45%	51	11.9	5.4
NDI/Machine	37	2.8	1.9	74%	58	290.5	145.4

Table 41. High-Bay Area Vertical Illuminance – Baseline HID Lighting.

	Average (fc)	Max:Min	Avg:Min
Criteria	30.0	-	-
High-Bay Area	15.3	5.8	3.1

Table 42. High-Bay Area Surface Luminance – Baseline HID Lighting.

	Average (cd/m^2)	Maximum (cd/m^2)	Max:Min	Avg:Min
Floor	48	103	4.5	2.1
Walls	45	90	5.6	2.8
Ceiling	25	40	3.5	2.2
Equipment	28	69	7.4	3.0
Luminaires	24,164	48,360	5.5	2.7

- Spectral Data:
  - Average Color Temperature: 4340K
  - Average CRI: 75

High-Bay Area – Advanced LED Lighting: The measurements taken in the high-bay area of Building 3907 show that the improved lighting system meets or exceeds criteria. The lighting layout in the space was not able to change, but the LED luminaires installed have improved distribution, increasing the uniformity of light in the space and providing light in places where the old lighting system was not capable of doing so. The LED luminaires also increase the vertical illuminance in the space to meet criteria, which aids workers in reading instruments, gauges and monitors on the large equipment that exists in the space. The occupied light level in the space has been dimmed to 70% after occupants mentioned discomfort under full light output. Measurements in this report were recorded under those conditions.

The luminaire to ceiling contrast was reduced when changing from HID to LED luminaires resulting in lower glare potential. The LED system improved ceiling uniformity which may improve visual comfort and perceived brightness of the space. The wall to ceiling contrast was increased slightly with the LED lights, but there was significantly more light on the walls. More light on the walls may improve visual comfort and perceived brightness of the space.

Table 43. High-Bay Area Horizontal Illuminance – Advanced LED Lighting.

	Measured Values				Baseline Values		
	Average (fc)	Max:Min	Avg:Min	% Off of Criteria	Average (fc)	Max:Min	Avg:Min
Criteria per UFC 3-530-01	50	-	<5:1		50	-	<5:1
Section 1	38	2.6	1.5	77%	22	3.4	1.9
Section 2	48	4.0	2.1	96%	22	8.2	4.6
Section 3	53	4.5	3.3	105%	26	3.3	2.3
Section 4	67	1.8	1.5	133%	29	1.9	1.5
Section 5	66	3.4	2.4	132%	36	2.6	1.7
Section 6	63	3.8	2.5	126%	42	1.7	1.3
Section 7	54	4.2	2.4	107%	39	2.4	1.7
Section 8	47	2.6	1.7	93%	32	2.4	1.6
Pumps & Manifolds	47	5.8	3.0	93%	23	8.4	5.0
NDI/Machine	58	4.4	2.7	117%	37	2.8	1.9

Table 44. High-Bay Area Vertical Illuminance – Advanced LED Lighting.

	Average (fc)	Max:Min	Avg:Min
Criteria	30	-	-
Industrial High-Bay Area	30	2.4	1.5

Table 45. High-Bay Area Surface Luminance – Advanced LED Lighting.

	Average (cd/m^2)	Maximum (cd/m^2)	Max:Min	Avg:Min
Floor	138	388	7.9	2.8
Walls	107	190	4.4	2.5
Ceiling	53	78	2.5	1.7
Luminaires	33,978	61,040	6.1	3.4

- Spectral Data:
  - Average Color Temperature: 4340K
  - Average CRI: 75

Office Area Baseline Fluorescent Lighting: The previous lighting in the office spaces of Building 3907 far exceeded the criteria. The original layout and light output of the luminaires was placing too much light on the working surfaces throughout all spaces. This much light may cause fatigue for workers and result in reduced productivity. Multiple employees in the general office area noted their discomfort with the amount of glare. This can be seen in the comparison of the measured vertical illuminance values to the criteria for vertical illuminance. Reducing the amount of light on the work plane in this area helped reduce energy costs and also improved worker's productivity and wellbeing.

Throughout the administrative area, the luminaire to ceiling ratio was high, resulting in high contrast. High contrast may cause visual fatigue and discomfort. Additional light on the walls may help reduce contrast and increase visual comfort.

Table 46. Office Area Surface Luminance – Baseline Fluorescent Lighting.

Luminance - General Office Area Florescent Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	58	225	22.5	5.8
Walls	60	109	6.1	3.3
Ceiling	33	69	4.9	2.3
Desktop	93	117	1.9	1.5
Luminaires	1,820	6,070	47.4	14.2
Windows	2,555	3,720	22.5	7.2

Luminance - Conference Room Florescent Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	10	17	2.8	1.7
Walls	38	57	3.5	2.2
Ceiling	23	23	1.0	1.0
Desktop	29	32	1.3	1.2
Luminaires	618	1,550	12.0	5.2
White Board	50	60	1.4	1.1

Luminance - Engineering Special Purpose Florescent Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	21	31	3.4	2.4
Walls	86	106	1.9	1.5
Ceiling	48	73	2.1	1.4
Desktop	465	168	3.7	2.4
Luminaires	2,920	3,830	15.0	6.3

- Spectral Data:
  - Conference Room
    - Average Color Temperature: 3830K
    - Average CRI: 82
  - Engineering Special Purpose
    - Average Color Temperature: 3790K
    - Average CRI: 82
  - Office Space
    - Average Color Temperature: 3790K
    - Average CRI: 82

Table 47. Office Area Horizontal Illuminance Baseline Fluorescent Lighting.

Horizontal Illuminance - Office Area Baseline Fluorescent Lighting	Measured Values				Calculated Values		
	Avg (fc)	Max/ Min	Avg/ Min	% Off of Criteria	Avg (fc)	Max/ Min	Avg/ Min
Criteria	30		2:1		30		2:1
Conference Room	46	3.0	2.0	153%	77	3.2	2.2
Counsel Room	42			140%	32	3.2	2.0
Engineering Special Purpose	72	2.7	2.0	240%	76	4.0	3.0
Engineering Supervisor	48			160%	52	2.3	1.6
Planning Special Purpose	45	1.8	1.5	150%	74	2.5	1.9
Schedule Supervisor	65			217%	52	3.2	2.0
Desk 1_Top	35	2	2.0	116%	35	3.6	2.2
Desk 2_Top	37	1.2	1.1	122%	40	3.3	1.9
Desk 3_Top	44	1.3	1.2	145%	34	2.6	1.9
Desk 4_Top	39	1.7	1.4	131%	42	2.9	1.8
Desk 5_Top	45	1.5	1.3	149%	45	2.8	1.9
Desk 6_Top	*				33	2.9	1.9
Desk 7_Top	27	1.3	1.2	89%	23	2.7	1.9
Desk 8_Top	46	1.6	1.4	153%	48	2.4	1.8
Desk 9_Top	36	3.1	2.1	120%	54	2.4	1.9
Desk 10_Top	36	4	2.7	121%	45	2.6	1.8
Desk 11_Top	*				44	2.3	1.8
Desk 12_Top	42	1.4	1.2	138%	54	2.6	2.0
Desk 13_Top	51	1.4	1.2	169%	60	1.4	1.2
Desk 14_Top	45	1.8	1.4	149%	66	1.7	1.5
Desk 15_Top	42	1.9	1.5	141%	57	1.8	1.4
Desk 16_Top	53	1.5	1.3	178%	58	1.9	1.4
Desk 17_Top	46	1.5	1.3	154%	66	1.6	1.4
Desk 18_Top	52	1.2	1.1	173%	52	2.1	1.5
Desk 19_Top	34	1.2	0.7	113%	64	1.3	1.1
Desk 20_Top	42	1.9	1.4	140%	67	1.4	1.2
Desk 21_Top	49	1.2	1.1	163%	56	1.8	1.4
Desk 22_Top	*				40	2.6	1.9
Desk 23_Top	51	1.6	1.3	169%	52	2.0	1.6
Desk 24_Top	46	1.8	1.4	152%	55	2.1	1.6
Desk 25_Top	51	1.3	1.2	169%	44	2.2	1.6
Desk 26_Top	*				25	4.5	2.5
Desk 27_Top	*				25	2.0	1.5
Desk 28_Top	41	1.6	1.3	137%	35	2.7	1.8
Desk 29_Top	22	2.7	2.1	72%	40	2.7	1.8
Desk Top Averages:	**42**	**1.7**	**1.4**	**140%**	**47**		

* Task light was on at this work station

Table 48. Office Area Vertical Illuminance Fluorescent Lighting (Baseline).

Vertical Illuminance - Office Area Fluorescent Lighting	Measured Illuminance (fc)	% Off of Criteria	Calculated Illuminance (fc)
Criteria	15	-	15
Desk 1 Facing Monitor	14	93%	10
Desk 2 Facing Monitor	15	101%	12
Desk 3 Facing Monitor	18	117%	14
Desk 4 Facing Monitor	15	103%	13
Desk 5 Facing Monitor	15	100%	14
Desk 6 Facing Monitor	15	97%	13
Desk 7 Facing Monitor	7	45%	9
Desk 8 Facing Monitor	24	160%	31
Desk 9 Facing Monitor	17	116%	33
Desk 10 Facing Monitor	18	122%	36
Desk 11 Facing Monitor	23	152%	34
Desk 12 Facing Monitor	14	90%	31
Desk 13 Facing Monitor	30	200%	36
Desk 14 Facing Monitor	20	136%	43
Desk 15 Facing Monitor	18	120%	44
Desk 16 Facing Monitor	26	175%	44
Desk 17 Facing Monitor	25	168%	42
Desk 18 Facing Monitor	24	157%	33
Desk 19 Facing Monitor	20	133%	37
Desk 20 Facing Monitor	26	173%	42
Desk 21 Facing Monitor	20	133%	44
Desk 22 Facing Monitor	33	222%	31
Desk 23 Facing Monitor	20	136%	32
Desk 24 Facing Monitor	22	146%	35
Desk 25 Facing Monitor	19	125%	34
Desk 26 Facing Monitor	21	139%	25
Desk 27 Facing Monitor	15	97%	14
Desk 28 Facing Monitor	13	87%	19
Desk 29 Facing Monitor	4	28%	10
Facing Monitor Average	**19**	127%	**28**

Office Area Phase 1 LED Uplight/Downlight Pendant Lighting: The Phase 1 lighting in the office spaces of Building 3907 exceeded criteria, but indirect lighting has reduced glare and high contrast, creating a more visually comfortable environment. Occupants in private offices and at the reception desk (desk number 26) asked for 40% light output, the general office area was set to 75% light output and the conference rooms were set to 70% light output. The measurements in this report were taken under the requested light outputs. Most occupants in the space said that they enjoyed the new lighting and were comfortable with the light levels. Few employees thought that the lighting in the space was too dim and one of those employees had nonoperational task lighting. The reduction in glare and improved uniformity was noticed by employees who previously sat directly below a baseline troffer.

Throughout the administrative office area, the luminaire to ceiling contrast was reduced, but there was less uniformity on the ceiling, creating bright and dark areas. Because the pendants were so close to the ceiling, the light did not have enough room to spread across the ceiling, resulting in a non-uniform ceiling. The luminance of the walls was also reduced with the pendants, resulting in a space that does not feel as bright.

Table 49. Office Area Surface Luminance – Phase 1 LED Lighting.

Luminance - General Office Area Phase 1 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	7	11	3.6	2.4
Walls	40	59	2.4	1.6
Ceiling	322	1,211	75.7	20.1
Desktop	42	84	7.0	3.5
Luminaires	4,986	6,383	1.8	1.4
Luminance - Conference Room Phase 1 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	11	13	1.3	1.2
Walls	80	95	1.7	1.5
Ceiling	258	429	7.8	4.7
Desktop	30	35	1.3	1.1
Luminaires	4,464	7,022	2.9	1.8
White Board	89	111	1.7	1.4
Luminance - Engineering Special Purpose Phase 1 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	7	10	2.4	1.7
Walls	45	53	1.4	1.2
Ceiling	163	276	5.2	3.1
Desktop	8	9	1.2	1.1
Luminaires	2,564	3,386	2.0	1.5

- Spectral Data:
  - Conference Room
    - Average Color Temperature: 3490K
    - Average CRI: 85
  - Engineering Special Purpose
    - Average Color Temperature: 3497K
    - Average CRI: 85
  - Office Space
    - Average Color Temperature: 3506K
    - Average CRI: 85

Table 50. Office Area Horizontal Illuminance Phase 1 LED Lighting.

Horizontal Illuminance - Office Area LED Lighting Phase 1	Measured Values with Daylight				Measured Values without Daylight				Baseline Values
	Avg (fc)	Max/ Min	Avg/ Min	% Off of Criteria	Avg (fc)	Max/ Min	Avg/ Min	% Off of Criteria	Avg (fc)
Criteria	30	2:1			30	2:1			30
Conference Room	60	2.0	1.5	199%	60	2.0	1.5	199%	46
Engineering Special Purpose	35	9.6	4.0	115%	35	9.6	4.0	115%	72
Engineering Supervisor	39			130%	39			130%	48
Planning Special Purpose	42	0.2	0.1	141%	42	0.2	0.1	141%	45
Schedule Supervisor	33			108%	33			108%	65
Desk 1_Top	30			100%	27			90%	35
Desk 2_Top	66			219%	45			151%	37
Desk 3_Top	53			176%	30			101%	44
Desk 4_Top	24			80%	24			80%	39
Desk 5_Top	51			171%	51			171%	45
Desk 6_Top	52			172%	52			172%	*
Desk 7_Top	25			82%	25			82%	27
Desk 8_Top	55			182%	43			144%	46
Desk 9_Top	40			133%	40			133%	36
Desk 10_Top	37			124%	39			131%	36
Desk 11_Top	39			131%	40			132%	*
Desk 12_Top	*				*				42
Desk 13_Top	43			142%	42			140%	51
Desk 14_Top	40			133%	38			127%	45
Desk 15_Top	40			133%	39			130%	42
Desk 16_Top	36			120%	36			120%	53
Desk 17_Top	39			129%	35			117%	46
Desk 18_Top	56			185%	56			185%	52
Desk 19_Top	51			171%	51			171%	34
Desk 20_Top	51			169%	51			169%	42
Desk 21_Top	51			169%	51			169%	49
Desk 22_Top	53			177%	53			177%	*
Desk 23_Top	*				*				51
Desk 24_Top	51			171%	51			171%	46
Desk 25_Top	53			178%	53			178%	51
Desk 26_Top	27			91%	27			91%	*
Desk 27_Top	22			72%	19			64%	*
Desk 28_Top	18			59%	18			61%	41
Desk 29_Top	12			41%	8			27%	22
Desk Top Averages:	**41**			137%	**39**			129%	**42**

* Task light was on at this work station

Table 51. Office Area Vertical Illuminance Phase 1 LED Lighting.

Vertical Illuminance (fc) Office Area LED Lighting Phase 1 With Daylight	With Daylight		Without Daylight		Baseline Conditions Illuminance (fc)
	Avg (fc)	% Off Of Criteria	Avg (fc)	% Off Of Criteria	
Criteria	15	-	15	-	15
Desk 1 Facing Monitor	20	134%	22	143%	14
Desk 2 Facing Monitor	30	197%	16	105%	15
Desk 3 Facing Monitor	19	125%	18	123%	18
Desk 4 Facing Monitor	15	97%	15	97%	15
Desk 5 Facing Monitor	21	141%	21	141%	15
Desk 6 Facing Monitor	30	201%	30	201%	15
Desk 7 Facing Monitor	10	65%	10	65%	7
Desk 8 Facing Monitor	30	202%	25	165%	24
Desk 9 Facing Monitor	18	120%	14	92%	17
Desk 10 Facing Monitor	20	132%	18	122%	18
Desk 11 Facing Monitor	21	139%	20	131%	23
Desk 12 Facing Monitor	24	160%	24	160%	14
Desk 13 Facing Monitor	43	287%	18	119%	30
Desk 14 Facing Monitor	38	256%	21	137%	20
Desk 15 Facing Monitor	37	248%	24	161%	18
Desk 16 Facing Monitor	16	110%	16	110%	26
Desk 17 Facing Monitor	35	232%	14	94%	25
Desk 18 Facing Monitor	36	237%	36	237%	24
Desk 19 Facing Monitor	32	216%	32	216%	20
Desk 20 Facing Monitor	38	250%	38	250%	26
Desk 21 Facing Monitor	37	250%	37	250%	20
Desk 22 Facing Monitor	41	273%	41	273%	33
Desk 23 Facing Monitor	43	284%	43	284%	20
Desk 24 Facing Monitor	37	250%	37	250%	22
Desk 25 Facing Monitor	35	235%	35	235%	19
Desk 26 Facing Monitor	3	21%	3	21%	21
Desk 27 Facing Monitor	16	107%	12	77%	15
Desk 28 Facing Monitor	10	65%	9	61%	13
Desk 29 Facing Monitor	10	63%	7	45%	4
Facing Monitor Average	**26**	176%	**23**	150%	**19**

Office Area Phase 2 LED Troffer Lighting: The Phase 2 lighting in the office spaces of Building 3907 meets the horizontal illuminance criteria and the lighting feels appropriate for the space. The vertical illuminance is significantly lower than that measured during Phase 1, and the original baseline lighting in the space, but essentially meets the vertical illuminance criteria. Most occupants in the space said that they like the new lighting and are comfortable with the light levels. The LED troffer lights installed have less glare than the original fluorescent troffer lights, and no complaints or issues were heard while taking measurements. Occupants in private offices have asked for 40% light output, the general office area is set to 60% light output and the conference rooms are set to 60% light output. The measurements in this report were taken under the requested light outputs.

The LED troffer lights had similar luminaire to ceiling, and ceiling to wall contrast as the original fluorescent lights. The ceilings were darker, but more uniformly illuminated than the pendant lights. Visual comfort is expected to be similar to the original fluorescent lighting.

Table 52. Office Area Surface Luminance Phase 2 LED Lighting.

Luminance - General Office Area Phase 2 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	12	16	2.3	1.7
Walls	45	53	1.5	1.3
Ceiling	27	40	2.5	1.6
Desktop	42	51	1.5	1.3
Luminaires	2,559	6,155	54.0	22.5

Luminance - Conference Room Phase 2 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	9	13	1.7	1.2
Walls	58	91	3.7	2.4
Ceiling	27	35	1.7	1.3
Desktop	34	56	2.6	1.6
Luminaires	5,073	7,407	1.9	1.3
White Board	68	76	1.4	1.3

Luminance - Engineering Special Purpose Phase 2 LED Lighting				
	Average (cd/m^2)	**Max (cd/m^2)**	**Max:Min**	**Avg:Min**
Floor	8	15	4.8	2.6
Walls	100	167	2.6	1.6
Ceiling	33	41	1.6	1.3
Desktop	53	90	6.9	4.1
Luminaires	4,106	5,064	1.7	1.3

- Spectral Data:
  - Conference Room
    - Average Color Temperature: 3997K
    - Average CRI: 86
  - Engineering Special Purpose
    - Average Color Temperature: 4105K
    - Average CRI: 86
  - Office Space
    - Average Color Temperature: 4067K
    - Average CRI: 86

Table 53. Office Area Horizontal Illuminance Phase 2 LED Lighting.

Horizontal Illuminance (fc) - Office Area LED Lighting Phase 2	Measured Values without Daylight				Baseline Values
	Avg (fc)	Max/ Min	Avg/ Min	% Off of Criteria	Avg (fc)
Criteria	30	<2:1			30
Conference Room	57	1.9	1.5	191%	46
Engineering Special Purpose	52	1.6	1.3	172%	72
Engineering Supervisor	27			89%	48
Planning Special Purpose	51	1.1	1.0	169%	45
Schedule Supervisor	25			82%	65
Desk 1_Top	21	1.8	1.4	69%	35
Desk 2_Top	23	1.7	1.3	76%	37
Desk 3_Top	25	1.5	1.2	84%	44
Desk 4_Top	32	1.1	1.0	106%	39
Desk 5_Top	28	1.9	1.5	93%	45
Desk 6_Top	*	*	*	*	*
Desk 7_Top	17	1.1	1.0	55%	27
Desk 8_Top	27	1.1	1.0	89%	46
Desk 9_Top	24	1.5	1.2	78%	36
Desk 10_Top	24	1.6	1.3	79%	36
Desk 11_Top	31	1.2	1.1	103%	*
Desk 12_Top	29	1.0	1.0	96%	42
Desk 13_Top	33	1.1	1.1	108%	51
Desk 14_Top	27	2.1	1.6	91%	45
Desk 15_Top	24	2.2	1.6	80%	42
Desk 16_Top	3	1.1	1.0	111%	53
Desk 17_Top	29	1.0	1.0	96%	46
Desk 18_Top	23	1.0	1.0	77%	52
Desk 19_Top	34	1.0	1.0	113%	34
Desk 20_Top	33	1.1	1.1	111%	42
Desk 21_Top	30	1.3	1.1	98%	49
Desk 22_Top	27	1.3	1.1	91%	*
Desk 23_Top	25	1.3	1.2	84%	51
Desk 24_Top	28	1.3	1.2	93%	46
Desk 25_Top	26	1.0	1.0	87%	51
Desk 26_Top	19	1.5	1.2	65%	*
Desk 27_Top	21	1.8	1.5	69%	*
Desk 28_Top	79	8.2	3.4	263%	41
Desk 29_Top	14	1.1	1.1	48%	22
Desk Top Averages:	**29**			95%	**42**

* Task light was on at this work station during measurements

Table 54. Office Area Vertical Illuminance Phase 2 LED Lighting.

Vertical Illuminance (fc) - Office Area LED Lighting Phase 2	Measured Values w/out Daylight		
	Avg (fc)	% Off of Criteria	Baseline Values
	15	-	15
Desk 1 Facing Monitor	8	51%	14
Desk 2 Facing Monitor	11	74%	15
Desk 3 Facing Monitor	12	79%	18
Desk 4 Facing Monitor	13	86%	15
Desk 5 Facing Monitor	9	59%	15
Desk 6 Facing Monitor	21	140%	15
Desk 7 Facing Monitor	5	34%	7
Desk 8 Facing Monitor	16	107%	24
Desk 9 Facing Monitor	13	84%	17
Desk 10 Facing Monitor	15	102%	18
Desk 11 Facing Monitor	14	92%	23
Desk 12 Facing Monitor	13	84%	14
Desk 13 Facing Monitor	16	105%	30
Desk 14 Facing Monitor	14	95%	20
Desk 15 Facing Monitor	13	88%	18
Desk 16 Facing Monitor	15	102%	26
Desk 17 Facing Monitor	17	110%	25
Desk 18 Facing Monitor	15	100%	24
Desk 19 Facing Monitor	18	120%	20
Desk 20 Facing Monitor	15	98%	26
Desk 21 Facing Monitor	15	98%	20
Desk 22 Facing Monitor	15	99%	33
Desk 23 Facing Monitor	17	110%	20
Desk 24 Facing Monitor	15	102%	22
Desk 25 Facing Monitor	17	116%	19
Desk 26 Facing Monitor	9	63%	21
Desk 27 Facing Monitor	7	46%	15
Desk 28 Facing Monitor	8	50%	13
Desk 29 Facing Monitor	10	64%	4
Facing Monitor Average	**13**	88%	**19**

6.0 PERFORMANCE ASSESSMENT

6.1 PO1: LIGHTING ENERGY USAGE

Associated Performance Objectives	**PO1: Lighting Energy Usage** Energy consumption from lighting in office buildings and high-bay areas
Performance Objective Analysis Overview	The principal analysis objective is to obtain an accurate measurement of the total lighting energy consumption and energy cost in the two demonstration areas for three lighting solutions: existing lighting equipment (baseline) and two high-efficiency LED lighting solutions to be installed and evaluated. The baseline energy consumption of lighting in the demonstration areas was measured with Dent electric meters for a period of twelve months at the beginning of the project. Then, the baseline light fixtures were replaced with the first advanced lighting solution. In the high-bay area, those operated for ten months, while in the office area the first lighting solution (pendants) operated for five months. After five months, the office area lighting solution was replaced by the second advanced solution (troffers), which operated for an additional five months. Energy consumption of all three lighting solutions were measured and compared. By reporting measured reductions in lighting energy costs achieved by the two advanced lighting solutions relative to energy costs of the baseline lighting fixtures, we will enable informed cost-benefit decision making by government entities in future government lighting projects.
Statistical Methodologies	We measured and report total monthly energy consumption of the two advanced lighting solutions in each of the two demonstration areas (high-bay and office areas) using Dent energy meters on lighting circuits. Each of the advanced solutions were operated and measured for five months. We also report the total energy used in each five-month period. We estimate the baseline lighting energy consumption during those two five-month periods as follows: First, we measured daily lighting energy consumption of the baseline lighting equipment over a period of twelve months (before the first advanced solution is installed). From this data, we compute the mean daily energy consumption of the baseline lighting equipment. Then, for each month that advanced lighting solutions were installed, we compute an estimated energy consumption of the baseline equipment during that period by multiplying our measured mean daily baseline energy consumption by the number of days in the month under evaluation.
Graphical Methodologies	We produce separate bar charts showing measured monthly lighting energy consumption for both the high-bay and office demonstration areas. We produce separate charts for each of the two advanced lighting solutions. In each bar chart, we also graph the estimated energy consumption of the baseline lighting equipment to enable direct comparison of the advanced lighting solutions vs. the baseline lighting solution.
Modeling and Simulation	N/A
Sensitivity Analysis	N/A

Anecdotal Perspectives	N/A
Industry Standards	IPMVP, FEMP guidelines [IPVMP, FEMP]
Internal Validity	We monitored the lighting energy data regularly during the demonstration phase to check for concern over data integrity from Dent data loggers. Furthermore, we compared lighting energy consumption measurements (measured internally by the Enlighted lighting solution) against measurements made by Dent data loggers on lighting circuits to confirm that Dent data loggers are performing as expected.
External Validity	This project separately tests advanced lighting solutions in two types of environments commonly found in military installations: an office space with open cubicles, conference rooms, and private offices; and a large, open high-bay area. The findings from the high-bay area will be broadly applicable to many locations in military facilities with large, open areas, such as warehouses, manufacturing areas, shipping/receiving docks, etc., while the open office findings will be relevant to typical office environments. By evaluating lighting in both types of environments, we will maximize the applicability of the findings to other military installations. Furthermore, by demonstrating large reductions in lighting energy consumption while improving lighting controls and lighting quality, this project seeks to facilitate easier adoption of this lighting technology at other government sites.

In the following sections, we first analyze the baseline lighting energy consumption of the original HID lights, which were present in the high-bay, and the energy consumption of the original fluorescent troffer fixtures, which were present in the office area, before the installation of the demo system. Next, we analyze the energy consumption and savings of the demo system relative to the baseline. We note that in the office area, two types of demo lighting solutions were installed: in Phase 1, a pendant lighting solution with direct/indirect lighting, and later in Phase 2, a troffer solution. We analyze these lighting options separately. Finally, we performed an in-depth analysis of the sources of energy savings achieved by the demo system compared to the baseline. The sources of energy savings include occupancy detection and daylight harvesting.

6.1.1 Baseline lighting energy consumption

To quantify the baseline lighting energy usage of the original (non-LED) lights, we installed Dent data loggers at circuit breakers to monitor lighting energy consumption in the office and high-bay areas over a ten-month period before our demo system was installed. In this section, we analyze the lighting energy consumption data from that baseline period (11/14/2017 to 9/16/2018).

One issue to note is that for the high-bay area, two lighting circuits extended outside of the demonstration area and powered lights in a small area containing restrooms. Hence, the energy consumption reported by Dent data loggers for the high-bay area is greater than the true consumption of the high-bay, since the measurements include the restroom lights outside of the high-bay demo area. We acknowledge this introduces some systematic error into our measurement of high-bay lighting energy consumption. However, the external area is much smaller than the

high-bay area, so we expect the error is small. Furthermore, we note the Dent data loggers were wired to the same circuits before and during the demo period, so the change in energy consumption between those periods should be primarily due to the upgraded lights in the demo area. Hence, the computed energy savings should be accurate. For completeness, we note that there are no such concerns for the office area, since no office lighting circuits extended outside of the office demo area.

Dent data loggers recorded lighting energy consumption in the office and high-bay areas (separately) at 15-minute intervals, and we aggregated this baseline data into daily totals for each area. From this we computed the mean daily lighting energy consumption, which was 57 kWh per day for the office area and 269 kWh per day for the high-bay area. Figure 21 plots the daily energy consumption in the high-bay area (blue dots) as well as the mean daily energy consumption (solid line), and Figure 22 shows the same quantities for the office area.

Total energy consumption of high-bay and office area lights during the baseline period is listed in Table 5, column 2. Column 3 lists the mean daily energy consumption for lights in the office area, high-bay area, and the total (office + high-bay). Column 4 lists the projected yearly baseline lighting energy consumption, which is computed separately for office and high-bay areas using the formula

Projected baseline yearly energy = (mean daily energy) * (365.25 days per year)

For completeness, monthly energy consumption during the baseline period is also listed in Table 6 and plotted in Figure 23.

6.1.2 Energy consumption and savings of the demo system

We next analyze the energy consumption and savings of the demo system lights. We perform the analysis separately for high-bay and office areas.

6.1.2.1 High-bay lighting

The high-bay demo lighting system was commissioned in October 2018, and the high-bay demo period ran from 10/25/2018 to 9/2/2019. Dent data loggers served as our primary measurement device for lighting energy consumption, which was necessary to facilitate direct comparison to the baseline energy measurements. However, the Enlighted lighting system also recorded energy usage data, which served as a backup measurement system for the demo period.

One challenge during the high-bay demo period was that one of the Dent data loggers failed on one of the high-bay lighting circuits on two occasions, resulting in data loss. The first data loss was from 10/25/2018 to 12/6/2018, and the second outage was from 4/6/2019 to 7/22/2019. The outages were detected on regularly-scheduled data retrievals, and the loggers were repaired after each outage, but irrecoverable lighting energy data loss occurred in the high-bay during those periods. However, we used the energy consumption data from the Enlighted lighting system during those outages, as we discuss below.

6.1.2.1.1 Imputing missing high-bay Dent data

The most straightforward approach to dealing with the missing high-bay Dent data would be to directly use energy consumption measurements from the Enlighted during the Dent outage periods. However, this is problematic: in periods where we have both Dent measurements and Enlighted measurements, the two measurements do not precisely agree. There are two likely reasons for this disagreement. First, in the high-bay area, the Dent measurements include energy consumption from a small number of lights outside of the demo area, and energy consumption of those lights are not recorded by the Enlighted system (since they are not part of that system.) Second, it's likely there is some miscalibration in the Enlighted measurements. This is supported by our observations that even in the office area, where the Dent loggers and Enlighted system monitor the same lights, there are small differences in energy consumption measurements reported by the two systems. This is further supported by [Cortese 13] (see page 87), who similarly reported small disagreements between energy consumption reported by an Enlighted system compared to a calibrated energy meter.

In Figure 24, we plot the daily high-bay lighting energy consumption reported by Dent loggers vs the Enlighted system over a three-month period (1/1/2019 – 3/31/2019). As can be seen in the figure, the two measurements are linearly related. A least-squares linear regression between the two measurements over the three-month fitting period yielded a best-fit line of

(daily high-bay energy Dent) = 0.9382 * (daily high-bay energy Enlighted) + (5.87 kWh).

The fit's R^2 was 0.9994, indicating a very high degree of linear correlation. To validate that this relationship held over time, we similarly plotted Dent vs Enlighted daily high-bay energy measurements over the period 8/1/2019 to 8/31/2019 in Figure 25, along with the same best-fit line. As can be seen in Figure 25, the linear fit continued to model the relationship between the two measurements with excellent agreement.

We next used the linear model to fill in the missing Dent data: for each day in the outage periods where high-bay Dent data was missing, we used the total daily energy consumption reported by the Enlighted system and corrected it with the linear formula to estimate the total daily energy consumption (as Dent loggers would have measured it):

(daily high-bay energy Dent) = 0.9382 * (daily energy Enlighted) + (5.87 kWh)

We then proceeded to analyze the Dent data over the entire high-bay demo period 10/25/2018 to 9/2/2019.

6.1.2.1.2 High-bay energy consumption and saving analysis

Daily high-bay energy consumption over the high-bay demo period is plotted in Figure 26 (red dots). For comparison, the figure also shows energy consumption over the baseline period (blue dots). From the figure, one can see the demo system achieved substantial energy savings in the high-bay.

The mean daily high-bay energy consumption over the demo period was 84 kWh per day, and the total high-bay lighting energy consumption over the demo period was 26,390 kWh. These are shown in columns 1 and 2 of Table 7.

We define the baseline energy consumption over the high-bay demo period as

Demo baseline energy = (mean daily baseline energy) * (number of days in the demo period) ,

where the mean daily baseline energy was 269 kWh per day. This gives a high-bay demo baseline energy consumption of 84,120 kWh (column 3 of Table 7). The energy savings is

Energy savings = Baseline energy – Consumed energy

which is 57,730 kWh (column 4 of Table 7). Finally, we express the high-bay energy savings during the demo period as a percent of the baseline consumption with the formula

$$\text{Energy savings (as \% baseline)} = 100\% * \frac{\text{Energy savings}}{\text{Baseline energy}} .$$

We find the high-bay lighting energy savings was **69%** of the baseline (column 5 of Table 7). This was below the project goal of 80% lighting energy savings relative to baseline.

For completeness, we also compute the expected yearly energy consumption of the high-bay demo lights with the formula

Projected yearly energy consumption = (mean daily energy) * (365.25 days per year),

where the mean daily energy consumption was 84 kWh. The projected yearly baseline energy was computed by the same method (using a baseline mean daily energy consumption of 269 kWh). The difference between the projected yearly baseline and projected yearly energy consumption is the projected yearly energy savings. The projected yearly high-bay energy consumption and energy savings are listed in Table 8.

Finally, Table 9 lists the monthly energy consumption (column 2) and savings (column 4) of the demo system in the high-bay, as well as baseline energy consumption (column 3). Monthly consumption and baseline consumption are also plotted in Figure 27.

6.1.2.2 Office pendant fixtures with direct/indirect lighting

Similar to the high-bay, we used Dent measurements of office lighting energy consumption (which occurred at 15-minute intervals), and we aggregated that into daily energy consumption. There were no losses of office lighting energy consumption data from Dent data loggers, so no imputation of missing data was required. The office pendant lighting demo period ran from 10/25/2018 to 3/24/2019, after which pendant lights were removed and replaced by troffers.

Daily pendant energy consumption over the pendant demo period is plotted in Figure 28 (green dots). For comparison, the figure also shows energy consumption over the baseline period (blue dots) and the office troffer period (red dots). From the figure, one can see both office demo systems (pendant and troffers) achieved substantial energy savings relative to baseline.

The mean daily pendant energy consumption over the pendant demo period was 17 kWh per day, and the total pendant lighting energy consumption over the pendant demo period was 2,520 kWh. These are shown in columns 1 and 2 of Table 10.

Once again, we define the baseline energy consumption over the pendant demo period as

Demo baseline energy = (mean daily baseline energy) * (number of days in the demo period).

The mean daily office baseline energy was 57 kWh per day. This gives baseline energy consumption of 8,589 kWh for the pendant demo period (column 3 of Table 10). The pendant energy savings is computed as

Energy savings = Baseline energy – Consumed energy

which is 6,068 kWh (column 4 of Table 10). The pendant lighting energy savings during the pendant demo period, expressed as a percent of the baseline consumption, is

$$\text{Energy savings (as \% baseline)} = 100\% * \frac{\text{Energy savings}}{\text{Baseline energy}} .$$

We find the pendant lighting energy savings was **71%** of the baseline (column 5 of Table 10). This was also below the project goal of 80% lighting energy savings relative to baseline.

The expected yearly energy consumption of the pendant demo lights is computed with the formula

Projected yearly energy consumption = (mean daily energy) * (365.25 days per year),

where the mean daily energy consumption was 17 kWh. The projected yearly baseline energy was computed by the same method (using a mean daily baseline office energy of 57 kWh). The difference between the projected yearly baseline and projected yearly energy consumption is the projected yearly energy savings. Table 11 lists the projected pendant lighting yearly energy consumption and energy savings.

Finally, Table 12 lists the pendant lighting energy consumption, baseline consumption, and energy savings for each month in the pendant demo period 10/25/2018 to 3/24/2019. Monthly consumption and baseline consumption are plotted in Figure 29.

6.1.2.3 Office troffer lighting

After the pendant lighting demo concluded, pendant lights were removed from the office area and replaced by troffer fixtures. The troffer lighting demo period ran from 3/29/2019 to 9/2/2019. The analysis of troffer data is identical to that of the pendant data.

Daily troffer lighting energy consumption over the troffer demo period is plotted in Figure 28 (red dots). For comparison, the figure also shows energy consumption over the baseline period (blue dots) and the pendant period (green dots).

The mean daily troffer energy consumption over the troffer demo period was 19 kWh per day. That was a slight increase above the pendant average of 17 kWh per day, but it was still far below the baseline office lighting energy consumption of 57 kWh per day. The total troffer lighting energy consumption over the troffer demo period was 2,971 kWh. These are shown in columns 1 and 2 of Table 13.

The baseline energy consumption during the troffer demo period was 8,987 kWh (column 3 of Table 13). This gave a troffer energy savings of 6,016 kWh (column 4 of Table 13). The troffer lighting energy savings during the troffer demo period was **67%** of the baseline energy consumption (column 5 of Table 13). This was below the project goal of 80% lighting energy savings relative to baseline, and also below the savings of 71% achieved by the pendant lights.

Table 14 lists the projected yearly energy consumption and savings of the troffer system.

Table 15 lists monthly energy consumption (column 2) and savings (column 4) of troffer lights compared to baseline consumption (column 3) over the troffer demo period (3/29/2019 to 9/2/2019). Monthly consumption and baseline consumption are plotted in Figure 30.

Finally, Table 16 lists projected yearly energy consumption and energy savings of the entire demo system (high-bay + office). Results are listed separately for (high-bay + pendant lights) and (high-bay + troffer lights).

6.1.2.4 Total lighting: office + high-bay

We also computed projected yearly energy consumption from lighting of the entire demo system (high-bay + office) by adding the projected yearly energy consumptions for the high-bay and office areas. We report these figures separately for (high-bay + pendants) and (high-bay + troffers) in column 2 of Table 16. Similarly, we compute projected yearly energy savings of (high-bay + pendants) and (high-bay + troffers) in column 3 of Table 16. These savings are expressed relative to the total baseline (high-bay + office baseline), as a percentage, in column 4 of Table 16. From column 4, we see the projected yearly savings of (high-bay + pendant) lights is **69%** of baseline, and the savings of (high-bay + office troffer) lights is **68%** of baseline.

6.1.2.5 Breakdown of sources of lighting energy savings

In this section we analyze the sources of energy savings to gauge their relative importance. We do so separately for the high-bay, pendant, and troffer systems.

6.1.2.5.1 High-bay lighting energy savings breakdown

The high-bay demo area did not contain windows or other sources of external illumination, so there was no opportunity for energy savings from daylight harvesting. Instead, the only energy savings occurred from dimming or turning off the lights due to lack of occupancy. Hence, we analyze the amount of savings that occurred due to occupancy control of the lights. Note that for the savings breakdown in this section, we compare the energy usage of the system (with occupancy-based dimming) to the hypothetical scenario of the same LED lights with occupancy control disabled. This allows us to determine the relative importance of occupancy control.

The first task is to determine the amount of power used by each light fixture when it operated at its peak illumination (without any dimming from lack of occupancy). This quantity is different than the fixture's factory-rated power usage because illumination levels of fixtures were adjusted during the installation and commissioning process to ensure desired illumination levels on working surfaces. Hence, the energy consumption must be determined from measurement data. Furthermore, Dent data loggers did not monitor individual fixtures, only circuits containing many fixtures. Hence, we must rely on energy consumption measurements from the Enlighted system to get fixture-level power information.

The simplest approach to determining the peak power usage of each fixture would simply be to take the maximum power reading of each fixture as recorded by the Enlighted system. However, upon inspecting the data, we discovered there are a small number of anomalously-large power readings recorded by the Enlighted system. These are one-off readings, which occur at single time stamps; adjacent power readings are lower in value. An example is shown for one high-bay fixture in Figure 31. From the figure, it is clear that this fixture uses about 105 W of power when it is on at its full brightness (without occupancy-based dimming). However, there is one anomalously high reading (above 120 W) on 6/14/2019. It is unclear if the large readings are real, or bad readings (perhaps due to hardware limitations, or perhaps corrupted packets over the wireless network). Regardless, these anomalous readings are not reflective of the normal energy consumption of the lights. Hence, to filter out these outliers, we estimate the peak energy consumption of each fixture as the 99th quantile of power measurements for that fixture. In Figure 31, the solid red line shows the 99th quantile, which is our estimate of peak power usage for that fixture.

From that peak power usage, we compute the energy consumption each fixture would use if it were on continuously for one day with no occupancy-based dimming. We call this the *always-on baseline*, as it is the daily energy consumption that would arise from that fixture if it were always powered on:

(Always-on baseline, daily) = (peak power usage, in Watts) * (24 hours * 1 kW/1000W)

(Note that this always-on baseline is not related to previous baselines discussed in this report.)

The actual daily energy consumption of each fixture is reduced by occupancy control, which dims or turns off the lights when the space is unoccupied. Hence, we compute the occupancy-based savings as the difference between the always-on baseline and the actual consumption

Occupancy savings = (Always on baseline, daily) – (daily consumption of the fixture)

We compute these quantities daily for each fixture and add them produce totals for the entire high-bay demo area. This is shown in the top graph in Figure 32. Furthermore, we also express the occupancy savings as a percent of the always-on baseline:

$$\text{Occupancy savings, \%} = 100\% * \frac{\text{Occupancy savings,kWh}}{\text{Always-on baseline,kWh}}$$

This is shown in the bottom graph of Figure 32. These quantities are summarized in Table 17. Table 18 lists the occupancy-based savings and energy consumption as a percentage of the always-on baseline. We find occupancy-based savings was 61% of the always-on baseline, and the energy consumption was 39%.

6.1.2.5.2 Pendant lighting energy savings breakdown

Unlike the high-bay area, the office area did contain exterior windows which allowed sunlight to enter the space. Sensors on the Enlighted fixtures detected this additional light and reduced their illumination accordingly, which resulted in energy savings we term *daylight harvesting*. In addition, office lights dimmed or powered off when spaces were unoccupied. Hence, we analyze the amount of office lighting energy savings achieved due to daylight harvesting and occupancy control. We start with daylight harvesting.

The Enlighted system directly reported the amount of energy saved by daylight harvesting per day in the office area. Intuitively, energy savings from daylight harvesting should be greater on clear days than on overcast days. We seek to verify this (to check that the daylight harvesting feature worked correctly.)

To compare daylight savings to sky conditions, we need a way to quantify how clear or cloudy the sky was each day. To do so, we downloaded NOAA local climatological data for Oklahoma City over the demo period. [NOAA-CDO]. This data reported sky coverage, at an hourly frequency, in units of *oktas*, where each okta represents one eighth of the sky covered by clouds. We converted this into a percentage of the sky clear (reported at an hourly frequency) with the formula

$$\text{Percentage sky clear} = 100\% * (1 - \frac{\text{\# oktas coverage}}{8})$$

We needed to combine the hourly values into one sky clarity number per day. We note that daylight harvesting can only occur when the sun is up and the space occupied, so we focus on business hours when the sun is up: we take the hourly values of sky clarity between 7am and 5pm and compute the mean of the sky clarities to get one number per day. In Figure 33, we plot daylight harvesting savings (blue curve, left vertical axis, in kWh) compared to the mean daily sky clarity (red curve, right axis, a percentage). We see the two curves are correlated. This suggests the daylight harvesting feature indeed worked correctly, achieving greater savings on clear days.

Next, we quantify the savings achieved by daylight harvesting and occupancy control. Similar to the high-bay energy breakdown analysis, we compare the energy usage of the system to the hypothetical scenario of the same LED lights with occupancy control and daylight harvesting disabled. This allows us to determine the relative importance of occupancy control and daylight harvesting. We begin by analyzing the pendant solution in this section, followed by the troffer lights in the following section.

We compute the *always-on baseline* energy consumption of pendant lights in the same fashion as high-bay lights: we compute the 99th quantile of power reading per fixture, then compute the total energy of all fixtures in the pendant lighting system if all fixtures were powered on 24 hours per day.

As mentioned, the Enlighted system directly reports the amount of energy saved by daylight harvesting (in kWh) per day in the office area, as well as the energy consumed. The remaining energy reduction below the always-on baseline is due to occupancy control:

Occ. savings, daily = (Always on baseline, daily) – (daily consumption) – (daylight harvesting)

We compute these daily quantities and summarize them in Table 19 and Table 20. We also graph them over a two-week period in Figure 34. The top graph shows quantities in kWh, and the bottom graph shows quantities as a percent of the always-on baseline. For the pendant demo period, we find that over the entire office area, savings due to daylight harvesting was 0.83% of the always-on baseline, and savings from occupancy control was 68% of the always-on baseline.

However, only a small number of office light fixtures were near the exterior window, so it makes sense to separately analyze those fixtures immediately along the window. Hence, we repeat the prior analysis, but only include office pendant fixtures directly adjacent to the window.

The results are summarized in Table 21 and Table 22 and plotted in Figure 35. We find that for pendant lights adjacent to the window, savings due to daylight harvesting was greater – 1.9% of the always-on baseline, and savings from occupancy control was 63% of the always-on baseline. This shows that fixtures near the window achieved greater energy reduction from daylight harvesting compared to the office area average.

6.1.2.5.3 Troffer lighting energy savings breakdown

We repeat the same lighting energy breakdown analysis for the troffer system as was used for the pendant system. Results for the entire office area are summarized in Table 23 and Table 24 and plotted in Figure 36. We find that, over the entire office area, the energy savings from daylight harvesting was 2.4% of the always-on baseline, and savings from occupancy control was 54% of the always-on baseline. Results which only include light fixtures directly along the windows are listed in **Table 25** and Table 26 and plotted in Figure 37. We find that for troffers along the window, energy savings from daylight harvesting was 6.2% of the always-on baseline, and savings from occupancy control was 53% of the always-on baseline.

We observe that energy savings from occupancy (as a percent of the always-on baseline) was less for the troffer period (54%) than for the pendant period (68%.) This was caused by occupancy sensors which were overly-sensitive in the troffer period. We observed in the Enlighted data that during the troffer period, occupancy sensors frequently recorded intermittent occupancy in overnight periods (when the office area was unoccupied). This caused lights to power on intermittently throughout the overnight periods, resulting in increased energy consumption and decreased occupancy-based savings. For further discussion, see Section 8.1.4.

We note that savings from daylight harvesting were greater in the troffer period than over the pendant period. This may in part be due to brighter and longer days during the troffer period (3/24/2019 to 9/2/2019), which occurred over the summer, than the pendant period (10/25/2018 to 3/24/2019), which occurred over winter. This may also be in part due to reduced occupancy savings achieved by the troffer system. (For further discussion, see Section 8.1.4.) Specifically, if occupancy control was less effective in the troffer system than in the pendant system, the troffer lights would be on more of the time, including during periods when areas were unoccupied, but sunlight was available. This would allow more opportunity for savings from daylight harvesting.

6.2 PO2: HVAC ENERGY SAVINGS

Associated Performance Objectives	**PO2: HVAC Energy Savings** Energy consumption from the HVAC system in the selected areas.
Performance Objective Analysis Overview	We compared the HVAC energy consumption of the demonstration solution (with occupancy-based dynamic HVAC control) in the demo areas against the baseline (no dynamic HVAC control). We reported the reduction in HVAC energy consumption of the demonstration solution relative to the energy consumption of the baseline. We operated the dynamic HVAC control in a 2+1 mode, with dynamic occupancy-based HVAC control enabled for two subsequent days, then disabled for the third day, repeating. This allowed us to compare energy savings of dynamic HVAC control vs baseline (no dynamic HVAC control) throughout the demo period, with a goal of controlling for variations caused by changes in weather, occupancy patterns, and HVAC equipment condition. This approach was necessary as energy consumption for cooling and fans changed significantly throughout the demo period.
Statistical Methodologies	Investigation of the data revealed that HVAC energy consumption was not strongly dependent upon outside temperatures (see Section 6.2.2 and 5.5.2.3 for details and results). This surprising finding may be related to several serious mechanical problems present in the building's HVAC system, including fans which were broken for several months, valves that were stuck and non-functional, and components placed into manual override mode as later described in Section 8.1.3. We expect these issues seriously impaired HVAC system's ability to respond to control signals and modulate energy consumption, which may explain the low correlation between energy consumption and outside temperature. While HVAC energy consumption was not strongly dependent upon outside temperature, HVAC energy consumption patterns changed significantly on several dates due to equipment failures, repairs, maintenance, and equipment being placed into manual override mode by technicians in the building.
Graphical Methodologies	Time series plots of energy consumed by the HVAC system show the alternate operation of the baseline HVAC and the new occupancy optimized operation. Energy savings realized by occupancy control are plotted as time series as well. Energy consumption versus weather are graphed to analyze sensitivity.
Modeling and Simulation	N/A
Sensitivity Analysis	We assess what factors affect the HVAC energy savings more by graphically analyzing the energy consumption and savings vs weather, as well as energy consumption and savings vs time. (Analysis vs time facilitates correlation of energy consumption to major HVAC mechanical events, such as equipment failure and maintenance.)
Anecdotal Perspectives	N/A
Industry Standards	IPMVP, FEMP guidelines [IPVMP, FEMP]
Internal Validity	We monitored the HVAC energy data regularly during the demonstration period to check for concerns over data integrity from Honeywell-EBI system.

	Our primary measurement of heating and cooling loads at air handling units was made using measurements with BTU meters on the hot and cold-water pipes of air handlers. To verify the measured heating and cooling loads at air handlers, we separately calculated the air handlers' heating and cooling loads using a physics formula and measurements of dry bulb air temperatures, enthalpies, and air flows recorded at the air handlers. We found the primary and secondary measurements to be in good agreement.
External Validity	We report daily reductions in HVAC energy consumption by the demonstration system (dynamic HVAC control) vs the baseline and also indicate the daily cooling loads in kBTUs. The breakdown of the HVAC energy savings achieved with different daily heating/cooling loads will allow the results to be applied to a variety of military installations in different climates with different heating or cooling needs. We report reductions in HVAC energy consumption for the high-bay area and the open office area separately. Hence, the information reported will be widely applicable to a variety of environments found at military installations—both office environments and large, open, high-bay areas such as warehouses, manufacturing spaces, storage areas, etc.

In the following sections, we analyze the energy consumption of the various components of the HVAC system, including chillers, boilers, return and supply fans, and VFD reheat coils. We add the energy components to arrive at total HVAC energy consumption. We separately analyze consumption on baseline days (when occupancy control was disabled) as well as days when occupancy-based control applied setbacks to HVAC setpoints (resulting in reductions in energy consumption), and we compare them to quantify energy savings.

We note that some HVAC energy quantities, such as the chilled water load at air handling units (AHUs), were measured for entire air handling units. However, the air handlers supplied air to both the demonstration areas and additional rooms that were not part of the demo. Hence, these AHU energy measurements are greater than the actual energy consumption of our demo areas (only). In the next section, we describe the measurements made at AHUs. In the section after that, we examine impacts of weather on the AHU energy consumption. In the latter sections, we scale AHU energy measurements to compute energy consumption of demo areas (only).

6.2.1 Energy consumption of Air Handling Units (AHUs)

Two air handling units supplied conditioned air to the demo areas: AHU 101 supplied the high-bay area (as well ground floor rooms outside of the demo area), while AHU 202 supplied the office area (as well as other second floor rooms outside the demo area). We installed BTU meters on the hot and chilled water coils of both AHUs to measure each AHU's hot and chilled water loads. We also installed electricity meters on the circuits powering each AHUs' fans. These energy measurements were collected and stored in the Honeywell EBI server. We summed the high-frequency energy measurements into daily totals, which we graph in Section 5.5.2.2.

Figure 38 plots daily chilled water load for AHU 101. This is the total thermal cooling energy delivered to the AHU by a cold water pipe from the building's chillers. We separately plot daily consumption on baseline days (blue dots), when occupancy control was disabled, and on days when occupancy-control was enabled (red dots). Figure 40 plots the daily chilled water load for AHU 202. It is clear from both figures that less energy was consumed when occupancy control was enabled.

We note that BTU meter measurements are only shown starting in late March, which is explained by two unfortunate circumstances. First, there was a programming error in the controller which communicated BTU measurements to the EBI server. This was fixed in early March 2019. This resulted in invalid BTU meter data before March 6, 2019, so we excluded those measurements from the graphs. The second issue was that we experienced severe, repeated network disruptions due to an overloaded BACnet network and EBI point server. This caused repeated lockups of controllers and significant loss of data before May 7, 2019.

We also performed a consistency check on chilled water loads measured by BTU meters. We did so by independently computing the daily chilled water load using measurements of air flow and enthalpy. We first computed chilled water power (cooling energy per time) for each AHU with the formula

$$\text{AHU cooling (power)} = (\text{AHU air flow})*(h_{mixed} - h_{sup}),$$

where h_{sup} and h_{mixed} are the enthalpies of supply and mixed air (measured at the air handler), and AHU air flow is the total flow rate of air (cubic feet per minute) delivered by the air handler. We integrated power over time to get daily totals for chilled energy consumption. Figure 43 and Figure 44 compare cooling loads in AHU 101 and 202 as measured by BTU meter vs the physics-based calculation. The BTU meter measurements and physics-based calculations agree extremely well for AHU 202. We note that AHU 202's airflow measurements were calibrated with a station hood, which likely explains the good agreement. The BTU meter measurements and physics-based calculations do not agree as well for AHU 101, but the curves are quite similar, particularly in the month of June 2019 where they differ only by a scaling factor. We believe this may be partly explained by less-precisely calibrated airflow measurements at AHU 101. We also suspect there may also be issues with enthalpy measurements in AHU 101. Regardless, the agreements are strong enough to have confidence in the BTU meter measurements.

We note that air handling units had hot water pipes, but the BTU meters measured no hot water load at the air handlers – even in winter. Surprisingly, we observed significant chilled water loads even in winter. Evidently, Building 3907 generated significant internal heat year-round. This may be explained by industrial activities, such as welding, which occur in the high-bay production area. Accordingly, there are no plots for AHU hot water load.

Daily energy consumption of air handler supply fans are shown for AHU 101 in Figure 39 and for AHU 202 in Figure 41. Energy consumption of AHU 202's return fan is shown in Figure 42. (Note that AHU 101 had no return fan.) We note that there were significant changes in fan energy consumption throughout 2019 which were caused by several issues outside of our control. For example, AHU 202's return fan broke in April 2019, and was repaired in early July 2019.

This explains the dramatic fall and rise in energy consumption visible in Figure 42. Furthermore, in July, the return fan was placed into manual override mode and its speed was increased by technicians at the building to increase cooling into spaces. This appears to have caused AHU 202's supply fan to work less hard, which may explain the fall in AHU 202's supply fan energy consumption in early July, as seen in Figure 41. AHU 101's supply fan had a dramatic decrease in energy consumption in late July. We are not clear about the cause, but personnel at the building confirmed to us that maintenance was done on AHU 202 around that time, which included replacement of the filter. We note that airflow from AHU 202 did not drop significantly around the time that energy consumption dropped, so the maintenance evidently made the fan more energy efficient. That could be explained by replacing a clogged filter.

6.2.2 Analyzing the influence of weather on AHU energy consumption

We next analyze the influence of weather on daily AHU energy consumption, using the AHU energy measurements discussed in the previous section. We use *degree days* to quantify outside weather conditions. Degree days are computed as $(T_{mean} - 65F)$, where T_{mean} is the mean value of the daily high and low temperature, and 65F is 65 degrees Fahrenheit. Hence, degree days (roughly) measure the average daily outside temperature conditions. Degree days are often strongly correlated with heating or cooling energy consumption of HVAC system, so they are commonly used in HVAC studies to normalize energy consumption between days with different weather. Hence, we compute and plot the various components of daily AHU energy consumption (as analyzed in the prior section) vs degree days to study the impact of weather.

Our graphs are shown in Section 5.5.2.3. Figure 45 and Figure 47 show the daily chilled water load vs degree days for AHU 101 and 202, respectively. Figure 46 and Figure 48 show the daily supply fan energy consumption of AHU 101 and 202 vs degree days. Figure 49 shows the daily energy consumption of AHU 202's return fan vs degree days.

In general, we see very little correlation between AHU energy consumption and degree days. The only exception is the chilled water load for AHU 202, which modestly rose with rising degree days. Generally speaking, the changes in AHU energy consumption seem to be dominated by mechanical causes, such as when the AHU 202 return fan broke in April 2019, when it was replaced and placed into manual override mode (with an increased speed, in July 2019), and when maintenance was done on AHU 101's supply fan in late July 2019.

Hence, we believe the lack of correlation between energy consumption and degree days may be explained by the various mechanical issues with the HVAC components of AHU 101 and 202, including the broken return fan, stuck valves, and equipment in manual override mode.

6.2.3 HVAC energy consumption and savings in demo areas

In the following sections, we analyze the energy consumption and savings of the high-bay and office demo areas (**only**). We analyze each component of HVAC energy usage separately.

Caution: we note that we experienced severe, repeated network disruptions due to an overloaded BACnet network and EBI point server. This caused repeated lockups of controllers and significant loss of data before May 7, 2019. Hence, in the HVAC calculations in following sections, we **only include data from May 7, 2019 to Sept. 1, 2019** when the HVAC system worked reliably.

6.2.3.1 Supply and return fans

In this section, we analyze the consumption and savings of supply and return fan energy used to condition the demo spaces (**only**). As we have previously mentioned, the air handling units served large areas, including rooms outside of the demo areas. Hence, we compute the fan energy that was used to supply air to **each demo area only**. We do so by scaling the total energy consumption by the fraction of air that went to the demo area. We use the following formula:

Fan energy = (area air flow)/(AHU air flow) * (total measured fan energy)

Here, 'Fan energy' is the energy used to blow air to the demo area (only) per day. 'area air flow' is the amount of air delivered to a demo area per day (measured in cubic feet), which is computed by summing the air flow through all VAVs serving that demo area. 'AHU air flow' is the total amount of air delivered by the AHU's fan per day (in cubic feet). Finally, 'total measured fan energy' is the total energy consumption of the AHU fan (per day) as measured by the electricity meter.

Note that the ratio (area air flow)/(AHU air flow) simply scales the total fan energy by the fraction of air flow that went to the demo area. This fraction of air flow to demo areas is plotted (daily) for the high-bay demo area in Figure 50 and for the office area in Figure 57. From the figures, we see that about 80% of AHU 101's air flow went to the high-bay demo area, and about 35% of AHU 202's air flow went to the office area. From the figures, we see the fraction of air flow to demo areas decreased when occupancy-based HVAC control was enabled.

In Figure 51, we plot the daily supply fan energy consumption used by the high-bay demo area (only), as computed with the previous formula. (Note that for 'total measured fan energy' we used the AHU 101 supply fan energy, which was plotted in Figure 39.) Blue dots show daily consumption on baseline days (when occupancy-based HVAC control is disabled). Red dots show daily consumption on days when occupancy-based control was enabled. It is clear from the figure that occupancy control substantially reduced supply fan energy consumption for the high-bay.

We next quantify the supply fan energy savings of baseline vs occupancy-controlled days. This means we need to compare those two energy consumptions (which occurred on different days, due to the 2+1 schedule). In our original demo plan, we had planned to use degree days (computed from outside air temperatures) to normalize the comparison. However, upon examination of the data, we found that energy consumption of the various HVAC components was not strongly correlated with degree days. We hypothesize this is because of (1) the large internal heating that occurred in the building and (2) the numerous mechanical issues and manual overrides present in the HVAC system. Regardless, the original method would not have been successful. However, we noticed that energy consumption was fairly consistent from one baseline day to the next (which occurred every 3 days), with major changes caused by e.g., HVAC maintenance or shutdowns over holidays, but not weather. Hence, to compare baseline and occ-controlled energy usage, we linearly interpolated between baseline measurements. This is shown as the green line in Figure 51. Then, for each occupancy-controlled day, we compute the daily energy savings as the difference between the interpolated baseline consumption for that day (green line in the figure) and the occ-controlled energy consumption for that day (red dots in the figure).

We plot the high-bay area daily supply fan energy savings in Figure 52 (blue dots). Note that only two of every three days have an energy savings computed, since occupancy control ran for two days and was disabled the third (repeating). The figure also shows the mean daily energy savings (red line), which was 37 kWh per day. There was no return fan for the high-bay (AHU 101).

The computation proceeds analogously for the office area fans. We plot the office area daily supply fan energy consumption in Figure 58. Once again, baseline measurements (no occ-control) are shown in blue, consumption with occupancy control is shown in red dots, and the green line is the interpolated baseline usage. Once again, the difference between the interpolated baseline (green) and occ-control (red) is the computed energy savings, which is shown in Figure 59. The office area return fan energy consumption is shown (daily) in Figure 60, and the savings is shown in Figure 61.

6.2.3.2 Chilled water

We next compute the amount of electrical energy used by chillers to supply chilled air to the demo areas (only), via the AHUs. We compute the daily chiller energy consumption for each demo area as

Chilled water energy = (area air flow)/(AHU air flow)*(cooling load)/(chiller efficiency),

Here, 'Chilled water energy' is the amount of electrical energy consumed by the chiller to cool the demo area per day. (area air flow)/(AHU air flow) is the fraction of the AHU's airflow that went to the demo area that day. 'cooling load' is the amount of thermal energy consumed by the AHU, as measured by the BTU meter on the AHU's chilled water pipe. (This is shown in Figure 38 for AHU 101 – high-bay – and in Figure 40 – office.) Finally, 'chiller efficiency' is the ratio of cooling energy supplied by the chiller, divided by the input electrical energy. This is also known as coefficient of performance (COP). From the building design documents, building 3907 has two identical chillers (both York model YKM2M4K1-CBG centrifugal chillers), with a COP of 5.784. Hence, we use **5.784** for chiller efficiency in the formula. (We note that since chillers are heat pumps, the efficiency can be greater than 1.)

In Figure 53, we plot the calculated electrical energy consumed by the chillers to cool the high-bay area, per day. Once again, blue dots show energy consumption on baseline days (without occupancy-based control), red dots show consumption on occ-controlled days, and the green line interpolates between baseline days. The difference between the interpolated baseline and the occ-controlled consumption is the computed energy savings per day. This is plotted in Figure 54 (blue dots). The mean daily savings in the high-bay was 104 kWh per day area (solid red line).

Figure 62 plots the calculated electrical energy consumed by the chillers to cool the office demo area, per day. Blue dots are baseline days, red dots are occ-controlled days, and the green line interpolates between baseline days. Figure 63 shows the daily chilled water energy savings due to occupancy control in the office area. The red line shows the mean daily energy savings, which was 16 kWh per day.

Note that BTU meter measurements showed that AHU 101 and AHU 202 did not consume hot water from boilers, only chilled water from chillers. Hence, we do not analyze hot water energy consumption from the AHUs for the demo areas. However, VAV reheat elements did consume energy from boilers; this is analyzed in the next section.

6.2.3.3 VAV reheat

The VAV boxes serving the office and high-bay demo areas consumed energy to reheat air from AHUs which was too cold, so we analyze VAV reheat energy in this section. Note that the VAVs were powered by hot water from the boilers. Hence, we compute the amount of energy consumed by boilers to heat the demo areas.

It would have been cost prohibitive to install BTU meters at every VAV box, since quality BTU meters cost thousands of dollars. Instead, we computed the VAV reheat energy consumption using a physics formula (below) and quantities that could be measured more cost-effectively, namely air temperatures and air flow. First, the heating power consumed at each moment by each VAV was computed with the formula

$$\text{Reheat power} = (\text{VAV air flow})*c_p*(T_{dis} - T_{sup})/(\text{boiler efficiency}),$$

where 'VAV air flow' was the flow of air measured through that VAV at that timestamp (in cubic feet per minute), c_p was the specific heat of air, T_{dis} was the temperature of air discharged at the VAV (measured by a thermometer after the VAV reheat coil), and T_{sup} was the temperature of air supplied by the AHU serving the VAV. (Note: we assume the temperature of the air entering the VAV before the reheat coil is the same as the temperature of supply air leaving the AHU.) 'boiler efficiency' is the ratio of thermal energy delivered to the AHU via hot water divided by the energy consumed by burning natural gas.

According to the design drawing for Building 3907, there are three identical boilers—all model BMK 2 made by AERCO, which are powered by natural gas. The design drawings indicate an efficiency of **0.86**, which we used in the previous formula.

We then integrated Reheat power over time to get the reheat energy consumed per day by each VAV. We summed all VAVs serving each demo area to get the total daily energy for each area.

Figure 55 shows the computed daily energy consumption consumed by boilers to provide reheat for the high-bay area (only). Once again, blue dots show energy consumption on baseline days, red dots show consumption on days with occupancy control enabled, and the green line interpolates between baseline days to facilitate computation of energy savings. Daily reheat energy savings for the high-bay is shown in Figure 56 (blue dots); the mean daily energy savings was 193 kWh (equivalent to 659 kBTU) per day.

Similarly, Figure 64 shows the daily reheat energy consumed by boilers to condition the office area, and Figure 65 shows the daily energy savings. Mean daily energy consumption was 58 kBTU/day. We observe that office area reheat energy was zero through most of June and July, but it increased significantly in late July and August. Technicians at the base told us that AHU 202's return fan was placed into manual override and the speed increased in July to increase the amount of chilled air delivered to spaces. It appears that too much chilled air was delivered, so the VAV reheat elements heated the air before it entered the office area to avoid excessive cooling.

We comment that this is not an optimal way to run a building's HVAC system: excessive cooling followed by reheating needlessly wastes energy. However, maintenance of the HVAC equipment was beyond our control.

6.2.3.4 Total HVAC energy consumption and savings

Next, we summarize the mean daily energy consumption and savings from the various HVAC components.

Table 28 summarizes the mean daily **baseline** HVAC energy consumption of the high-bay area, by source, in the period May 7, 2019 – Sept. 1, 2019. We find that in the baseline period, supply fans consumed on average 110 kWh/day, chilled water required 530 kWh/day, and VAV reheat consumed 1618 kBTU/day. In the final row, we add the energy consumption from each source (each converted to common units of kWh using the conversion factor: 0.293 kWh per kBTU) to get the total mean daily baseline energy consumption, which was 1114 kWh/day.

Column 2 of Table 29 summarizes the mean daily high-bay energy consumption with occupancy control enabled. Column 3 lists the mean daily the energy savings achieved by occupancy control, and column 4 lists the energy savings relative to baseline consumption. We find that total high-bay HVAC energy **savings was 30%** of the baseline consumption. **This significantly exceeded our target of 20% savings**.

Table 30 lists the mean daily baseline energy consumption of the office area, by source, in the period May 7, 2019 – Sept. 1, 2019 (similar to Table 28 for the high-bay). Mean daily baseline consumption was: 18 kWh for the supply fan, 15 kWh for the return fan, 166 kWh (567 kBTU) for VAV reheat, and 113 kWh for chilled water. The final row lists the total mean daily HVAC energy consumption (converted into common units of kWh), which was 312 kWh.

Column 2 of Table 31 lists the mean daily office area energy consumption with occupancy control enabled. Column 3 lists the mean daily energy savings achieved with occupancy control, and column 4 lists the energy savings relative to baseline consumption. We find that total office area HVAC energy **savings was 12%** of the baseline consumption. **This was below the performance objective of 20% savings**.

If we combine the office and high-bay areas and compute total savings and total baselines, we find the overall system's HVAC savings was **26% of baseline**, which **exceeded the performance objective.**

We believe the failure to reach the performance objective in the office area was caused by overactive Enlighted occupancy sensors in the office area. As we discussed in Section 1.1.1.1.5, occupancy sensors in the office area were overly sensitive from May 1, 2019 to the end of the demo period. This overlaps with the HVAC data analyzed in this section (May 7 – Sept. 1). Overactive occupancy sensors in the office incorrectly detected intermittent occupancy throughout the overnight period when the office was unoccupied. (This is discussed further in Section 6.5.2 and illustrated in Figure 82. See also the discussion in Section 8.1.4.) The false detection of occupancy throughout the overnight period reduced occupancy-based energy savings of the troffer lights (phase 2) compared to the pendant lights (phase1), as illustrated in Figure 28.

Similarly, false detection of occupancy would reduce HVAC energy savings, since HVAC setpoint setbacks are not applied when occupancy is detected. One implication is that holistic lighting and HVAC systems like this demo system must be configured carefully to avoid loss of lighting and HVAC energy savings due to overly-sensitive occupancy sensors.

6.2.3.5 Projected yearly energy consumption and savings

Finally, we use the previous results to estimate yearly energy consumption and savings for the HVAC system. To do so, we take the mean daily energy consumption and savings values from the prior section and multiply them by 365.25 days per year. These results are listed in Table 32.

We acknowledge that it is not ideal to estimate yearly HVAC energy consumption using only data from May 7 – Sept. 1, and we originally planned a much longer HVAC demo period, but data losses caused by network and controller issues meant a more complete analysis is not possible, and yearly projections are required for the economic analysis of the demo system. We also note that (as we mentioned earlier in the HVAC analysis) HVAC energy consumption in building 3907 was not strongly correlated with weather. Furthermore, there was no AHU heating in winter (nor in summer), and there was AHU cooling in both winter and summer. Therefore, the yearly energy consumption extrapolated from summer measurements may be reasonably close.

In Table 33, we break down the projected yearly energy consumption of the entire demo system (office + high-bay) by energy source: electricity (used to power chillers and AHU fans) and natural gas (used to heat water for the VAV reheats). These figures are used in the economic analysis in Section 7.0.

6.3 PO3: PLUG-LOAD ENERGY USAGE

Associated Performance Objectives	**PO3: Plug-Load Energy Usage** Electrical energy consumption from plug-loads in the office area.
Performance Objective Analysis Overview	We compare the plug-load energy consumption of both occupancy-controlled plug-loads and uncontrolled plug-loads during the demonstration period against a baseline of entirely uncontrolled plug-loads. This will enable an assessment of the possible benefits of occupancy-based control for non-critical plug-loads.
Statistical Methodologies	We measured total monthly energy consumption of plug-loads during the demonstration period and compared measured quantities to the baseline (uncontrolled plug-loads). To determine the baseline energy consumption of uncontrolled plug-loads, we operated all plug-loads in an uncontrolled mode for nearly three months at the start of the project and measured the daily total energy consumption of the plug-loads. From that sample, we computed the mean daily baseline energy consumption of plug-loads. Then, for each month of the demonstration period, we multiplied the mean daily baseline energy consumption by the number of days in the month to compute the estimated baseline plug-load energy consumption for that month.
Graphical Methodologies	Time series plots of interval-averaged energy consumed by plug-loads show the differences between the uncontrolled and the new controlled plug-loads for both the baseline and the demonstration periods. Histograms of energy consumption are graphed for the baseline and demonstration periods.
Modeling and Simulation	N/A
Sensitivity Analysis	We assess what factors affect the plug-load energy consumption by graphically analyzing the energy usage between the controlled and uncontrolled plugs for both the baseline and the demonstration periods.
Anecdotal Perspectives	N/A
Industry Standards	IPMVP, FEMP guidelines [IPVMP, FEMP]
Internal Validity	We monitored the plug-load energy data regularly during the demonstration phase to validate the integrity of data stored in the Enlighted Energy Manager.
External Validity	We reported the reduction in electrical energy consumption of our controlled plug-load solution relative to the baseline (uncontrolled plug-loads), both in absolute terms and as a percentage. This method naturally facilitates adjustment for regional differences in electricity prices since multiplication of the reported energy savings by regional electricity prices will yield estimates of cost reductions on a per-region basis. The plug-load demonstration occurred in a typical office environment consisting of cubicles, private offices, and conference rooms, so the findings will be widely applicable to other similar office environments.

There were 15 plug-load controllers installed in the 5,000 square foot office area. However, one plug-load controller was faulty and was excluded from the analysis. Each plug-load controller in the demo system was connected to two plugs (outlets): one occupancy-controlled plug and one uncontrolled plug (Shown in Figure 76). Hence, half of the plugs (uncontrolled) maintained power constantly, while the other half of the plugs were occupancy controlled so the data analyzed consisted of 14 controlled outlets and 14 uncontrolled outlets. Only controlled plugs were capable of achieving energy savings from occupancy control. After inspecting the collected data, it became apparent that energy usage patterns in uncontrolled plugs changed significantly partway through project, while usage patterns for controlled plugs remained relatively stable. Hence, to more precisely measure the energy savings realized by controlled plugs, we separately analyzed the energy consumption of controlled and uncontrolled plugs. For completeness, we also analyzed total energy consumption (controlled + uncontrolled plugs).

Figure 76. Labeled Outlets Connected to Enlighted's Plug-load Controller.

6.3.1 Controlled plugs

To determine the energy savings achieved by occupancy-controlled plugs, we compared the energy consumption of controlled plugs before and after the activation of the occupancy control feature. To determine a baseline for controlled plug energy consumption, the Enlighted system collected plug-load energy consumption data for a baseline period from Dec. 13, 2018 to Mar. 5, 2019. During the baseline period, controlled plugs were configured to maintain power regardless of sensed occupancy. The mean daily energy consumption of controlled plugs during the baseline period was 0.178 kWh / day. Daily energy consumption of controlled plugs during the baseline period are indicated by blue markers in Figure 66 and Figure 67; the mean daily energy consumption is indicated by the solid blue line. Monthly totals for controlled plug energy consumption during the baseline period are listed in column 2 of Table 34, and the cumulative total for the entire baseline period is shown in the final row. The total controlled plug energy usage during the baseline period was 15 kWh.

Next, occupancy control of controlled plugs was enabled, and the Enlighted system collected plug-load energy data during the demo period from Mar. 6 – Sept. 2, 2019. Daily energy consumption of controlled plugs in the demo period is indicated by red dots in Figure 66 and Figure 67. Monthly totals for controlled plug energy consumption during the demo period are listed in column 2 of Table 35, and the cumulative total for the entire demo period is shown in the final row. Total controlled plug energy usage during the demo period was 20 kWh. The mean daily consumption over the demo period was 0.110 kWh/day.

From Figure 66 and Figure 67, we observe that there was a significant decrease in daily energy consumption of controlled plugs when occupancy control was enabled at the start of the demo period. Also note in the figures the repeating pattern of two red markers with minimal energy consumption: these indicate weekends, when the office space was lightly occupied, and occupancy control achieved greater energy savings.

To quantify the energy savings during the demo period, we compute the baseline energy consumption of controlled plugs during each month of the demo period. This is computed by multiplying the mean daily energy consumption from the baseline period (0.178 kWh / day) with the number of days in each month on the demo period. As a formula:

$$\text{Baseline_Controlled} = (0.178 \text{ kWh / day}) * (\text{\# of days in demo month})$$

Monthly totals for the calculated baseline energy consumption of controlled plugs during the demo period are listed in column 2 of Table 36. The energy savings achieved by occupancy control during the demo period is computed as the difference between the calculated baseline energy consumption of controlled plugs and the measured energy consumption of controlled plugs. The monthly savings are reported in column 4 of Table 36, and the cumulative savings over the entire demo period is listed in the final row. The cumulative total energy savings achieved by controlled plugs during the demo period was **12 kWh**.

We remark that the validity of the energy savings calculation depends upon the consistency of plug-load usage patterns by office space occupants in the baseline and demo periods. An inspection of Figure 66 indicates controlled plug energy usage patterns in demo and baseline periods were relatively consistent, aside from a decline in energy consumption at the onset of occupancy control.

6.3.2 Uncontrolled plugs

Uncontrolled plugs maintained power constantly, regardless of sensed occupancy, so they could not achieve energy savings. Hence, we simply summarize energy usage of uncontrolled plugs during the baseline and demo periods.

Daily energy consumption of uncontrolled plugs is shown in Figure 68, where blue markers indicate the baseline period and red markers indicate the demo period. From the figure, we see that daily energy consumption from uncontrolled plugs roughly doubled during the summer months (May to Sept.) compared to the prior period. Because of this large change in energy usage patterns over the summer, it was important to analyze uncontrolled plugs separately from controlled plugs.

Monthly energy consumption from uncontrolled plugs is summarized in column 3 of Table 34 (for the baseline period) and column 3 of Table 35 (for the demo period). Cumulative totals for each period are shown in the final rows of Table 34 and Table 35. The total energy consumed by uncontrolled plugs was 72 kWh during the baseline period and 299 kWh during the demo period.

6.3.3 Total (controlled + uncontrolled plugs)

We also computed the total energy consumption, which is the sum of energy consumption from controlled and uncontrolled plugs. Daily total energy consumption for both the baseline and demo periods is shown in Figure 69. From the figure, we see that total daily energy consumption increased significantly in the period May – Sept. 2019; which was driven by the large increase in energy use by uncontrolled plugs during that period. Total energy consumption from each month of the baseline and demo periods are shown in column 4 of Table 34 and Table 35, respectively, and cumulative totals over each period are shown in the final rows. The total plug-load energy consumption over the baseline period was 87 kWh, and it was 319 kWh over the demo period.

6.3.4 Savings as a percent of baseline total energy consumption

To facilitate energy savings analysis, we also computed a baseline for total energy consumption during the demo period. This is an estimate of what the total energy consumption would have been if occupancy control had not been enabled for controlled plugs. This was computed by adding the calculated baseline for controlled plug energy consumption during the demo period (as described in Section 6.3.1 and reported in column 2 of Table 37) to the measured energy consumption of uncontrolled plugs in the demo period (shown in column 3 of Table 37 This quantity is listed (monthly) in column 4 of Table 37; the final row shows the total over the entire demo period. We find the baseline total plug-load energy usage over the demo period to be 331 kWh.

Finally, we computed the plug-load energy savings as a percentage of the total baseline usage. To do so, we divided the energy savings (from column 5 of Table 37) by the baseline total plug-load energy usage (column 4 of Table 37) and multiplied by 100; this is reported in column 6 of Table 37. We found that across the demo period, the total plug-load energy savings (12 kWh) was **4%** of the baseline total energy usage (331 kWh).

The amount of energy savings realized by plug-loads was below the performance objective of 20%. This can be explained by the behavior of occupants in the office area: occupants predominantly used uncontrolled plugs for electrical appliances. For instance, energy consumption from controlled plugs during the baseline period (15 kWh) was only 17% of the total consumption (87 kWh). During the demo period, the energy consumption of controlled plugs (20 kWh) was only 6.3% of the total plug energy consumption (319 kWh), and it was 6.0% of the baseline total consumption (331 kWh). Note that during the demo period, the energy consumption of uncontrolled plugs (299 kWh) was 90% of the baseline total consumption (331 kWh). Hence, even if (hypothetically) controlled plugs had used no energy during the demo period, they would have achieved a savings of at most 10% of the baseline, and the savings target of 20% reduction would not have been reached.

We note that if we compare the energy savings achieved by controlled plugs in the demo period (12 kWh) to the baseline energy consumption of controlled plugs (32 kWh), the savings is **38%**. Hence, occupancy-controlled plugs achieved substantial energy savings relative to controlled plug baseline consumption (with occupancy control disabled). Hence, we conclude that the primary limiting factor in realized energy savings was the behavior of office occupants, who preferentially used uncontrolled plugs.

6.3.5 Estimating yearly energy consumption and savings

We estimate the yearly energy consumption and savings of the plug-load system, which are required inputs for the cost analysis section. For uncontrolled plugs, we use all of the available data (both from the baseline and demo periods) and compute the mean daily energy consumption, which is 1.335 kWh/day, then we multiply by 365.25 to estimate a yearly consumption of uncontrolled plugs of 488 kWh. Note the actual computation included more significant digits than is shown above.

For controlled plugs in the baseline mode (no occupancy control): we compute the mean daily energy consumption in the baseline period, which was 0.178 kWh/day. We then multiply by 365.25 days to estimate yearly energy consumption of controlled plugs (with occupancy control disabled) of 65 kWh. We add this to the yearly energy consumption from uncontrolled plugs (488 kWh) to arrive at an estimate of yearly **baseline** plug energy consumption for controlled and uncontrolled plugs of **553 kWh/year**.

For controlled plugs with occupancy control enabled: we compute the mean daily energy consumption over the demo period, which was 0.110 kWh/day. We then multiply by 365.25 days to estimate the yearly energy consumption of controlled plugs (with occupancy control enabled) of 40 kWh. We add this to the estimated yearly uncontrolled plug energy consumption (488 kWh) to get an estimate of the yearly **demo** system plug-load energy consumption (both controlled and uncontrolled plugs, with occupancy control enabled for controlled plugs) of **528 kWh/year**.

Finally, our estimate of **yearly energy savings due to occupancy-based plug control** is 553 – 528 = **25 kWh/year**. (Note that actual numbers used in the computation included more significant figures than the two shown above.) These results are summarized in Table 38.

6.3.6 Percentage of daily energy usage outside business hours

To further analyze energy savings, we also computed the percentage of daily energy consumption that occurred outside of business hours (before 6 am or after 5 pm). This is less sensitive to changes in the absolute amount of energy consumed per day. Daily percentages are shown for controlled plugs in Figure 73, for uncontrolled plugs in Figure 74, and total (controlled + uncontrolled plugs) in Figure 75. Note the significant decrease in the percentage of energy consumed outside of business hours for controlled plugs in the demo vs baseline periods. This indicates savings from occupancy control. In contrast, the percentage of daily energy consumed outside of business hours stayed relatively constant for uncontrolled plugs. Mean values of the daily percentages are summarized in Table 39. We find that for controlled plugs, the mean daily percentage of energy consumed outside business hours dropped from 44% in the baseline period to 9% in the demo period. For uncontrolled plugs, the fractions stayed stable: 51% during the baseline period vs 48% during the demo period.

6.4 PO4: LIGHTING QUALITY

Associated Performance Objectives	PO4: Lighting Quality
Performance Objective Analysis Overview	Using the Light Right lighting quality survey, developed by PNNL, we compare the perceived lighting quality and lighting metrics before and after retrofit of the lighting and control system. This comparison reveals which lighting systems provide the best perception of visual performance and visual comfort and how these perceptions of lighting quality align with the lighting metrics.
Statistical Methodologies	Light Right survey responses were collected and analyzed. The mean and standard deviation of the survey responses were calculated for each question to determine statistical significance of the variation in responses.
Graphical Methodologies	We prepared pie charts for the baseline and demonstration periods for each survey question. An overall survey scoring system was developed to compare the overall perceived quality of the baseline and demonstration lighting systems.
Modeling and Simulation	Each lighting system was modeled, along with the physical geometry of the office furniture and industrial equipment, using AGI32 lighting analysis software to determine the lighting distribution throughout the space, and to compare to the established lighting standards.
Sensitivity Analysis	N/A
Anecdotal Perspectives	N/A
Industry Standards	Light Right survey [PNNL], Illuminating Engineering Society (IES) Recommended Practice for Office Lighting [IES-RP-1-12], Lighting for Industrial Facilities [IES-RP-7-17], and the Department of Defense Unified Facilities Criteria [UFC]
Internal Validity	The luminaire integrated light sensors that are part of the Enlighted control system monitored and maintained the light levels within the space such that the combined daylight and electric light meet the light level standards. The dimmed level reported by the Enlighted control system indicated the presence and level of daylight within the space.
External Validity	The purpose of this demonstration was to enable easier adoption of advanced LED lighting systems and lighting controls at other sites by improving lighting quality, lighting controls, and energy savings.

6.4.1 Summary of Lighting Survey Results:

6.4.1.1 Baseline Lighting Survey Results Summary

High-bay Area baseline:

Workers in the high-bay area were somewhat satisfied with the original baseline lighting. For administrative tasks, such as filing papers, reading papers, and working on the computer, the light levels were sufficient, but those working on industrial tasks such as welding, machining, and assembly thought that more light was needed. Some workers were bothered by flicker from the existing luminaires, which is known to cause discomfort and reduced productivity. The biggest complaint from occupants was that burnt out luminaires were not replaced in a timely manner.

Office Area baseline:

Workers in the office area were satisfied with the original baseline fluorescent lighting for the most part. The majority agreed that the lighting was sufficient for reading printed text, as well as viewing computer screens, and for filing and locating documents in the office. There were no complaints of glare. Some occupants would have liked to see increased light levels that are more uniform on their desks, while others believed that the lighting on their desks was sufficient. The only changes occupants would have liked to have seen were quicker replacement of burnt out luminaires.

6.4.1.2 Advanced LED Lighting Survey Results Summary

High-Bay Area Advanced LED Lighting:

In the industrial high-bay area, occupants thought that the new LED lights provided sufficient, if not too much light for all administrative tasks in the space, such as paper tasks, filing, and working on a computer. Occupants responded very positively to the increased light levels and distribution for preforming industrial tasks, such as welding, machining, and assembly. The number of occupants experiencing glare or discomfort did not change with the new lights, but the number of occupants noticing flickering from the lights decreased. Occupants said that the new lighting illuminates their work surfaces and the room surfaces evenly, and the new LED lights in the area are nice looking. Overall, the occupants are happy with the new LED lights and prefer them over the original baseline lighting system.

Office Area Advanced LED Lighting:

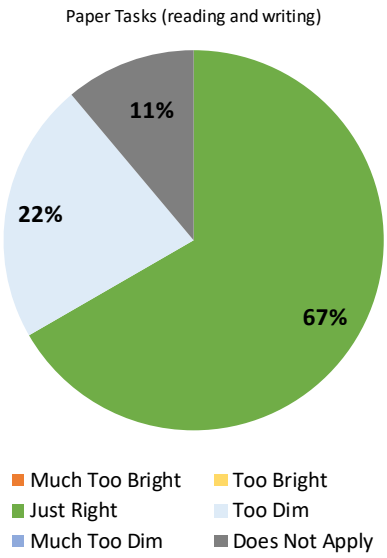
In the administrative office area, occupant surveys resulted in a preference for the Phase 2 troffer lighting. For the most part, occupants found the Phase 1 pendant style lighting to be dimmer that the original baseline lighting and the Phase 2 lighting, however the Phase 1 lighting resulted in less glare from a distance and from overhead lights. Occupants agree that the Phase 2 lighting evenly lit their work surfaces, as well as the room surfaces, and presented a good image for the organization. The Phase 2 lights, with the troffer fixtures, are the preferred lighting strategy based on occupant surveys.

6.4.2 High-Bay Area Occupant Survey Result Data

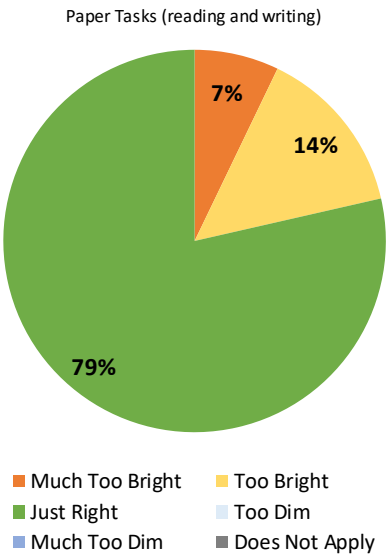
Note: The text highlights below each graph have been color coded based on results according to the table below:

Positive Result	Mixed Result	Negative Result

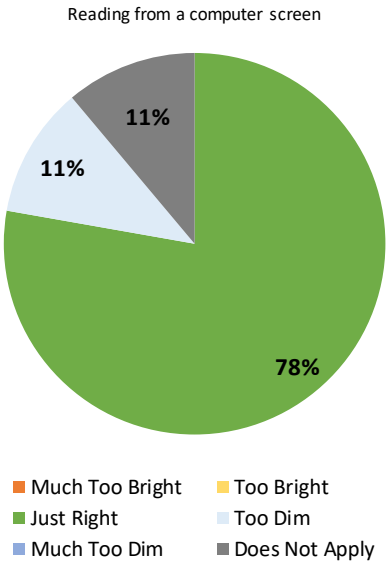
Original Lighting	LED Lighting Upgrade
Total Number of Survey: 9	Total Number of Survey: 14



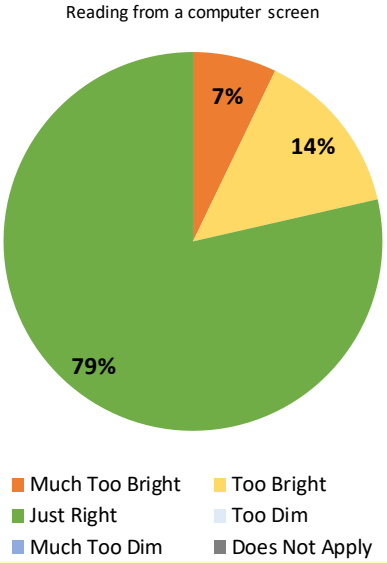
Most (67%) of occupants think that the lighting is just right for working on paper tasks, but 22% think it is too dim.



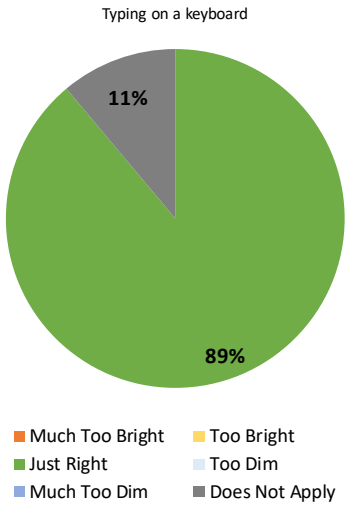
The majority (79%) of occupants think that the lighting is just right for working on paper tasks. The remaining occupants find the lighting too bright.



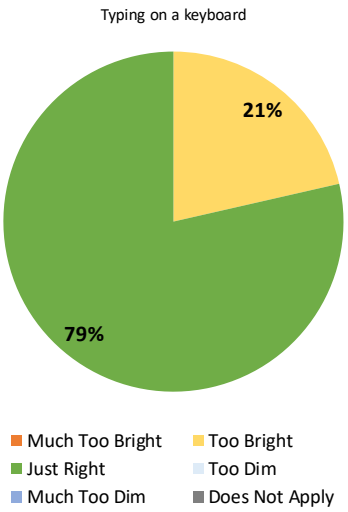
The majority (78%) of occupants think the lighting is just right for reading a computer screen.



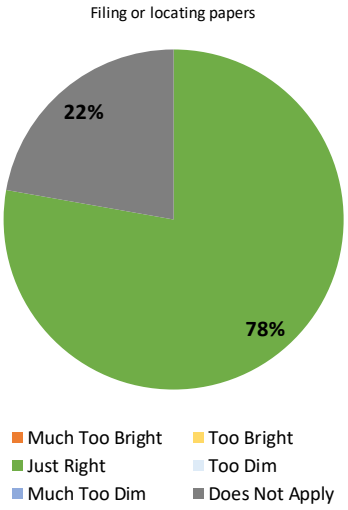
The majority (79%) of occupants think the lighting is just right for reading a computer screen. The remaining occupants find the lighting too bright.



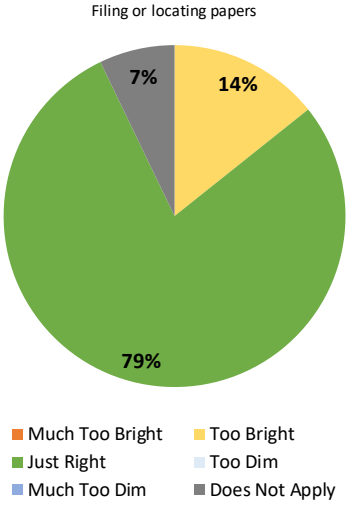
For applicable occupants, the lighting is just right for typing on a keyboard.



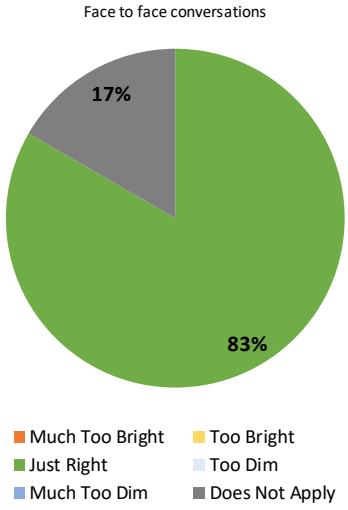
The majority (85%) of occupants think the lighting is just right for typing on a keyboard. The remaining occupants find the lighting too bright.



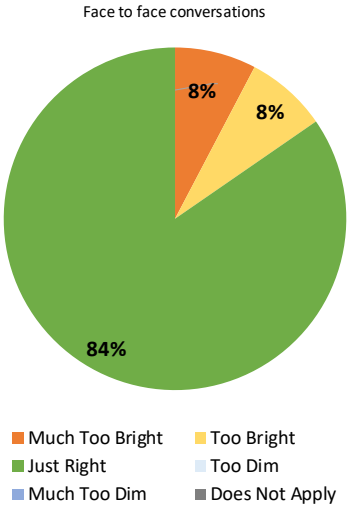
The majority (78%) of occupants think that the lighting is just right for filing and locating papers.



The majority (79%) of occupants think that the lighting is just right for filing and locating papers. The remaining occupants find the lighting too bright.

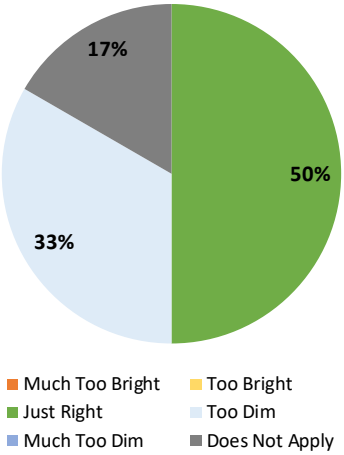


For applicable occupants, the lighting is just right for face to face conversations.



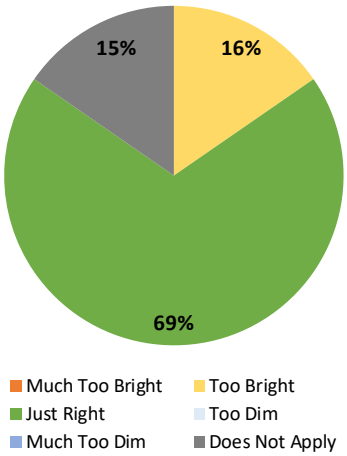
The majority (84%) of occupants think the lighting is just right for face to face conversations. The remaining occupants find the lighting too bright.

Industrial tasks such as welding, machining, assembly, etc.



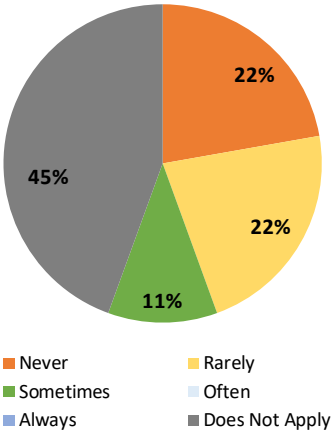
Half of the occupants think that the lighting is just right for industrial tasks. 33% of occupants think that the lighting is too dim for industrial tasks.

Industrial tasks such as welding, machining, assembly, etc.



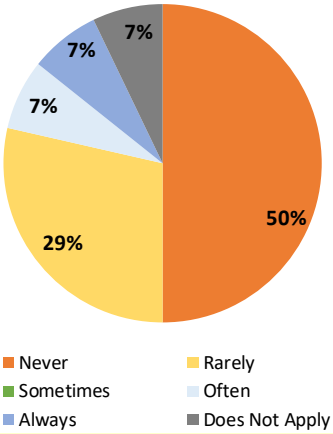
The majority (69%) of occupants think that the lighting is just right for industrial tasks. The remaining occupants find the lighting too bright or this questions does not apply to them.

Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)



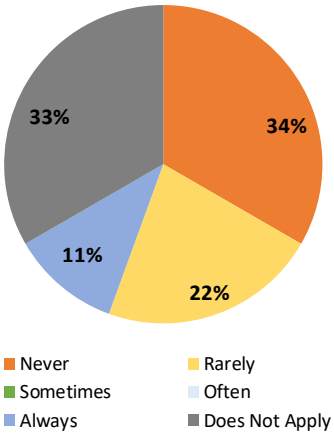
For occupants where it applies, the majority (83%) do not experience direct glare from the light fixtures, 17% responded that they "sometimes" experience glare from distant luminaires.

Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)



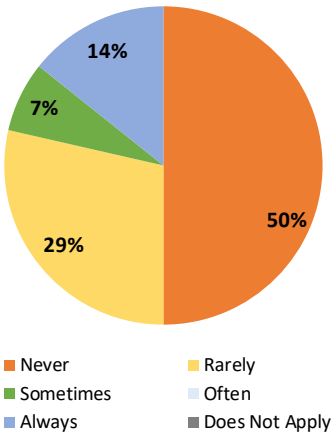
The majority (79%) of occupants do not experience direct glare from the light fixtures. Only 14% of occupants responded that they experience glare from distant luminaires.

Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)



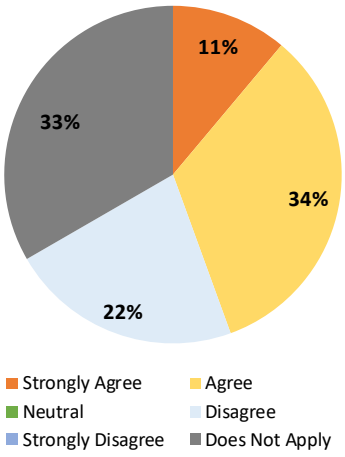
The majority of (56%) do not experience glare from the overhead lighting.

Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)



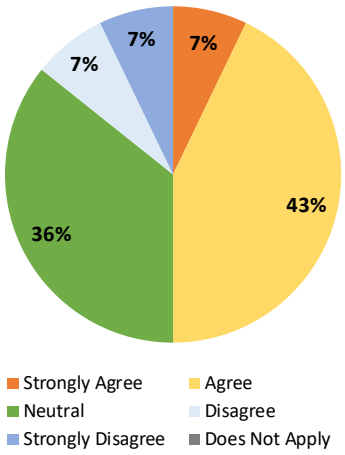
21% of occupants notice direct glare from the overhead lighting, while the rest never or rarely experience glare.

I am satisfied with my ability to control my overhead lighting



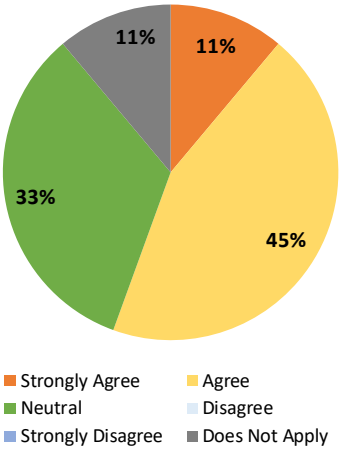
Occupants are split on satisfaction with their ability to control the overhead lighting.

I am satisfied with my ability to control my overhead lighting



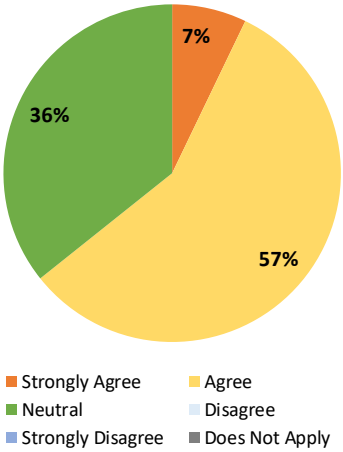
Most occupants are satisfied or nuetral about their ability to control the overhead lighting.

The lighting fixtures in Industrial area around my work space are nice looking.



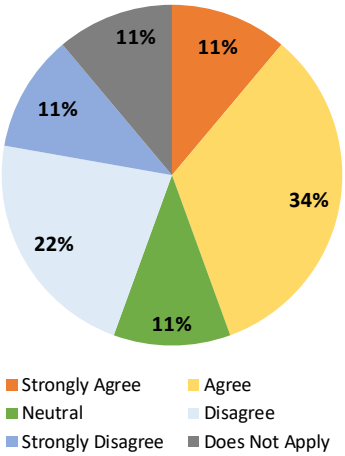
The majority of occupants (89%) are neutral or satisfied with the appearance of the light fixtures.

The lighting fixtures in the Industrial area around my work space are nice looking.



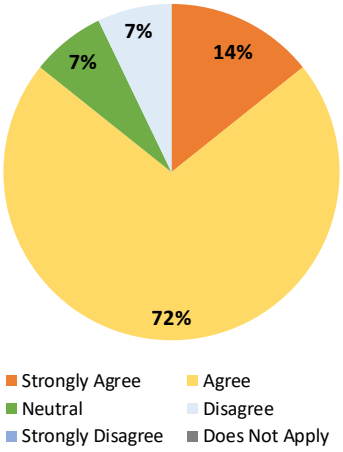
All occupants are neutral or satisfied with the appearance of the light fixtures.

My work surface is evenly lighted without very bright or dim spots

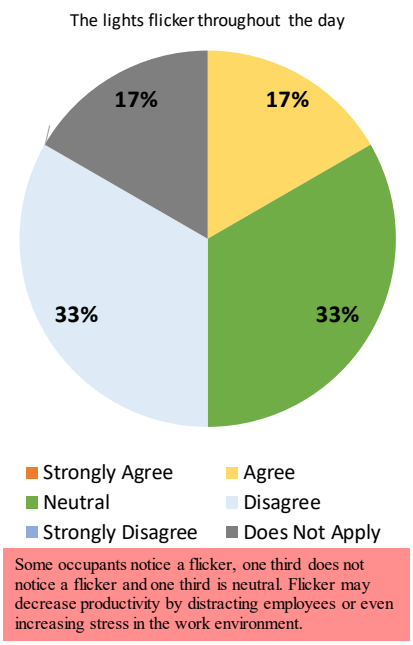


The majority (56%) of the occupants are neutral or satisfied with the uniformity of light on their work station. 33% of the occupants are not satisfied with the uniformity of the lighting at their workstation.

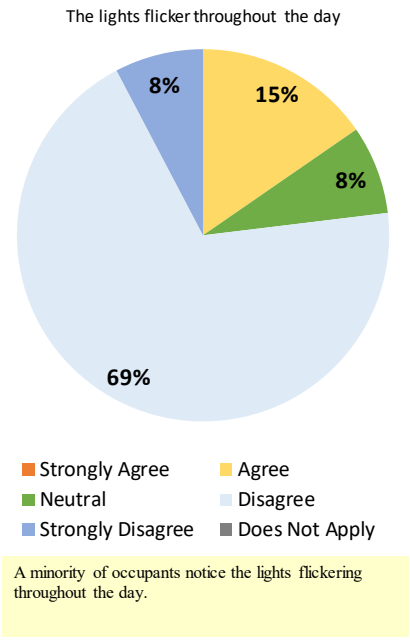
My work surface is evenly lighted without very bright or dim spots



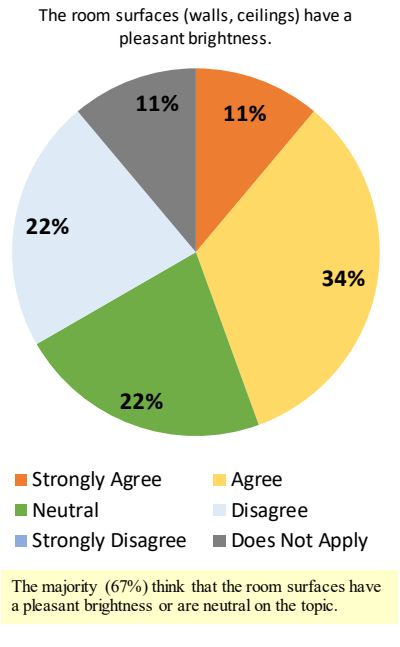
All occupants but one agree that there work surface is evenly illuminated.



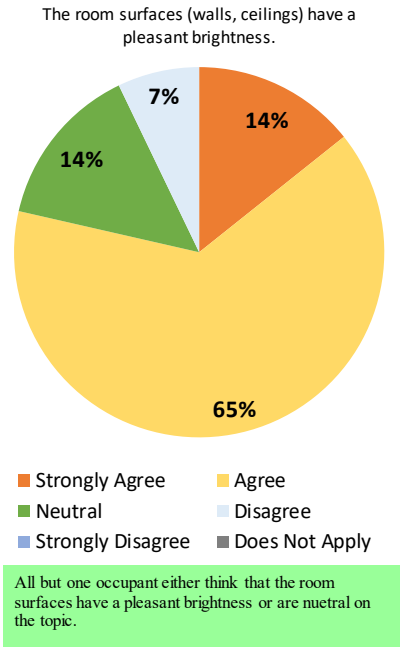
Some occupants notice a flicker, one third does not notice a flicker and one third is neutral. Flicker may decrease productivity by distracting employees or even increasing stress in the work environment.



A minority of occupants notice the lights flickering throughout the day.



The majority (67%) think that the room surfaces have a pleasant brightness or are neutral on the topic.



All but one occupant either think that the room surfaces have a pleasant brightness or are nuetral on the topic.

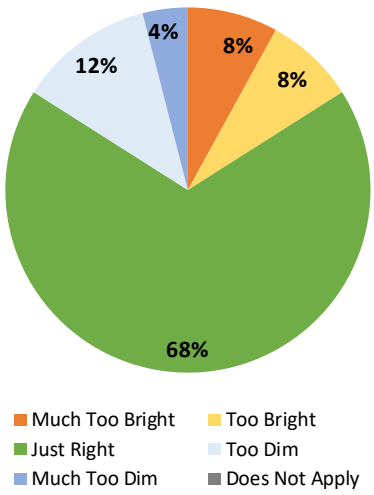
The changes most occupants would like to see (from high-bay area):

- Original Baseline Lighting
  - Have light bulbs replaced faster when they burn out, and fixtures repaired faster when they break.
- Upgraded LED Lighting
  - Great office space, please do not change.
  - This room seems really good.
  - Very good lighting in my area.
  - Please don't change the lighting.

6.4.3 Office Area

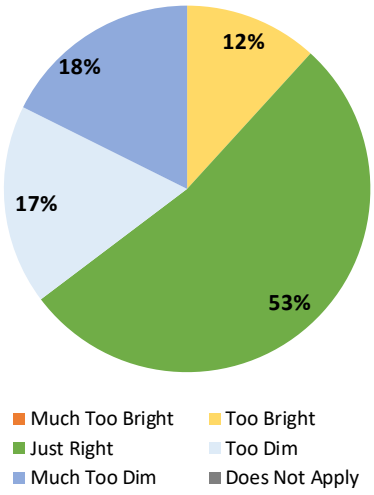
Original Lighting	Lighting Phase 1	Lighting Phase 2
Total Number of Survey: 25	Total Number of Survey: 17	Total Number of Survey: 19

Paper Tasks (reading and writing)



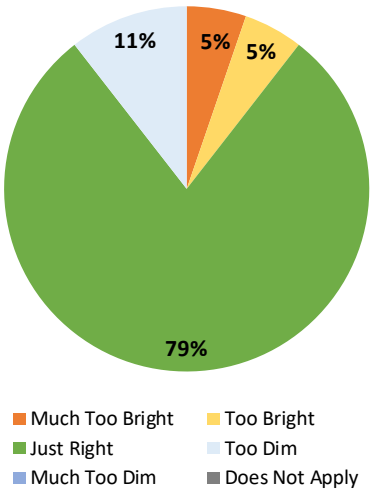
Most occupants (68%) responded that the light levels are "Just Right" for reading and writing. An equal number of occupants think it is too bright or too dim.

Paper Tasks (reading and writing)



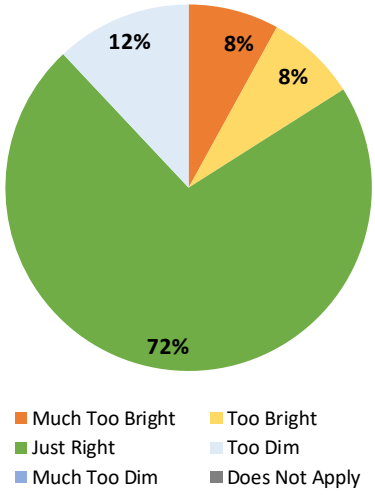
Most occupants (53%) responded that the light levels are "Just Right" for reading and writing. (35%) think it is too dim and (12%) think it is too bright.

Paper Tasks (reading and writing)



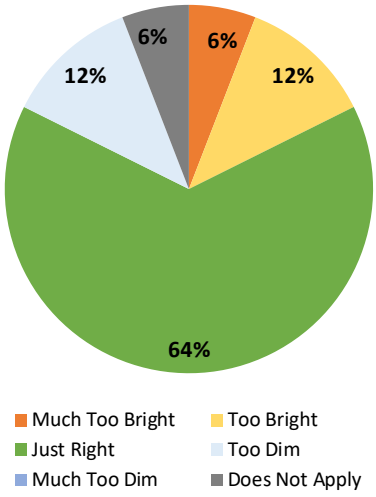
Most occupants (79%) responded that the light levels are "Just Right" for reading and writing. (11%) think it is too dim and (5%) think it is too bright.

Reading from a computer screen



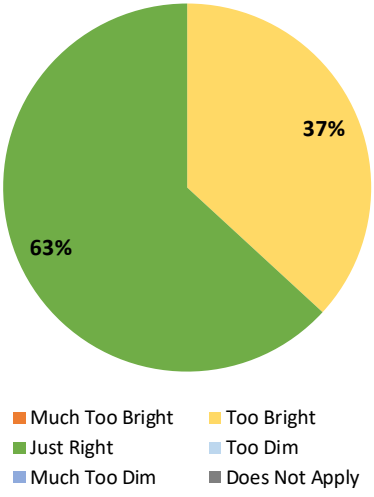
Most occupants (72%) responded that the light levels are "Just Right" for reading a computer screen.

Reading from a computer screen



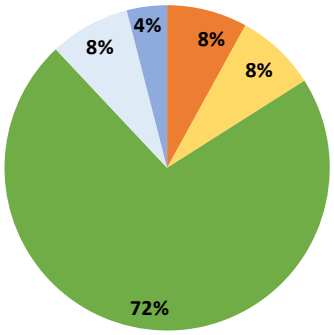
Most occupants (64%) responded that the light levels are "Just Right" for reading a computer screen.

Reading from a computer screen



Most occupants (63%) responded that the light levels are "Just Right" for reading a computer screen. The remaining 37% found the lighting to be too bright.

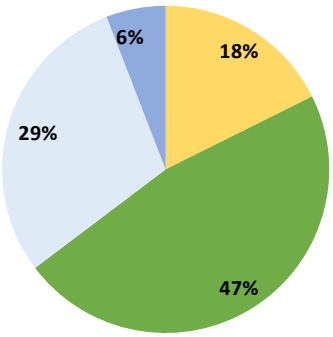
Filing or locating papers



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Most occupants (72%) are happy with the light levels for filing or locating papers.

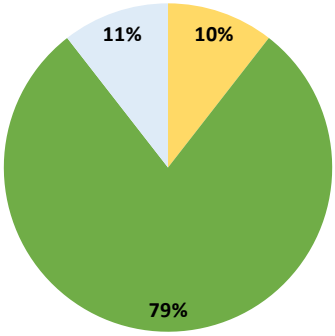
Filing or locating papers



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Occupants disagree with the light levels for filing or locating papers. (47%) think the light levels are just right, (29%) think the light levels are too dim and (24%) think it is too bright or much too bright.

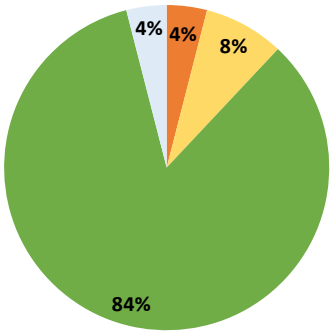
Filing or locating papers



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Most occupants (79%) are happy with the light levels for filing and locating papers. The remaining occupants were split on if the lighting was too bright or too dim.

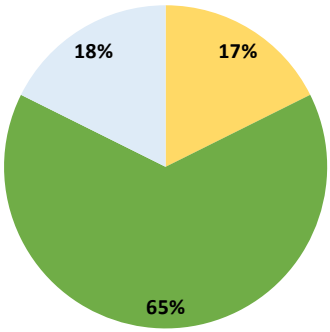
Face to face conversations



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Most occupants (84%) are happy with the light levels for face to face conversations.

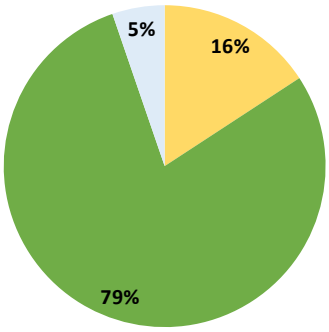
Face to face conversations



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Most occupants (65%) are happy with the light levels for face to face conversations. And equal amount of occupants think the light levels are too bright or too dim.

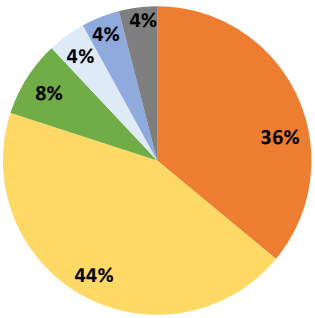
Face to face conversations



Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply

Most occupants (79%) are happy with the light levels for face to face conversations.

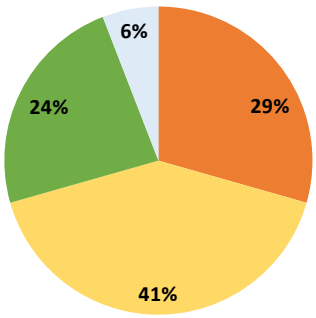
Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)



Never | Rarely | Sometimes | Often | Always | Does Not Apply

The majority of occupants (80%) are not affected by direct glare at their work station, but 16% are affected.

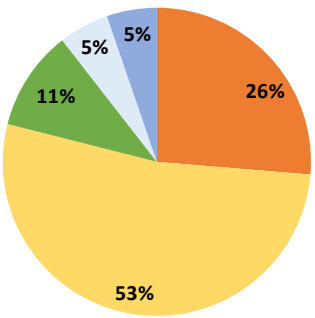
Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)



Never | Rarely | Sometimes | Often | Always | Does Not Apply

The majority of occupants (70%) are not affected or rarely affected by direct glare at their work station, but (30%) are affected.

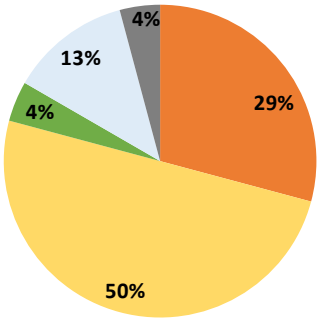
Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)



Never | Rarely | Sometimes | Often | Always | Does Not Apply

The majority of occupants (79%) are not affected or rarely affected by direct glare at their work station, but (21%) are affected.

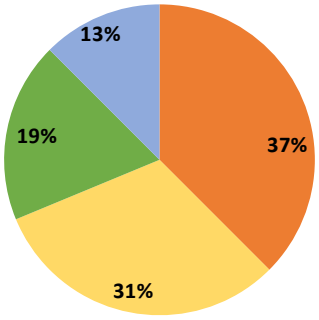
Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)



Never Rarely Sometimes Often Always Does Not Apply

The majority (79%) of occupants are not affected by glare from the overhead lighting.

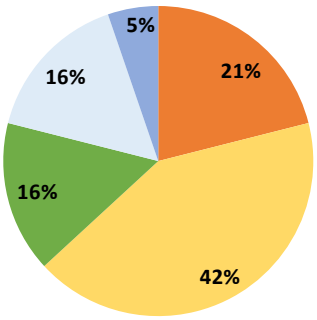
Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)



Never Rarely Sometimes Often Always Does Not Apply

The majority (68%) of occupants are not affected or rarely affected by glare from the overhead lighting.

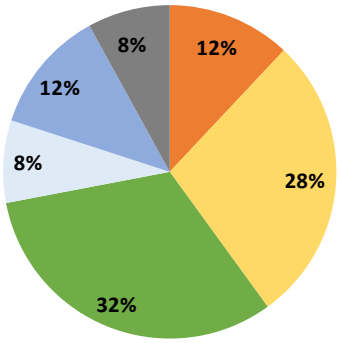
Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)



Never Rarely Sometimes Often Always Does Not Apply

The majority (63%) of occupants are not affected or rarely affected by glare from the overhead lighting. 21% of occupants often or always experience glare from the overhead lighting.

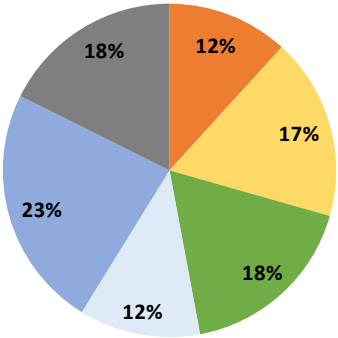
I am satisfied with my ability to control my overhead lighting



Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

The majority (72%) of occupants are neutral or satisfied with their ability to control the overhead lighting. A minority (20%) are not satisfied.

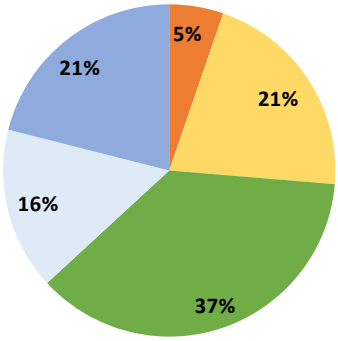
I am satisfied with my ability to control my overhead lighting



Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

The majority (47%) of occupants are neutral or satisfied with their ability to control the overhead lighting. A minority (35%) are not satisfied.

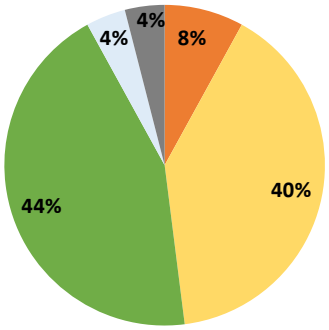
I am satisfied with my ability to control my overhead lighting



Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

The majority (63%) of occupants are neutral or satisfied with their ability to control the overhead lighting. A minority (37%) are not satisfied.

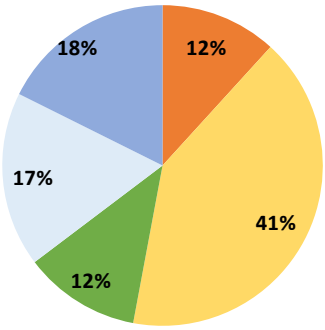
The lighting fixtures in the general office area around my work space are nice looking.



Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

The majority (88%) of occupants are neutral or agree that the lighting in the office space looks nice.

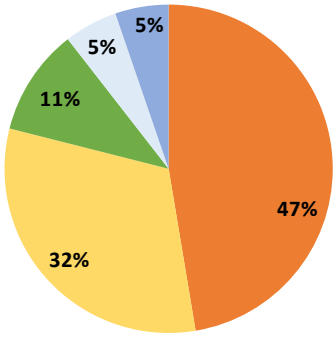
The lighting fixtures in the general office area around my work space are nice looking.



Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

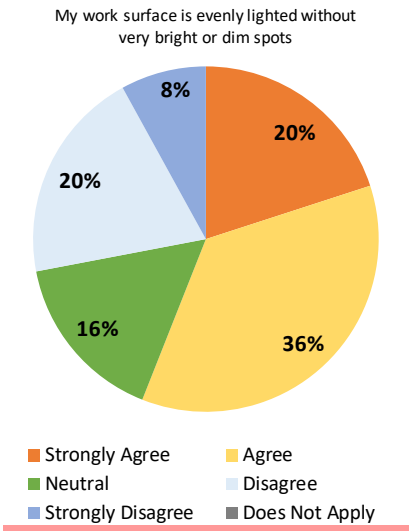
The majority (65%) of occupants are neutral or agree that the lighting in the office space looks nice.

The lighting fixtures in the general office area around my work space are nice looking.

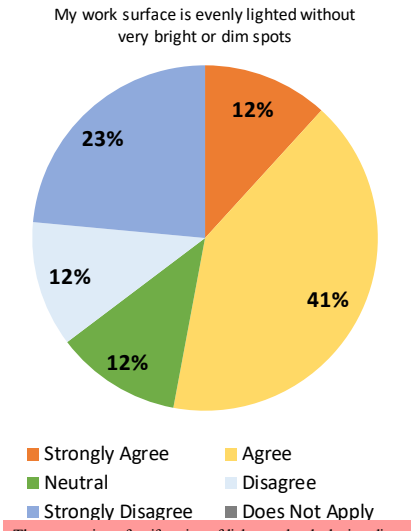


Strongly Agree Agree Neutral Disagree Strongly Disagree Does Not Apply

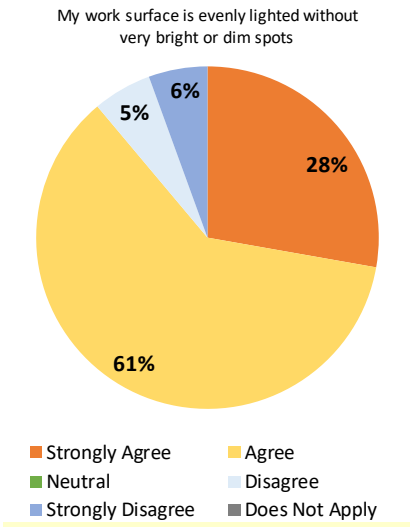
The vast majority (90%) of occupants are neutral or agree that the lighting in the office space looks nice.



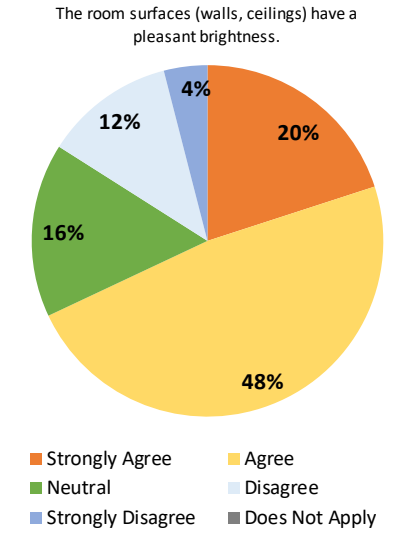
The perception of uniformity of light on the desks is split in the office area. 56% think their desk is uniformly lit, 28% think their desk is not uniformly lit, and 20% are neutral.



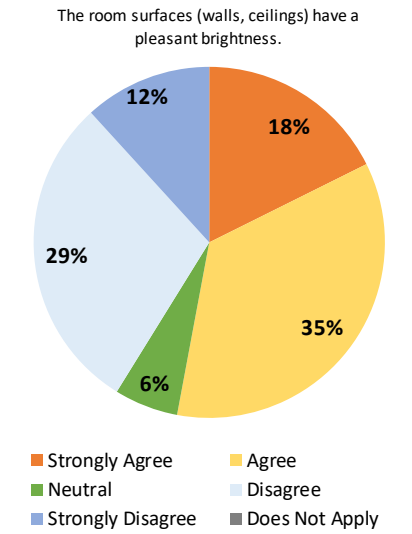
The perception of uniformity of light on the desks is split in the office area. 53% think their desk is uniformly lit, 35% think their desk is not uniformly lit, and 12% are neutral.



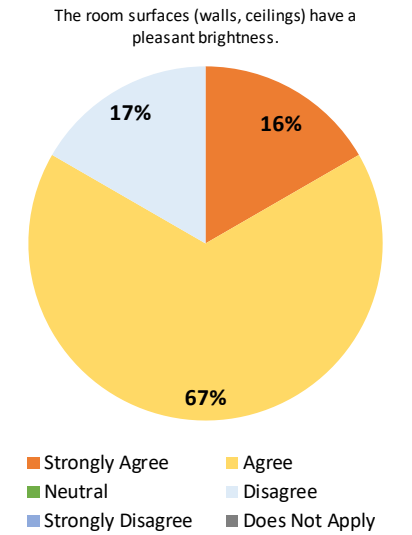
The majority (89%) of occupants think that their work surface has uniform brightness, however there are some (11%) occupants that are not satisfied with the unifomity of light on their desks.



The majority of occupants (84%) are neutral or agree that the walls and ceiling have a pleasant brightness. Some (16%) disagree.



The occupants of the office area are split on the brightness of the walls and ceiling. (53%) are agree that the walls and ceiling have a pleasant brightness while (41%) disagree and (6%) are neutral.



The majority (83%) of occupants agree that the room surfaces have a pleasant brightness.

The changes most occupants would like to see (from office area) based on survey responses:

- Original Baseline Lighting:
  - Being able to control the light output of the overhead fixtures (7)
  - Having Light bulbs replaced quicker once they burn out (5)
  - Make the overhead lights less glary (5)
  - Reduce the light output of the overhead lights (5)
  - Increase the light output of the overhead lights (4)
  - Six (6) occupants would not change anything about the baseline lighting in the office area.

- Phase 1 Lighting (Pendant luminaires)
  - Change the location of the overhead lighting fixtures relative to your workstation (9)
  - Change the aesthetic appearance of the lighting fixtures (6)
  - Be able to control the brightness/light output of the overhead lighting fixtures with a dimmer or high/low switch (5)
  - Make the overhead lighting fixtures less glary (5)
  - Three (3) occupants would not change anything about the lighting in the office area.

- Phase 2 Lighting (Troffer retrofit kit luminaires)
  - Better control of the lighting in the office area
  - Not having the lighting turn off when there is not enough motion in the space
  - One (1) occupant would not change anything about the lighting in the office area

6.5 OCCUPANCY ANALYSIS

In this section, we analyze patterns of occupancy in the high-bay and office areas, as measured by smart occupancy sensors built into each Enlighted light fixture. We analyze how average occupancy patterns changed throughout the day, throughout the week, and over the demo period. We separately analyze the high-bay and office areas. We also investigate a problem that occurred in the office area, where occupancy sensors became too sensitive (especially in Phase 2 – the troffer period) and had many false readings of occupancy in the overnight periods when the office was vacant. This caused lights to randomly turn on at night which reduced energy savings in the troffer demo period.

6.5.1 High-bay Area

Each light fixture in the Enlighted system contains a smart sensor which measures and reports several quantities (including occupancy below the fixture, light levels below the fixture, and air temperature) at 5-minute intervals. The Enlighted Energy Manager automatically collects and stores this data. This fine-grained occupancy information can provide a comprehensive view into occupancy patterns of areas across space and time.

To begin, we analyze occupancy data from the high-bay area. One interesting question to answer is when was the space occupied vs unoccupied? To answer this question, we separately group the occupancy data from all high-bay fixtures at every timestamp. Hence, at each 5-minute interval, we get occupancy readings from every high-bay fixture. From this, we compute the percentage of fixtures which reported any occupancy during the 5-minute interval. This results in a time series that literally measures the percentage of high-bay sensors detecting people every five minutes throughout the demo period. For illustration, we plot the first week of this time series in Figure 77. One can see weekdays where 80-90% of high-bay sensors detected occupancy, overnight periods where occupancy was near 0, a Saturday where roughly 50% of sensors detected occupancy (i.e., the space was more lightly-occupied than on weekdays), and a Sunday where the space was unoccupied.

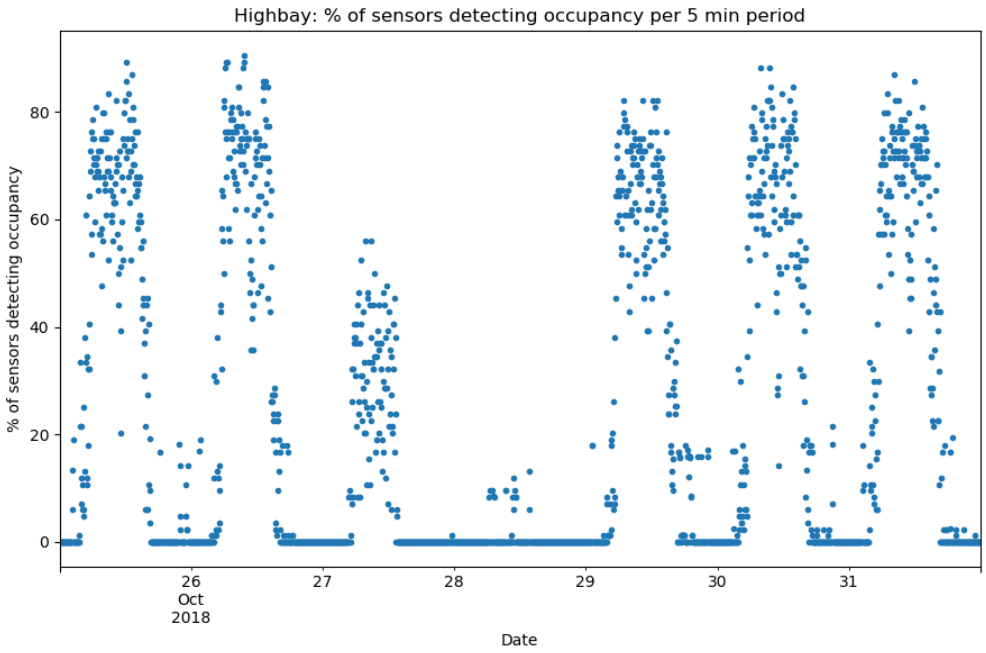


Figure 77. Each Dot Shows the Percentage of High-bay Sensors that Detected Occupancy in Each 5-Minute Interval During the First Week of the High-bay Demo.

To get a clearer understanding of typical high-bay occupancy throughout each day, we aggregate this data to into results per day. Specifically, we group this data by the day of the week (e.g. select all Mondays throughout the high-bay demo) and compute the median value of the % of sensors detecting occupancy at each time of the day (out of the 84 sensors in the high-bay area). Hence, this data tells us the typical amount of occupancy detected throughout the day, separately for each day. We plot this in Figure 78. From the figure, we can see that during weekdays, the high-bay was generally occupied from approximately 3:50 am to 4:40 pm, though people arrived later than normal on Monday mornings and left earlier than normal on Friday afternoons. The reduction in occupancy around 11 am is likely due to lunch. The space was less heavily occupied on Saturdays and was occupied for a shortened duration. The space was unoccupied on Sundays.

Using the data shown in Figure 78, we estimate the typical start and end of the occupied period per day. To make a quantitative estimate that is robust to a few small overnight occupancy readings, we define "occupied" as meaning the median percentage of sensors reading occupancy is greater than 3% (out of the 84 sensors in the high-bay area). The typical start and end times of space occupancy are computed and listed for each day of the week in Table 55.

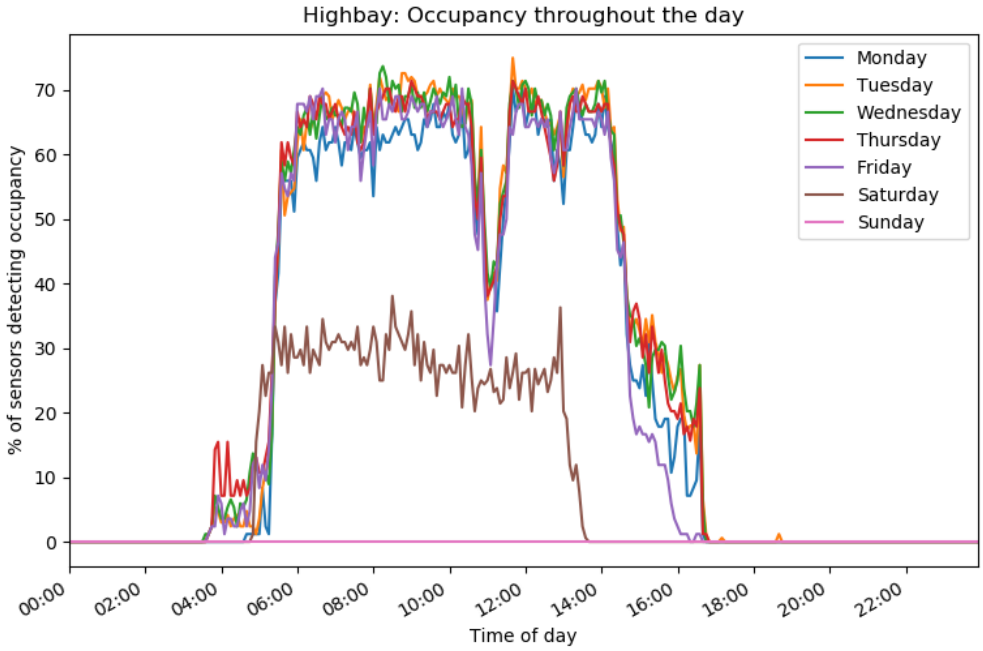


Figure 78. A Plot of Typical High-bay Occupancy Patterns Throughout the Day, for Each Day of the Week.

To produce the graph, we grouped occupancy measurements by time of day (separately for each day of the week), then computed the median value of the percentage of sensors reading occupancy at that time of day. Data from the entire high-bay demo period (10/25/2018 – 9/2/2019) was included.

Table 55. Summary of the Typical Periods When the High-bay Was Occupied, by Day of the Week.

We define the "occupied period" as when the median percentage of sensors reporting occupancy was greater than 3%.

Day of week	Occupied period began	Occupied period ended	Length of occupied period (hours)
Monday	5:05 am	4:35 pm	11.50
Tuesday	3:50 am	4:40 pm	12.83
Wednesday	3:50 am	4:40 pm	12.83
Thursday	3:50 am	4:35 pm	12.75
Friday	3:55 am	3:55 pm	12.00
Saturday	4:55 am	1:25 pm	8.50
Sunday	-	-	-

Finally, we also examine whether the high-bay occupancy patterns were stable over time, and we find that they generally were. Specifically, we separately analyze high-bay occupancy patterns during an early period (10/25/2019 – 3/24/2019) and during a late period (3/29/2019 – 9/2/2019). (Note these periods overlap with the pendant and troffer phases in the office area.) In each period, we computed the median percentage of sensors detecting occupancy, for each day of the week, as before. We plot this result for Mondays in Figure 79. As one can see, the occupancy patterns in the early and late periods are very similar, though it seems workers started slightly earlier and left work slightly later in the first period compared to the second period. Occupancy patterns for other days of the week are also consistent between early and late periods.

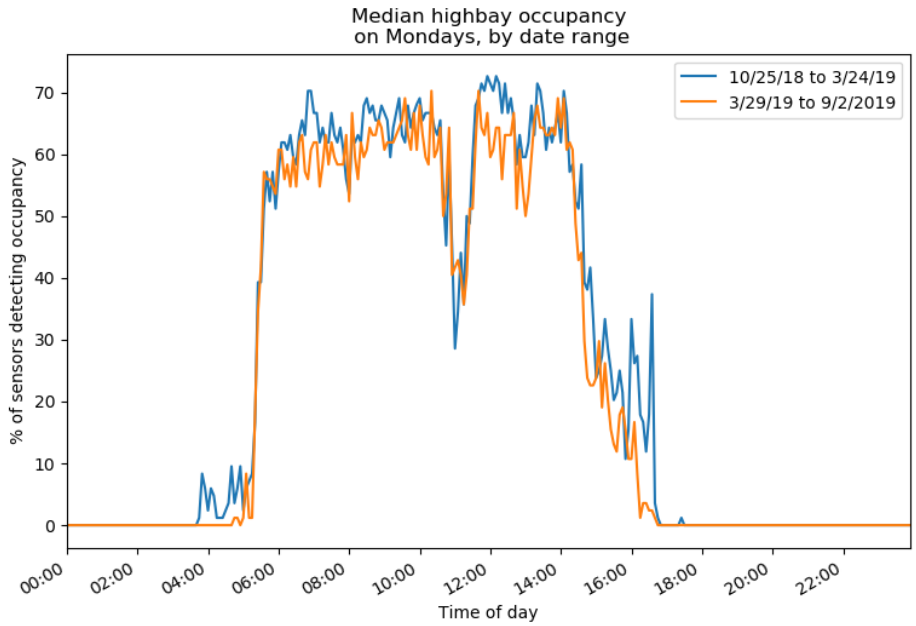


Figure 79. Plotting the Median Percentage of High-bay Sensors Reporting Occupancy at Each Time of the Day, on Mondays.

Plotted separately over an early and late period of the high-bay demo. (Date ranges indicated in legend.) Occupancy patterns are similar in each period.

6.5.2 Office Area

We repeat the previous analysis to study occupancy in the office area. We first look at occupancy patterns over the entire office demo period (10/25/2018 – 9/2/2019). Once again, we first compute the percentage of sensors detecting occupancy in the office at each timestamp during this period. Then, we group the data by days of the week and compute the median percentage of sensors detecting occupancy at each time of the day (out of the 68 sensors during Phase 1 with pendant fixtures, and out of the 84 sensors during Phase 2 with troffer fixtures). We plot this in Figure 80, showing separate curves for each day of the week. We see that the office area was generally occupied from 4:40 am to 5:20 pm on weekdays, though there is occasionally a small amount of occupancy later into the evening. Once again, we estimate the typical start and end times of the occupied period for each day of the week, which we again define as the period when the median percentage of sensors detecting occupancy is greater than 3%. This is summarized in Table 56.

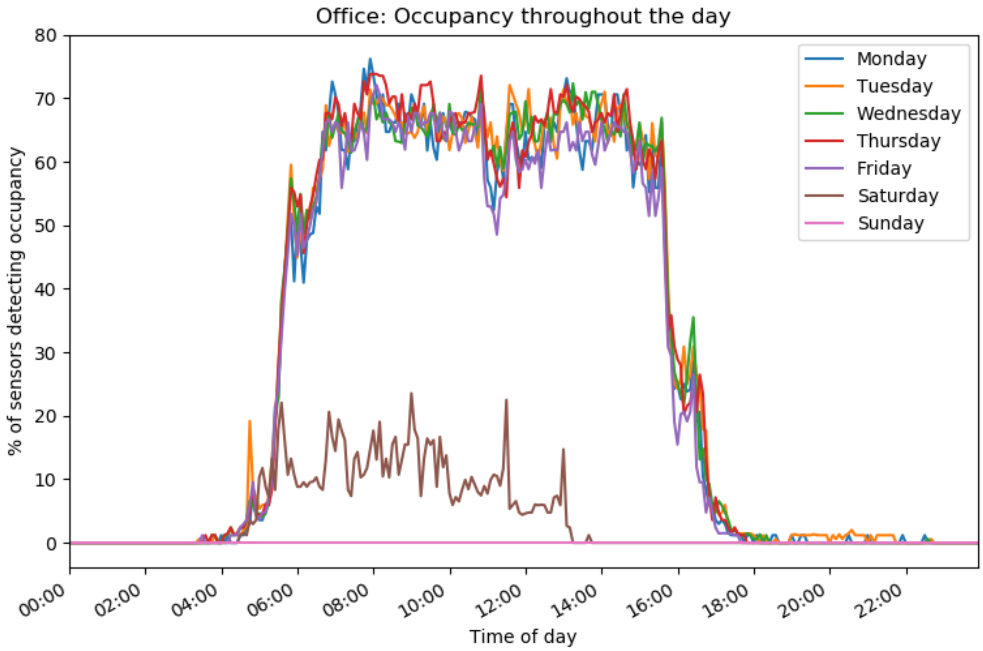


Figure 80. A Plot of Typical Office Area Occupancy Patterns Throughout the Day, for Each Day of the Week.

To produce the graph, we grouped occupancy measurements by time of day (separately for each day of the week), then computed the median value of the percentage of sensors reading occupancy at that time of day. Data from (10/25/2018 – 9/2/2019) was included.

Table 56. Summary of the Typical Periods When the Office Was Occupied, by Day of the Week.

We define the occupied period as when the median percentage of sensors reporting occupancy was greater than 3%.

Day of week	Occupied period began	Occupied period ended	Length of occupied period (hours)
Monday	4:45 am	5:10 pm	12.42
Tuesday	4:45 am	5:15 pm	12.50
Wednesday	4:40 am	5:20 pm	12.67
Thursday	4:40 am	5:15 pm	12.58
Friday	4:40 am	4:55 pm	12.25
Saturday	4:45 am	1:00 pm	8.25
Sunday	-	-	-

Next, we compare office area occupancy patterns over time. We find that patterns of human occupation of the office were generally stable, but we observe a problem with occupancy sensors in the office area, namely that they were too sensitive in later periods of the demo. This led to office lights powering on randomly at night, due to false occupancy detections, which reduced occupancy-based energy savings in the troffer period.

We start by examining occupancy during the first week of the office demo (during the pendant fixture period) in Figure 81. Each dot shows the percentage of office sensors that detected occupancy in each 5-minute interval during the first week of the office pendant demo. Note that no occupancy is detected during overnight periods. Hence, occupancy sensors worked well early in the pendant demo.

However, after we replaced the pendant fixtures with troffers, we received complaints from office workers that lights were not staying on when people were present. Hence, on May 1, 2019, we increased the sensitivity of the new sensors. This ensured office troffer lights stayed on and eliminated complaints from office workers, but it resulted in the sensors being too sensitive. We show this in Figure 83, were one can see that detected occupancy during overnight periods increased significantly after May 1. To view the issue more clearly, we zoom in on a one-week period (the last week of the troffer demo) in Figure 82, where one can see that in overnight periods, a small amount of occupancy was persistently detected. This led to lights turning on randomly throughout the night, in response to false detections of occupancy, which reduced energy savings.

Finally, for completeness, in Figure 84 we plot the office area analogue of Figure 79. Figure 84 shows the median percentage of office area sensors detecting occupancy in the pendant period (10/25/2018 – 3/24/2019) vs the troffer period (3/29/2019 – 9/2/2019), on Mondays. One can see that the shapes of the curves appear the same in each period, suggesting patterns of human occupancy were consistent. However, the percentage of sensors detecting occupancy is greater in the troffer period than pendants. Also, one can see that a small amount of occupancy is detected throughout the night in the troffer period, due to hypersensitive occupancy sensors, as previously discussed. This further confirms that sensors were too sensitive in the later (troffer) periods.

We comment that the Enlighted lighting system was programmed to utilize *occupancy zones* containing multiple light fixtures, where each occupancy zone aligned with a different room in the office. We configured the lighting system so that when any fixture in an occupancy zone detected occupancy, all of the lights in that zone powered on. This is a standard configuration option, and it was chosen to maximize occupant comfort. However, this had the unintended effect of sharply reducing energy savings when occupancy sensors became overly sensitive, since one false detection powered on all of the lights in that zone. In essence, this setting amplified the problem of occasional false occupancy detections. This significantly reduced the energy savings realized in the troffer period. See also the discussion of issues in Section 8.1.1.3.

We note that an alternative configuration of the Enlighted system is possible. In that configuration, a detected occupancy only powers on the single light attached to the fixture, not every light in the entire occupancy zone. This configuration setting is strongly recommended, especially for overnight periods, in situations where occupancy sensors may become hypersensitive. This could ensure that strong energy savings are achieved consistently.

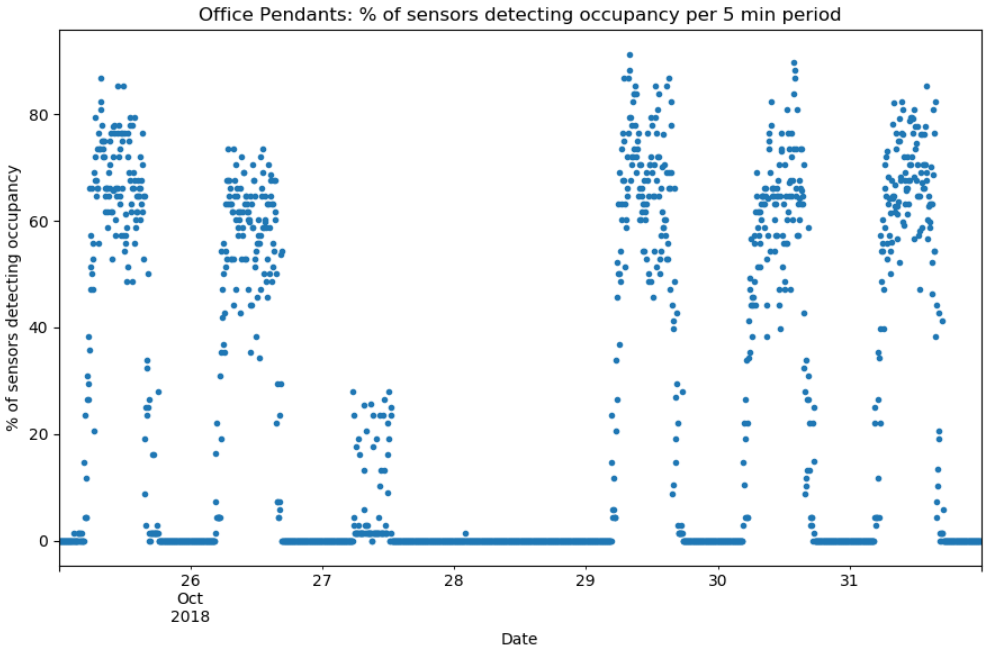


Figure 81. Occupancy in the Office in the First Week of the Pendant Demo Period.

Each dot shows the percentage of office sensors that detected occupancy in each 5-minute interval during the first week of the office pendant demo. Note that no occupancy was detected in overnight periods.

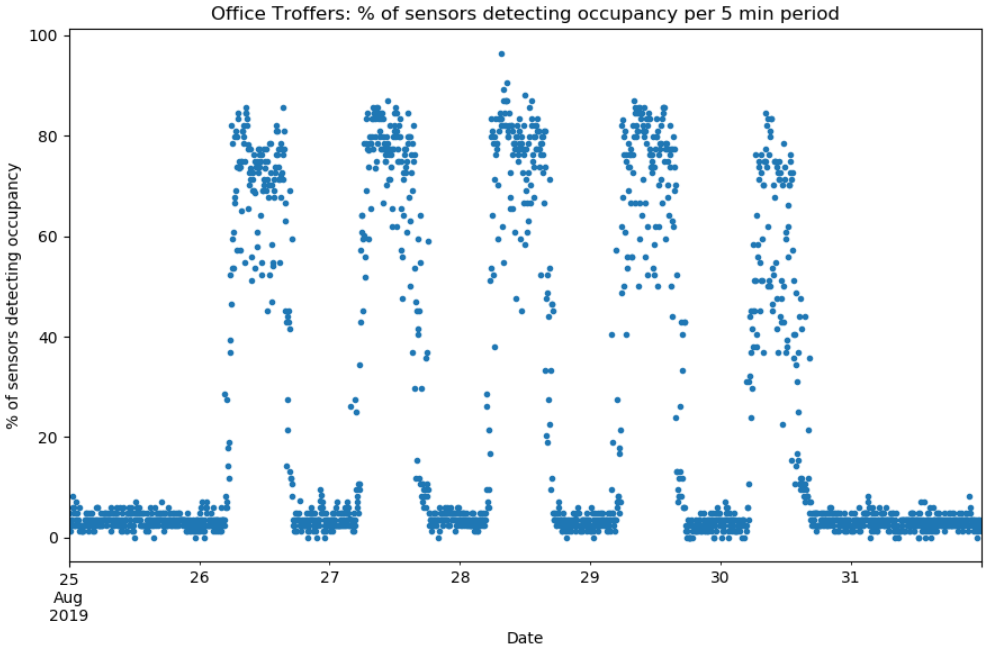


Figure 82. Occupancy in the Office Late in the Troffer Demo Period.

Note that a small amount of occupancy was detected throughout the night and on weekends, when the office was vacant. Hence, occupancy sensors were too sensitive, and had many false detections.

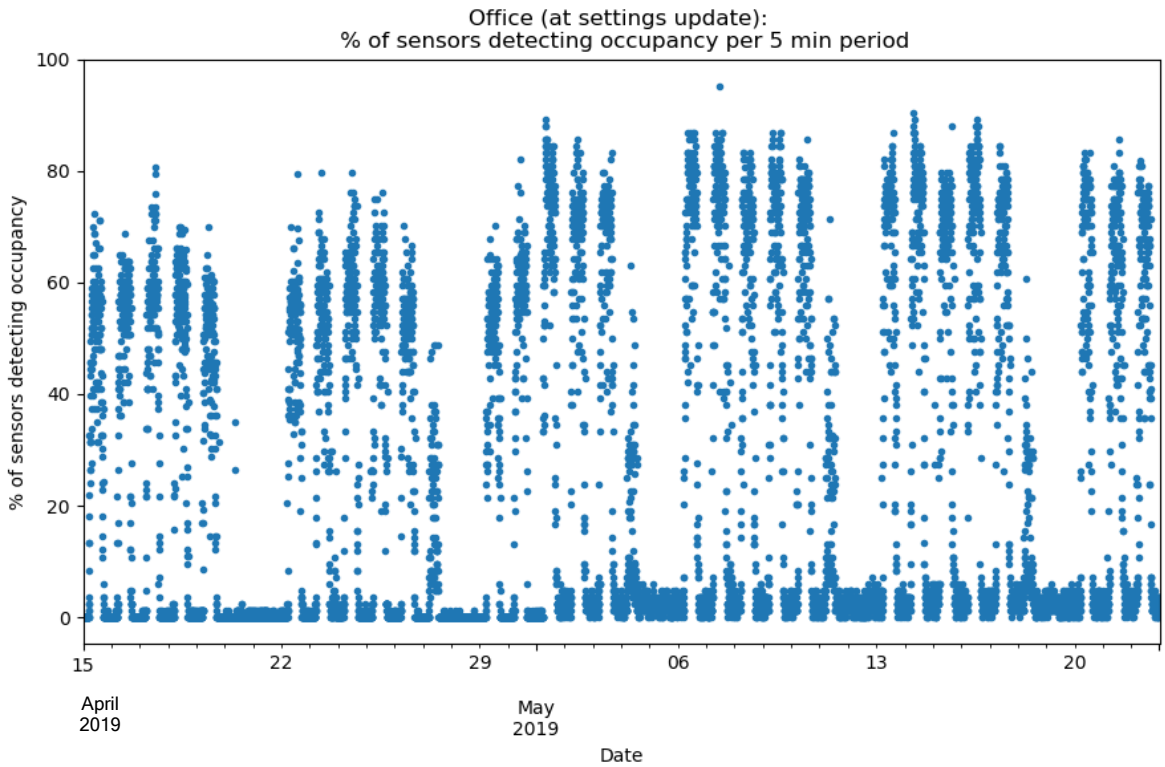


Figure 83. The Sensitivity of Occupancy Sensors Was Increased on May 1.

This resulted in an increase in the amount of occupancy detected in overnight periods (when the office was vacant).

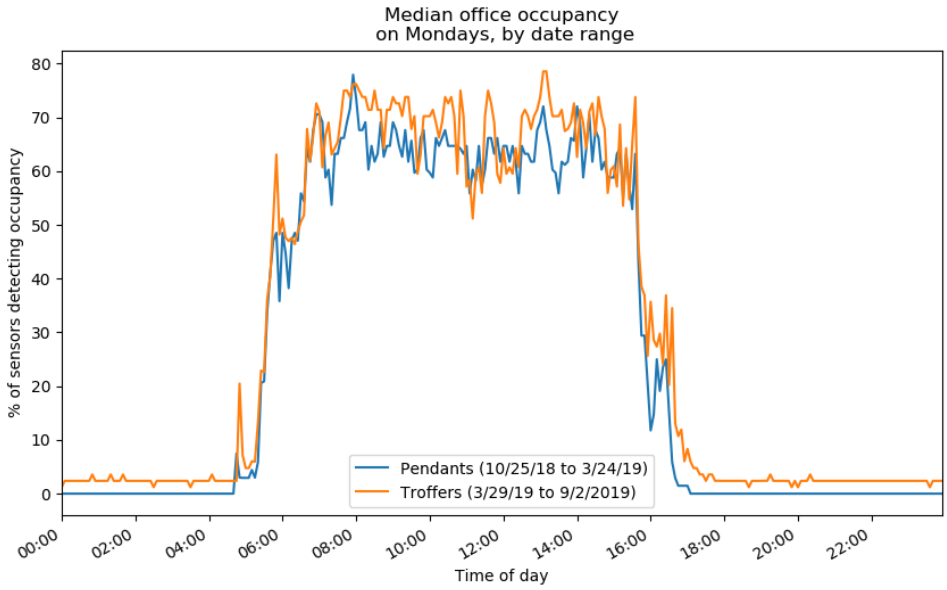


Figure 84. Plotting the Median Percentage of Office Sensors Reporting Occupancy at Each Time of the Day, on Mondays.

Plotted separately for the pendant and troffer demo periods. Note that occupancy sensors are too sensitive in the troffer period and detect occupancy throughout the night.

7.0 COST ASSESSMENT

This section describes the cost assessment of this Intelligent Building Management with Holistic Digital Lighting project. The demonstration project took place at Tinker Air Force Base in Oklahoma City, Oklahoma, and involved the retrofitting of lighting (from fluorescent lights to smart, IoT LED lights) in a 21,000 square foot high-bay industrial area and a 5,000 square foot office area. The study also upgraded plug-load controllers in the office area, as well as HVAC controllers (for office and high-bay areas) to enable occupancy-based control (OBC), which was previously lacking. This assessment considers the total installation costs, including hardware costs, labor costs, and operation and maintenance costs. We include a detailed breakdown of the various hardware costs, including a comparison of the costs of pendant light fixtures vs troffer fixtures. The project's costs are counterbalanced by substantial energy savings achieved. The associated cost savings and emissions reductions are location dependent because of electricity/fuel price variation as well as the mix of fuels used in electricity generation. Hence, we analyze cost effectiveness using three sets of energy prices: Oklahoma (where the demo took place), California (a high-energy-cost location), and the U.S. average. We also explore the cost effectiveness over different study periods. For a comparison with this demo system, we analyze a base case upgrade option of TLED lights with no occupancy-based control of HVAC or plug-loads.

7.1 COST MODEL

Table 57 summarizes the key elements of the cost model for this demonstration project. Each item in the table is discussed in detail in subsequent subsections.

Table 57. Cost Model for the Intelligent Building Management with Holistic Digital Lighting Demonstration System.

Cost Element	Data Tracked During the Demonstration	Costs
Hardware capital costs	Purchase price of: office light fixtures, high-bay light fixtures, lighting control hardware, plug-load control hardware, and HVAC integration hardware	Total price for demo with High-bay + pendants in the office: $75,376 High-bay + troffers in the office: $74,752
Installation costs	Labor costs for installation of: plug-load controllers, lighting equipment & HVAC controllers, and commissioning the lighting system	Estimate $49,371 (same for either lighting configuration)
Consumables	Not applicable	Not applicable
Facility operational costs	We measured energy consumption of the baseline system (fluorescent lights, no OBC of plug-loads or HVAC), as well as the energy consumption of the demo system (Enlighted LED lights + OBC of plugs and HVAC), using energy meters installed throughout the HVAC, lighting, and plug-load subsystems. From the measurements, we estimated yearly energy consumption of the demo system, as well as a base case upgrade option consisting of TLED lights without OBC of plug-loads or HVAC.	Estimate demo system will save 112,186 kWh/yr of electricity and 262 MMBtu/yr of natural gas compared to base case upgrade (TLEDs only)
Maintenance	This system does not require routine maintenance.	Minimal to none
Hardware lifetime	We tracked the status of the equipment throughout the project. (One high-bay light fixture burned out in the first month after installation and was replaced.)	Estimated 15-year hardware lifetime
Operator training	Training is optional: the system is user-friendly, and personnel can learn to administer the system by reading the owner's manual. Training was provided to one Air Force Employee (by Honeywell staff) to learn to be the system's owner/admin.	(Optional) $2,000 per training session provided by Enlighted staff. Not included in our cost analysis.

7.1.1 Hardware capital costs

Table 58 summarizes the hardware capital costs of the demonstration system. We note (1) these are the actual costs of the purchased equipment, not cost estimates, and (2) these are one-time costs. Costs are separately listed for the two hardware configurations tested this project: column 2 shows the hardware costs for the demo system with pendant light fixtures in the office area, and column 3 shows the hardware costs with troffer light fixtures in the office area. Row 2 lists the costs of light fixtures for the 5,000 square foot office area (pendants in column 2, troffers in column 3), which include built-in smart sensors. (Troffer light fixtures for the 5,000 square foot office were $624 less costly than pendants fixtures.) Row 3 lists the cost of light fixtures for the 21,000 square foot high-bay area. Row 4 lists the cost of lighting controls hardware, which includes Enlighted wireless gateways, the Enlighted Energy Manager, the Enlighted AIRE module, and Enlighted Room Controllers (ERCs, i.e. the wireless light switches). Row 5 lists the cost of plug-load controllers, which enabled occupancy control of power receptacles. Row 6 lists the cost of the HVAC integration hardware, which included a Contemporary Controls BACnet IP/MSTP Router and a Honeywell CPO-PC-6A HVAC controller; these were used to connect the occupancy signals from the Enlighted AIRE appliance into the HVAC system, enabling occupancy-control of the HVAC system. Row 7 lists the total hardware costs.

Note that we do *not* include the cost of the HVAC system, since that is a mandatory component of the building, independent of our demo system. Instead, we only include the cost of the additional control hardware necessary to interface and enable occupancy control of the existing HVAC system as long as it is BACnet compatible. Also, we do *not* include the costs of energy meters installed in this project for measurement and verification of energy consumption, since those would not be included in a typical building project.

Table 58. Hardware Capital Costs of the Demonstration System.

	High-bay + pendants (office)	High-bay + troffers (office)
Light fixtures for 5,000 ft^2 office	$17,811	$17,187
Light fixtures for 21,000 ft^2 high-bay	$48,399	$48,399
Lighting controls (for both office and high-bay areas)	$3,559	$3,559
15 plug-load controllers for office	$2,329	$2,329
HVAC integration hardware (for 2 air handling units)	$3,278	$3,278
Total	$75,376	$74,752

We note that the plug-load control hardware costs listed in Table 58 is *higher than would be found in typical building retrofit projects*: in this demo project, each plug-load controller was connected to one power outlet. However, it is more typical to connect multiple power outlets (e.g. 5 - 10 outlets) which are in close proximity and on the same circuit (e.g. in the same room) to one plug-load controller, to reduce hardware costs.

We also note that the Enlighted energy manager and AIRE appliances, which are a significant part of the lighting controls cost, are capable of servicing *significantly larger areas* than the relativity small demo areas used in this project. Hence, those hardware costs would be a smaller portion of overall costs in typical building retrofit projects. This reduced the apparent cost effectiveness of this demo project.

We briefly discuss the scaling of the costs: the costs of light fixtures and plug-load controllers scales linearly with the number of fixtures, which in turn scales linearly with the square footage of an installation. The costs of the lighting controls and HVAC integration hardware scales roughly linearly with the number of buildings serviced, e.g. one Enlighted Energy Manager can control all of the lights in a typical office/industrial building. For multiple buildings, or for extremely large campus or buildings, additional control hardware may be required.

7.1.2 Installation costs

Table 59 summarizes the installation costs of the demo system, which consists only of labor. Note this is a one-time cost. Row 2 shows the installation cost of the plug-load controllers (which was $7,700); note this is the actual installation cost (not an estimate). Installation of the plug-load controllers involved re-wiring each power outlet that was connected to a controller, mounting the controllers inside the outlets, and configuring the schedule and behavior of the plug-load control in the Enlighted Energy Manager console.

Row 3 lists an estimated cost to install the lighting fixtures and controls and the HVAC control equipment. Installation of the lighting system comprised a majority of the work and cost: this included replacing old light fixtures with new light fixtures; installing Enlighted Room Controllers (i.e. wireless light switches) in conference rooms in the office area; installing Enlighted wireless gateways throughout the building and running ethernet cable from the gateways to the Enlighted Energy Manager; and mounting the Enlighted Energy Manager, AIRE appliance, and PoE network switch in a cabinet in a mechanical room. HVAC integration was less involved, and simply required mounting the HVAC control hardware in the cabinet next to the Enlighted AIRE appliance and running cables to the HVAC equipment.

As mentioned, the cost listed in row 3 is an estimate: the actual installation cost included installation of the high-bay lights and pendant lights in the office area, plus the replacement of pendant lights with troffer lights in the office area. That price was **$47,300**. However, in a realistic building retrofit, one would not install two sets of lights into the same area. (We did so to compare lighting quality of two different lighting designs.) Third-party activities and installation costs were provided in aggregate and not itemized or disclosed in a manner which enables itemization of costs for installation for each office fixture installation separately, so instead we estimate the price of installation with one set of office lights. To do so, we take the actual price and multiply it by a scaling factor. We assume a uniform installation cost per square feet, and use the sizes of the high-bay and office areas to determine the scaling factor (assuming one office installation). Our estimated cost is:

$$\text{install cost (estimated)} = \left(\frac{21{,}000 + 5{,}000\ \text{ft}^2}{21{,}000 + 5{,}000 + 5{,}000\ \text{ft}^2}\right)\$47{,}300 = \ \$39{,}671$$

Notice the formula scales the actual cost ($47,300), assuming two office lighting installations (5,000 + 5,000 square feet), to estimate the price assuming one office lighting installation (5,000 square feet).

Row 4 lists the labor cost of commissioning the lighting system; this entails programming each lighting fixture and configuring the settings and schedules of the light fixtures in the Enlighted energy manager console. Note that commissioning a lighting system costs about $2,000 for every 200 pieces of lighting equipment, which is about 1 day of work. The lighting equipment that needs programming are principally light fixtures, but wireless gateways, ERCs, etc., also require programming.

Table 59. Labor Costs for Installation of the Demo System Components.

	High-bay + pendants (office)	High-bay + troffers (office)
Plug-load controllers (actual cost)	$7,700	$7,700
Lighting & HVAC control installation (estimated cost)	$39,671	$39,671
Lighting system commissioning (actual cost)	$2,000	$2,000
Total	**$49,371**	**$49,371**

7.1.3 Consumables

Not applicable.

7.1.4 Facility operational costs

Table 61 summarizes the projected yearly energy consumption of three options for building lighting and HVAC control. Electricity use (row 2) includes electricity used for light fixtures, plug-loads, fans in air handling units, and to power chillers (which supplied chilled water to the air handlers.) Natural gas usage (row 3) comes from boilers supplying hot water to VAV reheat boxes.

Column 2 of Table 61 shows the projected yearly energy consumption of the baseline building system, which consists of fluorescent lights and no occupancy-based control (OBC) of plug-loads or HVAC. (Note this was the state of the building before the demonstration began.) These estimates were made in Section 6.0 using data (Section 5.5) collected during the baseline period of this project with energy meters in the HVAC system and on the circuits powering the lights and plug-loads.

Column 3 shows the estimated energy consumption of the base case option for building upgrades, consisting of TLED lights without any occupancy-based control. We estimate a 25% reduction in lighting energy consumption over the baseline fluorescent lighting, as in [Bartholomew15], and no reduction in HVAC or plug-load energy use.

Column 4 of the table shows the projected yearly energy consumption of the demo system exhibited in this project, which consisted of a sophisticated Enlighted LED lighting solution combined with occupancy-based control (OBC) of plug-loads and HVAC. These projections were made (Section 6.0) using data (Section 5.5) collected during the demo phase of this project with energy meters in the HVAC system as well as on the lighting and plug-load circuits.

Column 5 estimates the yearly saving of this advanced Demo system (column 4) compared to the base case (TLEDs, no OBC of HVAC or plug-loads; column 3). Note this savings is recurring.

Natural gas energy consumption came only from boilers, which supplied hot water to the HVAC system. Electricity was used to (1) power the lights, (2) power plug-loads, and (3) power HVAC (such running fans in air handling units and running the chillers to provide chilled air to air handlers.) A breakdown of energy consumption/savings by source is shown in Table 60.

Table 60. Breakdown of Projected Yearly Electricity Consumption and Savings by Source.

	Baseline consumption	TLED (Base) consumption	HB + Pendants consumption	Saved (HB + Pend) vs Base (TLED)
Lighting electricity (kWh / yr)	118,930	89,197	36,886	52,311
Plug-load electricity (kWh / yr)	553	553	528	25
HVAC electricity (kWh / yr)	286,900	286,900	230,300	59,850
Electricity total (kWh / yr)	406,383	376,650	267,714	112,186

The method of calculating the HVAC energy savings, both electricity and natural gas, has some subtleties which warrants further discussion to avoid confusion. First, we recall that the HVAC system was operated in a 2+1 mode throughout the demo period, where occupancy control of the HVAC system was enabled for two sequential days, achieving energy savings, while occupancy control was disabled on the third day. For instance, in each 6-day period, occupancy control was enabled on days 1, 2, 4, and 5, and it was disabled on days 3 and 6.

The baseline energy consumption of the HVAC system was computed using measurements from the days when occupancy control was disabled, i.e. from days 3, 6, ... (This is shown in column 3, row 4 of Table 60 and column 3, row 3 of Table 61.)

The energy consumption of HVAC with occupancy control enabled was computed using measurements from days 1, 2, 4, 5, … (This is shown in column 4, row 4 of Table 60 and column 4, row 3 of Table 61.)

To compute the energy savings of occupancy control, we first estimated what the energy consumption on days 1, 2, 4, 5, … would have been, if occupancy control been disabled on those days. We did so by linearly interpolating between measurements on days when occupancy control was disabled, i.e. between days 0, 3, 6, …. We then subtracted from these estimates the actual energy consumption on days 1, 2, 4, 5, … when occupancy control was enabled.

This gave us estimated energy savings due to occupancy control on days 1, 2, 4, 5, …, which is shown in column 5, row 4 of Table 60 and column 5, row 3 of Table 61. Because of this calculation method, column 5 does not precisely equal (column 3 – column 4) for HVAC quantities in tables 58 and 59, though it is close. Since HVAC electricity consumption is incorporated into total electricity consumption, this also explains why column 5 does not precisely equal (column 3 – column 4) for row 5 of Table 60, or row 2 of Table 61.

Table 61. Projected Yearly Energy Consumption and Savings.

	Baseline energy consumption (fluorescent lights, no OBC of HVAC or plugs)	Base case energy consumption (TLED lighting upgrade, no OBC of HVAC or plugs)	Demo system energy consumption (Enlighted LED lighting, OBC of HVAC and plugs)	Energy savings (Demo vs base case)
Electricity (kWh/yr)	406,383	376,650	267,714	112,186
Natural gas (MMBtu/yr)	798	798	536	262

To convert the yearly energy costs and savings into dollars, we use the current industrial prices of electricity and natural gas in Oklahoma from the eia.gov website as of August 2019. We use **$0.0524/kWh** for electricity and **$1.81/MMBtu** of natural gas.

7.1.5 Maintenance

This demonstration system (consisting of Enlighted LED lights, smart plug-loads, and occupancy-based HVAC control) does not require routine maintenance. (Note that we do not include the HVAC system itself in this demo system, only the occupancy-based controllers. We assume the HVAC system is already a part of the building.) Building owners may wish to occasionally adjust lighting schedules or brightness settings of light fixtures. They can do so through the Enlighted Energy Manager. This is better characterized as routine *operation* rather than *maintenance*. Since these operations are infrequent and optional, we do not include a cost. Some corrective maintenance could be required to replace parts if equipment fails, but we expect that to be infrequent.

7.1.6 Hardware lifetime

One LED light fixture failed in the high-bay area after one-month of installation and was promptly replaced. However, there have been no similar reported issues since. LED lifespans are very long, so we believe that failure was an anomaly—e.g., perhaps a manufacturing defect. (We note that LED lights used in the office troffer fixtures have a 5-year warranty.) The more typical degradation mode of LED lights is that they gradually reduce light output over time as the fixtures age. The Flex Essential fixtures (high-bay area) are estimated by the manufacturer to operate for 309,000 hours until the LEDs depreciate to 70% of current output, while the Finelite HP2 (pendant fixtures) and ILP LEDs (troffer fixtures) are estimated to operate for 100,000+ hours before degrading to 70% of current output. Assuming 12 hours of usage per day, this is 20+ years of useful lifetime. The other hardware components in this demonstration project are designed for long lifetimes as well. Based on the product spec sheets, we estimate a hardware lifetime of approximately 15 years.

7.1.7 Operator training

At least one person needs to be the owner / admin of the Enlighted Energy Manager if a building manager wants to change the lighting system's behavior at later dates. (Typical changes might include changing lighting schedules or the light output settings of light fixtures.) Formal training is optional but not necessary: the Enlighted Energy Manager is user-friendly and institutive to use, and admins can learn its operation by reading the user manuals provided with the system. However, formal training is available from Enlighted. A training session takes less than one day and costs approximately $2,000. We comment that it is straightforward for admins who have received training to in turn train other admins, should the Government wish to avoid the recurring costs of formal training by Enlighted. Because training is optional, we do not include it in our cost estimates. (For completeness, we note that Honeywell staff provided user manuals and training to an Air Force employee at system handoff to become the owner/admin of the system.)

7.2 COST DRIVERS

Hardware costs are driven primarily by the size of the installation. Most of the hardware costs, such as light fixtures and plug-load controllers, scale linearly with the square footage of the installation. A smaller portion of the hardware costs (such as the Enlighted energy manager) scales with the number of buildings upgraded, since each Energy Manager can support several buildings. Another major component of installation costs is the labor cost of installing fixtures; a lesser amount is the cost to commission the lighting system (i.e., to program the lighting system). Labor costs are driven primarily by the size of the installation as well local labor rates (since local installers perform the light fixture installation.)

Cyber security compliance may be a significant cost driver: this project incurred significant delays, as well as cost over-runs, due to a protracted cyber security review and approval process that prevented a timely installation of the demo system.

Taxes, incentives, and rebates may be cost drivers, where applicable.

Finally, the cost-effectiveness of this demo system depends sensitively on local energy prices. For example, the collapse in natural gas prices in Oklahoma in the past four years (Figure 85) has adversely impacted the cost effectiveness of this demonstration project compared to original estimates.

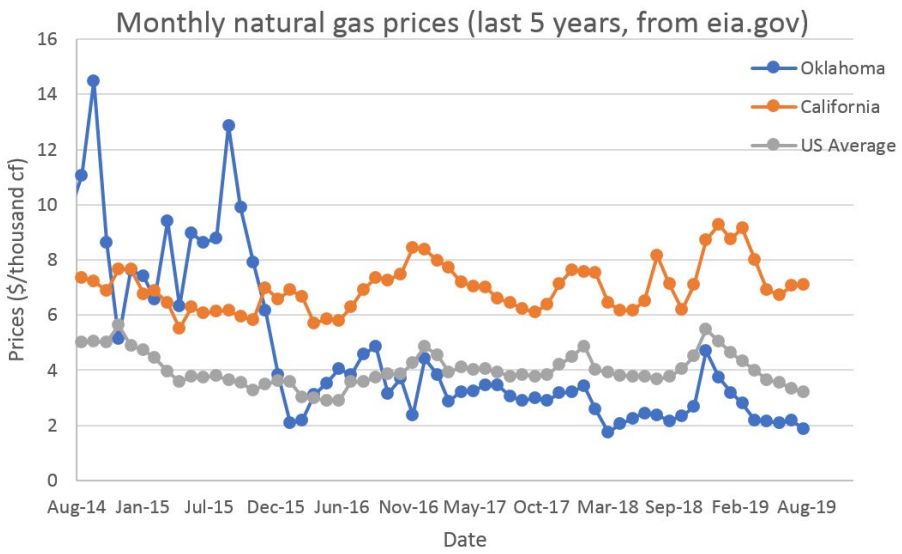


Figure 85. Industrial Natural Gas Prices ($/thousands of Cubic Feet) for OK (blue), CA (Orange), and the U.S. Average (Gray), per Month Over the Last 5 Years.

The collapse in natural gas prices in Oklahoma has reduced the cost-effectiveness of this demo system. Figures from eia.gov.

7.3 COST ANALYSIS AND COMPARISON

We next perform a BLCC analysis of the demonstration project using the NIST BLCC5 tool [BLCC5], version 5.3.19. The analysis assumes a 5,000 square foot office space and 21,000 square foot high-bay industrial area.

For the analysis, we consider a base case which entails replacing the facility's fluorescent lights with TLED lamps and no occupancy-based control of lighting, HVAC, or plug-loads. Following [Bartholomew15], we estimate an installation a price of $1 per square foot ($26,000 total) with incentives, and a reduction in lighting electricity consumption of 25% over baseline lighting energy consumption (fluorescent lights). We estimated the yearly baseline lighting energy consumption using measurements of actual energy consumption of the fluorescent lights (data in Section 5.5.1.1) which was extrapolated to yearly consumption (Section 6.1). We then assumed a 25% reduction of this quantity to estimate the base case yearly lighting energy consumption of TLED lights.

The alternative case is the Intelligent Building Management with Holistic Digital Lighting, consisting of smart Enlighted LED lighting with occupancy-based control of lights, plug-loads, and HVAC. We recall that two types of hardware were tested in the office area during this demo: pendant fixtures (Phase 1), and troffer fixtures (Phase 2). (High-bay fixtures were the same throughout the demo.) Pendants had slightly higher costs than troffers ($624 more), but they also had higher energy savings (due to overactive occupancy sensors in the troffer demo period.) Instead of performing two separate analyses, we perform one BLCC analysis using the pendant fixtures, since the system performed slightly better. We measured actual energy consumption of this system during the demo period and extrapolated the data to a yearly estimate (Section 5.5 and 6.0).

Estimated yearly energy consumption of the base case and Holistic Lighting case are summarized in columns 3 and 4 of Table 60, and energy savings of the Holistic Lighting compared to the Base case is in column 5. The main BLCC analysis assumes a location of Oklahoma City, Oklahoma, and uses current industrial natural gas and electricity prices of $1.81/MMBtu (gas) and $0.0524/kWh (electricity) as of August 2019, from eia.gov.

The main parameters of the BLCC analysis are summarized in Table 62.

Table 62. BLCC Analysis: Base Case and Alternative (Holistic lighting).

	Base case	Alternative: Holistic lighting case
Lighting	TLED retrofit savings 25% lighting energy over existing fluorescents, no occupancy-based control	IoT system with LED lights and embedded sensors and controls
HVAC	No occupancy-based control	Occupancy-based control applies setbacks to HVAC setpoints
Plug loads	Existing	Half of plugs are occupancy controlled, half are always powered on
Installation costs	$26,000 (Assuming $1/square foot)	$124,747 (Assuming pendants in the office)
Recurring	$0	$0
Location	Oklahoma City, Oklahoma	
Space	5,000 square foot office and 21,000 square foot high-bay	
Industrial Electricity price	$0.0524/kWh	
Industrial Natural gas price	$1.81/MMBtu	

These parameters were analyzed with the NIST BLCC5 tool (version 5.3.19). We performed the analysis for Oklahoma City assuming 5, 10, and 20-year studies. The results are summarized in Table 63.

Table 63. BLCC Analysis Results for Oklahoma, Comparing Base and Alternative Cases

Inputs		Outputs	Study period		
Project Name:	Holistic Lighting	**Results**	**5-yr**	**10-yr**	**20-yr**
Project Location:	Oklahoma	Energy Consumption Cost Savings	$27,702	$52,260	$92,107
Analysis Type:	MILCON Analysis, Energy Project	PV of Total Savings	$27,702	$52,260	$92,107
Base Date:	1-Nov-2019	Net savings	($71,045)	($46,487)	($6,640)
Beneficial Occupancy Date:	1-Dec-2019	Savings-to-Investment Ratio (SIR)	0.28	0.53	0.93
Study Period (years):	5, 10 or 20 yrs	Adjusted Internal Rate of Return (AIRR)	-19.79%	-3.30%	2.64%
Discount Rate:	3% (default)	Payback Period (simple and discounted)	not reached	not reached	17 yrs, not reached
Electricity Savings/ yr (kWh)	108,936.20	Electricity Savings (kWh)	544,606.70	1,089,213.40	2,178,426.70
Natural Gas Savings / yr (MMBtu)	262.20	Natural Gas Savings (MMBtu)	1,310.70	2,621.30	5,242.70
Total Cost Savings / yr	$6,351	Emissions Reduction			
Base Case Capital Costs	$26,000	Total CO2 Reduction (kg)	483,771.94	967,543.88	1,935,087.76
Holistic Lighting Capital Costs	$124,747	Total SO2 Reduction (kg)	1,376.42	2,752.83	5,505.66
Annual Maintenance	$0	Total NOx Reduction (kg)	736.52	1,473.05	2,946.09

From Table 63, one can see that payback was not reached in 5 or 10-year studies (for Oklahoma). In a 20-year study, simple payback was achieved in **17 years**, with a Savings-to-Investment Ration (**SIR**) of **0.93** and an Adjusted Internal Rate of Return (**AIRR**) of **2.64%**. (Discounted payback was not reached.) A few comments are in order. First, we note that the cost of our demo system (per square foot) is higher would be found in typical building retrofits. There are a few reasons, including that (1) our demo system occupied a rather small area (only 26,000 square feet), which constituted a small fraction of Building 3907; this is the nature of small demonstration projects. But our system still required expensive fixed costs, like an Enlighted Energy Manager, AIRE appliance, and HVAC controls. These devices are capable of servicing much larger areas than were occupied by the demo system. In larger installations, the relative costs of these devices (per square foot) would be less, which would improve economic viability. Reason (2): The plug-load installation was more expensive than is typical, since every outlet had its own plug-load controller, while it is more typical to connect many outlets to one controller to reduce costs. And reason (3): lighting energy savings from the Enlighted smart sensor system can achieve greater savings if the demonstration areas would have had greater daylight exposure, leveraging the daylighting feature of the smart sensors.

We also note that energy prices in Oklahoma have collapsed in the past four years (see e.g. natural gas prices in Figure 85). This has reduced the cost effectiveness of the Holistic Lighting solution. However, historically, energy prices are volatile, and even now they vary between regions. To study how changing energy prices affect the result, we repeated the 20-year study, assuming U.S. average electricity and natural gas prices, as well as California prices, which are above the national average.

Table 64. BLCC Analysis Results Using U.S. Average and California Industrial Energy Prices.

(Prices for Aug. 2019, from eia.gov).

	U.S. Average	California
Industrial Electricity Price ($/kWh)	0.0744	0.1527
Industrial Natural Gas Price ($/MMBtu)	3.09	6.84
SIR	1.34	2.86
AIRR	4.51%	8.53%
Simple payback (years)	12	6
Discounted payback (years)	14	7

From Table 64, we see that assuming U.S. average industrial prices for electricity ($0.0744/kWh) and natural gas ($3.09/MMBtu), the demo system would have **simple payback in 12 years** and **discounted payback in 14 years**, with a **SIR** of **1.34** and **AIRR** of **4.51%.**

Assuming California prices for electricity ($0.1527/kWh) and natural gas ($6.84 / MMBtu), the system achieves a much more attractive simple payback period of **6 years,** with discounted payback in **7 years**. The **SIR is 2.86**, and **AIRR is 8.53%**.

To conclude, this demonstration project achieved substantial reductions in energy consumption as well as huge reductions on greenhouse gas emissions. The cost effectiveness has been impaired by extraordinary declines in energy prices, caused by the fracking boom—which are particularly large in Oklahoma. However, the system is still an attractive investment option at prevailing U.S. average energy prices, and it is very attractive assuming higher energy costs such as California energy prices.

8.0 IMPLEMENTATION ISSUES

8.1 IMPLEMENTATION ISSUES

8.1.1 Lighting Issues

8.1.1.1 High-Bay Area

Installation of replacement LED fixtures in the high-bay area was relatively straightforward. The new fixtures produced more lumens than the original metal halide fixtures such that it would have been possible to illuminate the high-bay area with fewer fixtures. This would have reduced the cost of fixtures, but it would have required considerable extra work to reconfigure the fixture supports and power wiring support to the replacement fixtures. To avoid unnecessary additional work and costs, the original metal halide fixtures in the high-bay areas were replaced one-for-one with the LED replacement fixtures.

Since luminaires were not relocated, a luminaire with a wider distribution was chosen to provide uniform light levels on working surfaces, as well increased vertical light on equipment. Vertical illuminance aids workers when reading and operating large equipment and should be a factor when designing lighting layouts in industrial high-bay areas. The luminaire layout in the high-bay area is shown in Figure 14. This layout was established when the project began, and the intent of the original design is unknown.

In the industrial high-bay area, the largest occupant concern after upgrading to LED luminaires was too much lighting in the space. When implementing new LEDs in industrial high-bay areas it is essential to use a dimmable LED driver and luminaire. We found that it is best to start with more light than needed and dim the lighting until occupants are satisfied with the light levels. This will extend the life of the luminaires through a strategy called lumen maintenance and allow for more versatility in the space.

This dense network of sensors performed finely-grained control of light levels based on measured ambient light levels and occupancy. For example, we were able to take advantage of available daylighting through the windows in the administration areas. Enlighted Sensors in the fixtures near the windows measured lighting levels on working surfaces and adjusted the lighting outputs of their associated lighting fixtures. However, daylight harvesting was not possible in the industrial high-bay areas because there were no windows in these spaces.

The smart sensors also measure ambient temperature data. Although this temperature data was not used for HVAC control, the temperature data was analyzed, and the data appeared affected by fixture height and location of fixture with respect to HVAC supply ductwork. Conditioned air from the overhead HVAC supply was blowing directly across the fixtures in our high-bay demonstration area, resulting in skewed temperature data.

8.1.1.2 Office Area – Phase 1 (Pendants)

Physical installation of all lighting fixtures was a relatively straightforward process. Since this was a retrofit project and each of the pendant fixtures in the administration area had a larger area of coverage than the original 2x4 fluorescent troffers, fewer pendant fixtures were required to illuminate these spaces. As a result, the layout of the pendant fixtures was revised in Phase 1.

This required significant additional work to change the power wiring to the fixtures and to physically hang the new pendant fixtures. This would not have been a problem on a new installation but caused additional work and cost for this retrofit project.

When designing a direct/indirect pendant system in administrative office areas such as this one, it is essential to make sure that there is enough clearance between the luminaire and the ceiling to allow the light to uniformly illuminate the ceiling. In this space, the ceiling was 9'-0", resulting in the ceiling feeling lower, and the space felt more cluttered by the luminaires. For pendant fixtures in office areas, we recommend at least 12" of clearance, with a preference of 18" between the top of the luminaire and the ceiling with a batwing distribution for the uplight, and to mount the bottom of the fixture no lower than 8'-0" from the floor. A shallower luminaire would allow for additional clearance from the ceiling and a less visually cluttered space.

The Phase 1 pendant luminaire layout was also not coordinated with the furniture layout in the general office area. For pendant fixtures in office areas, we recommend aligning the luminaires with the tops of the cubicles to reduce shadowing on desks in the space, and to create a cleaner and more professional look in the space.

Lastly, we also recommend starting with more light than needed and dimming the lighting until occupants are satisfied with the light levels. This will extend the life of the luminaires through a strategy called lumen maintenance and allow for increased light levels if desired.

8.1.1.3 Administrative Area – Phase 2 (Troffers)

We recall that Phase 1 required rewiring to change from a layout suitable for troffers to one suitable for pendants. For the Phase 2 installation of the LED 2x4 troffer fixtures, it was necessary to change back to the original fixture layout, fixture wiring and support of the fixtures in the ceiling grid. This required additional work and costs.

When upgrading lighting in areas with ceilings lower than 10 feet, we recommend the use of recessed luminaires, such as troffers, to keep the ceiling open and reduce clutter. This was the preferred method in the administrative area because of this reason.

Again, for LED lighting retrofits, we recommend starting with more light than needed and dim the lighting until occupants are satisfied with the light levels. This will extend the life of the luminaires through a strategy called lumen maintenance and allow for increased light levels if desired.

8.1.2 Cybersecurity Issues

Throughout this demonstration project, we faced challenges related to cybersecurity. During the planning phase, the project experienced schedule delays while reviewing and developing the system design. Additional schedule delays were encountered during installation while trying to get network switch ports activated. Furthermore, during the demonstration period, cybersecurity constraints presented challenges for troubleshooting network-related configuration issues.

Our system was developed and designed with cybersecurity considerations as top priority and was implemented with controls to enable maximum security and maximum lockdown as an isolated standalone system. As such, this network isolation enables adequate system functionality but prevents authorized users from diagnosing, troubleshooting, or debugging any communication or system related issues. Furthermore, network isolation also prevents unlocking the system's maximum potential by restricting access to only local users with physical access to the system, where ideally facility managers and system administrators would have remote access (remote access can still be limited to an internal/organization private network) to manage or monitor the system for standard maintenance operations as normally implemented in corporate environments.

Figure 86 illustrates how the Enlighted system architecture might be implemented in a typical non-DoD application. This architecture would permit remote monitoring and control of the Enlighted systems. However, due to cybersecurity concerns, remote monitoring, control and data transmission over the internet was not permissible. As a result, a degree of valuable system functionality could not be implemented. For example, if remote access had been possible, this demonstration project might have benefited from an ability to remotely check the status of systems, access performance data and/or make adjustments. The Enlighted system does not currently have Authority to Operate (ATO) on DoD networks. As a result, a degree of useful functionality is currently not available.

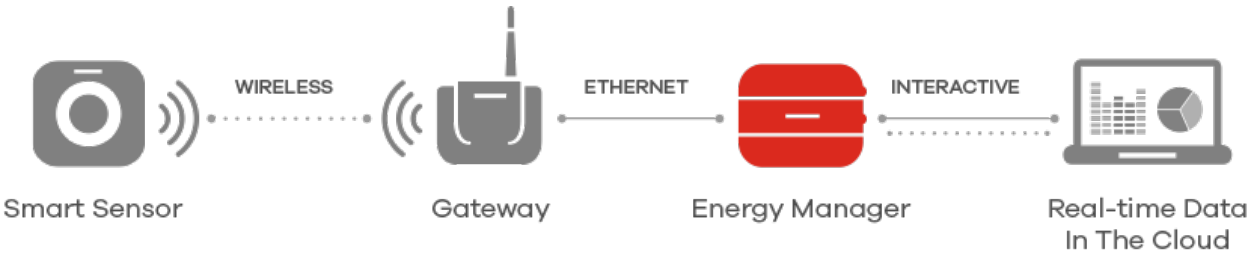


Figure 86. Enlighted System Architecture in a Non-DoD Application.

Figure 2 shows how the controls network was configured. Monitoring and control functions were implemented by interfacing a local computer (Management GUI) to the Enlighted Energy Manager by a hard-wired connection. System performance data (occupancy, lighting system status (ON/OFF), lighting levels, plug-load controller status (ON/OFF, current) and room temperatures) were accessible through the Management GUI.

8.1.3 HVAC Hardware and HVAC Interface Issues

Our project integration with the existing HVAC system faced issues during the demonstration, primarily due to physical hardware and BACnet network issues that were beyond the scope of this project. For example:

- AHU 101: the chilled water valve did not close correctly. This caused the supply air temperature to vary (uncontrolled) based on building load and chilled water temperature. The net effect was over cooling (supply air temperature too low), causing VAV boxes to be in a continuous reheat mode. Further complicating this condition was several VAV box reheat valves which did not function correctly. The supply fan was placed into a mode of manual operation to lower the fan flow in an attempt to address spaces being too cold.

- AHU 101: heat valve appeared operational, however there was no flow through the system.
- AHU 202: the chilled water was in manual override.
- AHU 202: the return fan was out of service from early April 2019 to mid-July 2019.
- AHU 202: the return damper was manually controlled. The net effect is potential times of dead heading the system. The return fan was being overridden and manually controlled.
- The HVAC supervisory controllers and BACnet routers were locking up, resetting and dropping the project's program which caused gaps in our data collection. These conditions were verified to be caused by overloading of BACnet network, site wide. Building 3907 was isolated on to a BACnet network of its own and communicating to an EBI point server of its own. This change was made May 7, 2019 and corrected the issue.

A detailed timeline of the HVAC system issues is shown on Table 65.

Table 65. HVAC issues timeline

Date	Components	Issue Type	Issue Detail
11/26/2018	AHU 101, AHU 202	Mechanical	Cooling valves not closing completely
11/26/2018	VAVs from AHU 101	Mechanical	Dampers at 100% cannot reach min flow.
11/26/2018	AHU 101	Controls	Seeing negative airflow calculations on cooling BTU data
12/13/2018	All	Commissioning	Commissioning of the ESTCP HVAC system integration
1/10/2019	CP01	Controls	TAC Case 01970584 opened for controller reset/lockup every few days
3/5/2019	CP01, CP04, CP07	Controls	Application corrections for all BTU calculations and associated engineering units. Incorrect scaling factor was found in all calculations due to copy/paste. Engineering units corrected.
3/26/2019	CP01	Controls	Controller locked up starting March 15 12:36pm.
4/6/2019	AHU 202	Mechanical	Return Fan VFD/Motor failed
4/16/2019	CP01	Controls	Controller locked up starting April 9.
4/17/2019	CP01	Controls	Continued issues with controller locking up randomly. Institute a controller restart every 24 hours.
4/23/2019	CP01	Controls	Controller locked up.
4/23/2019	AHU 101	Mechanical	Control issues with CHW valve not closing off, and HW valve at 100% and not doing any heating.
5/1/2019	Enlighted occupancy sensors – office area (AHU 202)	Smart sensors	The thresholds for the Enlighted occupancy sensors were changed in the office area. Occupants reported lighting not responding to occupancy, after this change, the sensors reported occupancy overnight when the office area was vacant.
5/7/2019	EBI System	Data, controls: resolved	Add new BACnet Point Server instance for 3907 BACnet traffic only. Change to UDP port 47809 for BACnet. This change was made to isolate BACnet traffic on customer network, and load balance BACnet interface at EBI front end system. Previously the system was being overloaded by BACnet traffic from other systems/buildings on the same network. This was causing disruptions, lockups, and outages of data in 3907. This issue is described in Section 8.1.4
7/2019	AHU 101, AHU 202	AHU filters replaced	Changes observed in system performance with fan kWh
7/10/2019	AHU 202	Mechanical: resolved	Return Fan VFD/Motor online (AHU 202)
7/16/2019	AHU 101	Controls	Control problems. Site requested requirement to cool at all costs. AHU 101 cooling valve is manually open, heating shut off.

8.1.4 Lighting Hardware Issues

Throughout the demonstration, there were no significant issues with lighting. However, one of the high-bay light fixtures failed within a month of commissioning and was promptly fixed and replaced.

Additional hardware issues included occupancy sensor failure. Unfortunately, the failure mode for occupancy sensors is that they can become too sensitive and detect occupancy when the space is vacant, causing the lights in the area to remain illuminated, and the HVAC in the area to remain in occupied mode, diminishing the overall energy savings capabilities of the system.

During Phase 1 (pendant fixtures in the office area), at commissioning, three sensors were identified to be causing areas to remain always on. These three sensors were replaced and reconfigured.

During Phase 2 (troffer fixtures in the office area), at commissioning, all sensors were tested to have proper sensitivity and calibration. One month after commissioning Phase 2, occupants indicated the sensors were not detecting occupants, so occupancy threshold settings were adjusted, and tested for proper functionality. However, the sensors became more sensitive and caused an increased number of random false occupancy detections. Interestingly these random false detections were observed to increase steadily over the course of the Phase 2 demonstration period. Where the lights do not stay constantly on, but they experience random false occupancy detections that trigger the lights to come on at various intervals during the overnight hours. For additional discussion see Section 6.5.2.

8.1.5 Plug-Load Controller Hardware Issues

The Plug-Load Controller demonstration period had to be delayed by three months, as the Plug-Loads experienced two issues during commissioning. First, the Enlighted Energy Manager had a firmware issue preventing the Plug-Load Controllers from saving data. And second, the Plug-Load Controller firmware was preventing communication with the Enlighted Smart Sensors for obtaining occupancy information, so the Plug-Loads remained in an always-on state. Both issues were promptly resolved by reconfiguring the devices with appropriate firmware and guidance provided by Enlighted, Inc.

In addition to the two broad firmware issues, one of the fifteen Plug-Load Controllers installed in the Office Area, appears to have been miss-wired during installation, because the data later revealed that both controlled and uncontrolled duplex outlets always displayed the same energy consumption without the ability to separate the loads from both outlets. This faulty controller was excluded from our analysis.

8.1.6 Installation, Configuration, and Commissioning Issues

Physical installation was relatively straightforward and smooth with no issues. Configuration and commissioning were also a relatively straightforward and smooth process, however, we observed that it is critical to have key stakeholders involved, and also critical to have skilled operators trained during this process. As previously mentioned, sensor configuration and calibration is required in order to achieve the optimal balance between occupant satisfaction and maximum energy savings.

8.1.7 Data Collection Issues

For this demonstration project, we collected data from three different system components: 1) HVAC data was stored on Honeywell's Enterprise Buildings Integrator System (EBI), 2) lighting data was measured and stored on Dent power loggers at the circuit panels, and 3) lighting data and plug-load data was measured and collected by Enlighted on the Enlighted Energy Manager controller.

All three data collection systems were tested and verified during system commissioning, however the Dent lighting power loggers and the Honeywell EBI HVAC data system had some outages during the demonstration period, causing gaps in the data.

The 6 Dent power loggers were online collecting data for almost 2 years, since the early baseline data collection started on September 20, 2017 and continued through the end of the demo period on September 10, 2019. Out of the six Dent power loggers collecting data from four different electric panels, only 1 device failed causing the data gaps. The same logger failed twice, the first instance appeared to be due to a power outage and a failed backup battery on the device. The second instance was a communication issue with the device when attempting to extract the data. The data gaps from the failed Dent power logger were only from the high-bay lighting, from October 3 through December 12, 2018 (71 days), and from April 6 through July 22, 2019 (108 days), for a total gap of 179 days missing from the high-bay lighting out of the 312 days of the demonstration period. This gap was mitigated by the backup lighting data collection from the Enlighted Energy Manager, which collected redundant lighting energy consumption data throughout the demonstration period.

The Enlighted Energy Manager was online throughout the entire demonstration period, and did not experience any outages, any data issues, or any gaps in the data collection.

The Plug-Load Controllers, once the firmware issues were resolved, collected continuous reliable data from the fourteen Plug-Load Controllers, for both controlled and uncontrolled duplex outlets. However, a separate data issue for Plug-Loads was the sparsity of the data that resulted from the small number of devices, from the selected installation locations, and from the lack of control over user behavior.

The HVAC system had significant issues which delayed the commissioning of the HVAC integration component. The Honeywell EBI system and the HVAC controllers initially experienced intermittent outages, disconnections, and lock-ups, which were later determined to be caused by an over-congested BACnet network, configuration issues, and an overloaded EBI server. As previously mentioned, the cybersecurity constraints prevented prompt root cause analysis.

8.2 END-USER CONCERNS

In the high-bay area, a one-for-one replacement of the existing metal halide fixtures was conducted. The replacement fixtures were mounted at the same height as the original fixtures. The light produced by these fixtures was extremely bright causing glare, such that the lighting levels within the work areas were somewhat uncomfortable. Workers found that looking at the lighting fixtures was uncomfortable, but they soon learned to avoid looking upwards at the fixtures. Fortunately, these fixtures were dimmable down to 10% using the standard 0-10V dimming interface so that their light output could be easily adjusted. We found that lowering the light output to 70% was an acceptable level which provided excellent illumination of work surfaces without being uncomfortable.

In the administration areas, the LED pendant fixtures that were installed in Phase 1 did a very good job of evenly illuminating the space. These fixtures were capable of providing varying levels of uplighting and downlighting. When the space was unoccupied it was possible to dim or shut off the downlighting while continuing to provide uplighting. This provided an opportunity to maintain some level of lighting to illuminate the ceiling while avoiding the "cave effect" resulting from the troffer's relative inability to illuminate the ceiling. Although the pendant fixtures reduced contrast and more evenly distributed light within the room, we found that the occupants of the administration areas preferred the LED troffer fixtures over the LED pendant fixtures.

The LED pendant fixtures installed in Phase 1 were replaced by LED troffers which also performed well. Ultimately, the occupants elected to retain the troffers rather than convert back to the pendant fixtures at the end of the demonstration period. Apparently, the occupants were not as comfortable with the look and feel of fixtures hanging from the ceiling. Perhaps, in a room with a 9-foot ceiling height, having fixtures hanging approximately 12 inches below the ceiling gave people a claustrophobic feeling. It would be interesting to see if occupants might be more receptive to pendant fixtures in a room with a greater ceiling height.

Other wireless devices downstream of the Enlighted Gateways included Enlighted Plug-Load Controllers, Enlighted Smart Sensors, and Enlighted Room Controllers. The effectiveness of the Plug-Load Controllers was somewhat difficult to determine as there was no way to control which socket (controlled or uncontrolled) of the duplex outlet workers plugged in their task lighting, personal items or other electrical devices.

Human behavior can significantly affect energy consumption in buildings. Hence, human behaviors and decisions can impact the potential for energy savings achieved in buildings. The impact of human behaviors on energy savings comes not just from the end-users, but also from management, facilities coordinators, maintenance technicians, and energy or maintenance policies & processes established by leadership. For this demonstration, we observed, and have previously discussed, the impact to our results from several types of human behaviors and decisions, including: plug-load outlet usage preference, HVAC manual overrides and maintenance issues, as well as the lighting design preference from management, and the lighting scheduling, dimming, and grouping configuration preferences. The benefit of an advanced, fully configurable building system is that it provides flexibility to the end-users, but the drawback is that it is possible to lose substantial energy savings through poor configuration choices, either intentionally or accidentally made, or through neglected maintenance (e.g. of the HVAC system).

8.3 PROCUREMENT ISSUES

There are no known procurement issues. All of the installed technologies are commercially available.

8.4 REGULATORY ISSUES

Lighting systems are required to comply with UFC 3-530-01 Interior and Exterior Lighting Systems and Controls.

To be fully integrated into an enterprise utility monitoring and control system, the Enlighted systems would need to be granted authority to operate (ATO) on DoD networks. In the interests of time and lack of available funding, pursuit of an ATO was not within the scope of this project.

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APPENDIX B HARDWARE INVENTORY

Table B.1: Project Hardware Inventory

Status	Item Type/Category	Description	Manufactuer	Model/Part #	Serial #	Location	Quantity
installed	control	Managed PoE Ethernet Switch	Linksys	Linksys: LGS308P Enlighted: SW-POE-8-4	14810C91809208	B3907: Mechanical Room 242	1
installed	control	PoE Ethernet Extender	BV-Tech	POE-SW502	n/a	B3907: 1st Floor high-bay	1
installed	control	Gateway	Enlighted	GW-2-01	6854f5f9d1fa, 6854f5f9d8db, 6854f5f9d212	B3907	3
installed	control	Energy Manager	Enlighted	EM-2-02	LR201803002160	B3907: Mechanical Room 242	1
installed	Enclosure fixture	Full Size Ring Cabinet	n/a	14506635-002/U	n/a	B3907: Mechanical Room 242	1
installed	Enclosure fixture	Door with Lock, For Full-Sized Standar	n/a	14506636-002/U	n/a	B3907: Mechanical Room 242	1
installed	control lights	light fixture Control Unit	Enlighted	CU-3E-1R	n/a	B3907	168
installed	control lights	XSR Driver	Enlighted	XSR 0-10v Driver	n/a	B3907	168
installed	control lights	Compact Sensor Cable	Enlighted	CBL-3-7F	n/a	B3907	168
installed	control lights	Ruggedized Highbay Sensor	Enlighted	SU-5S-HRB	-SEPARATE ATTACHED-	B3907: 1st Floor high-bay	84
installed	control lights	Compact Sensor	Enlighted	SU-5E-01	-SEPARATE ATTACHED-	B3907: 2nd Floor office area	84
installed	control lights	Wireless Light Switch (ERC)	Enlighted	WS-2-00	-SEPARATE ATTACHED-	B3907: 2nd Floor office area	9
installed	control plugs	Plug Load Controller	Enlighted	PC-01-20	-SEPARATE ATTACHED-	B3907: 2nd Floor office area	15
installed	control hvac	Aire Controller	Enlighted	AIRE-HW-01	LR201805014663	B3907: Mechanical Room 242	1
installed	control hvac	CPO-PC-6A	Honeywell	CPO-PC-6A	ED81-3F1A-0000-FFFF	B3907: Mechanical Room 242	1
installed	control hvac	BACnet IP/MSTP Router	Contemporary Controls	BACnet IP/MSTP Router	1V411798	B3907: Mechanical Room 242	1
installed	hvac sensor	BTU Meter	onicon	F-3500 & System 10 BTU Meter Package	n/a	B3907: Mechanical Room 242	2
installed	hvac sensor	BTU Meter	onicon	F-3500 & System 10 BTU Meter Package	n/a	B3907: Mechanical Room 241	2
installed	Light Fixture	F1- Rec Troffer	ILP VLN	VLN24-31WLED-UNIV-40-DIM(0-10V)-mod (Integral Enlighted Sensor)	n/a	B3907: 2nd Floor office area	84
installed	Light Fixture	High Bay Lights	Flex Essentials	Series 4.0 ES40P-A1-17K-4MS-40-80-FR-LV-XX-10V-mod (Integral Enlighted Sensor)	n/a	B3907: 1st Floor high-bay	84
storage	Light Fixture	F2-Dir/Ind Pendant Finelite 4-ft length 50/50	Finelite	Type 'P1-4': HP-2-ID-4ft-B-B-835-WSO-F-96LG-(voltage)-DC-FA-FE-(ceiling type)-mod (Integral Enlighted Sensor)	n/a	B3907: Mechanical Room 242	3
storage	Light Fixture	F2-Dir/Ind Pendant Finelite 8-ft length 50/50	Finelite	Type 'P1-8': HP-2-ID-8ft-B-B-835-WSO-F-96LG-(voltage)-DC-FA-FE-(ceiling type)-mod (Integral Enlighted Sensor)	n/a	B3907: Mechanical Room 242	11
storage	Light Fixture	F2-Dir/Ind Pendant Finelite 12-ft length 50/50	Finelite	Type 'P1-12': HP-2-ID-12ft-B-B-835-WSO-F-96LG-(voltage)-DC-FA-FE-(ceiling type)-mod (Integral Enlighted Sensor)	n/a	B3907: Mechanical Room 242	12
storage	Light Fixture	F2-Dir/Ind Pendant Finelite Recessed 4-ft length	Finelite	Type 'R1-4': HP-2-R-4ft-H-835-F-(voltage)-SC-(ceiling type)-mod (Integral Enlighted Sensor)	n/a	B3907: Mechanical Room 242	2
storage	Light Fixture	F2-Dir/Ind Pendant Finelite Wall Wash 4-ft length	Finelite	Type 'R2-4': HP-2-WW-D-FO-4ft-B-835-XX-XX-SC	n/a	B3907: Mechanical Room 242	14
storage	control lights	light fixture Control Unit	Enlighted	CU-3E-1R	n/a	B3907: Mechanical Room 242	68
storage	control lights	XSR Driver	Enlighted	XSR 0-10v Driver	n/a	B3907: Mechanical Room 242	68
storage	control lights	Compact Sensor Cable	Enlighted	CBL-3-7F	n/a	B3907: Mechanical Room 242	68
storage	control lights	Compact Sensor	Enlighted	SU-5E-01	-SEPARATE ATTACHED-	B3907: Mechanical Room 242	68

1 Lighting Fixtures

Lighting fixtures were installed in both the office and the high-bay areas. As mentioned in Section 4.1.4, the 10-month demonstration period in the open cubicle area in the office space was split into two 5-month periods, with an additional one-week switch-over installation period after the first 5-month phase. Each of the new recessed and pendant mounted fixtures were equipped with an Enlighted smart sensor built into the lighting fixture, except for the wall washers which had a remote Enlighted smart sensor installed in the ceiling tile next to each wall washer. The Enlighted smart sensors communicate with the Enlighted Gateways (Described in Section B.2) via an encrypted IEEE 802.15.4 wireless link. The Enlighted smart sensors combine motion detection (occupancy), space temperature measurement, lighting level measurement and Bluetooth beaconing capability. The beaconing capability will be permanently disabled. The smart sensors provide a 0-10-volt control signal to the driver of each fixture to turn the fixture ON/OFF and to control light levels.

Figure B.1 Enlighted Smart Sensor

1.1 High-Bay

The high-bay fixtures in the industrial high-bay area were replaced with new LED fixtures on a one-for-one basis. The new fixtures are Flex Essential (ES40P-A1-17K-4MS-40-80-FR-LV-XX-10V) producing 17,818 lumens at 107 Watts per fixture for an efficacy of 166. The color temperature was 4000K with 80 CRI. There were 84 fixtures replaced in the high-bay area.

Figure B.2: High-Bay Lighting Fixtures - Flex Essential

1.2 Office Area Phase 1: Pendants

The existing T8 fluorescent fixtures were replaced with new LED fixtures on a one-for-several basis. The new fixtures included 3 Finelite HP-2-ID-4ft-B-B-835-WSO, 11 Finelite HP-2-ID-8ft-B-B-835-WSO, 12 Finelite HP-2-ID-12ft-B-B-835-WSO pendant mounted (8 foot height) with 50% direct and 50% indirect light at 36.1 watts and 3772 lumens, two (2) Finelite HP-2-R-4ft-H-835-F-XX-SC, recessed mounted 28.3 watt with 2557 lumens, and 14 Finelite HP-2-WW-D-FO-4ft-B-835-XX-XX-SC, 10-watt, 915 lumen wall washers. There were 84 old fixtures removed and 42 new fixtures installed in the office area during the Phase 1 installation period before the start of the demonstration.

Figure B.3 shows the suspended pendant high performance 2" aperture Indirect/Direct linear LED luminaire with Flush, Top Glow™ and Bottom Glow™ options for up- and downlight.

Figure B.4 shows the Finelite high performance 2" aperture linear recessed LED luminaire.

Figure B.5 shows the Finelite high performance recessed asymmetric LED wall wash to deliver visual comfort and uniform vertical illumination.

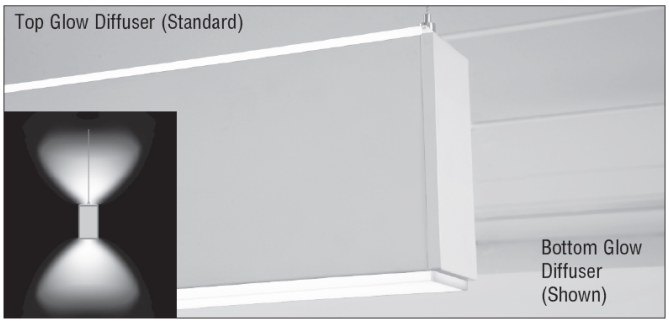


Figure B.3: Finelite Direct/Indirect Pendant Luminaires for Office Area (first five months)

Figure B.4: Finelite Wall Washer Luminaires for Office Area (first five months)

Figure B.5: Finelite Recessed Mounted Luminaires for Office Area (first five months)

1.3 Office Area Phase 2: Troffers

The Pendant fixtures installed in the office area at the start of the demo period were replaced with new retrofit troffer LED fixtures on a several-for-one basis. New troffer fixtures in the office area were installed corresponding a one-for-one basis to the baseline for the second five months of the demonstration. The new fixtures are Industrial Lighting Products (ILP) VLN24-31WLED-UNIV-40, recessed 31.4 watt, 2x4 troffers with 4,2387 lumens at 4000K color temperature and 80 CRI. There were 84 new troffer fixtures installed in the office area.

Figure B.6: ILP VLN Troffer Luminaires for Office area (Phase 2: second 5-months)

2 Enlighted Gateways (3 units)

The Enlighted Gateway is powered via a standard (IEEE 802.3af-2003) Power over Ethernet (PoE) network switch (private Enlighted network). The Enlighted Gateway's interface to the Enlighted Smart Sensors in the lighting fixtures (Section B.1) and to the plug-load controllers (Section B.6) will be via an AES-128 encrypted IEEE 802.15.4 wireless link, and the interface to the Enlighted Energy Manager will be via Ethernet (Private Enlighted Network). Gateways were installed in the ceiling, or overhang, as they should ideally be at the same elevation as the light fixtures with minimal interference between the gateway antenna and the sensors. The gateway distance from the PoE switch must be within 320 feet as CAT5e or CAT6 must be run between these devices.

The Enlighted Gateway is a system component that allows communication only between the Enlighted Energy Manager and the Enlighted Sensors in the Light Fixtures. All traffic flowing through the gateway is authenticated and encrypted. The Enlighted Gateway is not a standard internet gateway; it interfaces only with Enlighted components.

The Enlighted Gateway

L	3.01"	76.5mm
W	4.01"	101.9mm
H	1.38"	35.0mm
Weight	4.23 oz	120 grams

Figure B.7: Enlighted Gateway Specifications

3 Enlighted Energy Manager (1 unit)

The Enlighted Energy Manager interfaces to the Enlighted Gateways and to the Enlighted AIRE module via RJ-45 Ethernet (Enlighted Private Network). The Energy Manager is where the graphic user interface (GUI) for lighting control resides and allows for the programming and the user experience with the Enlighted local system. The Energy Manager typically gets mounted in an electrical room or Intermediate Distribution Frame (IDF) room. The Enlighted Energy Manager needs a 120v outlet for the device to be powered.

The Enlighted Energy Manager

Width	7.80"	198 mm
Height	1.65"	42 mm
Depth	5.71"	145 mm
Weight	2.64 lb	1.2 kg

Figure B.8: Enlighted Energy Manager

4 Enlighted AIRE Module (1 unit)

The Enlighted AIRE module interfaces with Enlighted's Energy Manager via Ethernet, and with existing HVAC equipment controllers via BACnet-MSTP RS-485 (described in Section B.5).

5 HVAC Control Interface

As shown in Figure B.9, the HVAC Control Interface was comprised of one Contemporary Controls BACnet IP/MSTP Router and one Honeywell ComfortPoint Open HVAC BACnet Controller (CPO-PC-6A). The Contemporary Controls BACnet Router connects to Enlighted Energy Manager and AIRE module private BACnet IP network, and to Honeywell CPO-PC-6A BACnet MSTP network. The Honeywell CPO-PC-6A is connected to the existing BACnet IP network in the building and communicates with the existing Honeywell EBI system.

The Honeywell CPO-PC-6A receives occupancy setback recommendations from Enlighted AIRE and processes the data to be sent to corresponding, existing, area HVAC BACnet controllers in the building. Setback recommendations (per zone/area) 'bump' the area space temperature control setpoint by +/- 2 deg F (adjustable) during building occupied times when no occupancy is detected in the area. Upon detected occupancy in the area, the area space temperature control setpoint becomes the existing, occupied, space temperature setpoint. The Honeywell EBI system historizes setback recommendation point objects and associated status items at 1-minute intervals. For this demonstration, the setback recommendation objects were attached to a schedule object (adjustable) to enable/disable the HVAC system to respond to the recommendations based on user selected time/date. In addition, setback recommendation objects can be manually overridden to disabled mode by operator.

The Contemporary Controls Router and Honeywell CPO-PC-6A were mounted in a full ring, metal enclosure in a mechanical room near the selected areas and existing building HVAC controllers. A 120 VAC, single phase, building power circuit is required at the new panel.

The Honeywell CPO-PC-6A device requires network connection (CAT5, 5E or 6) to existing building controls TCP/IP network. The BACnet device instance naming and BACnet network number scheme followed existing site standards.

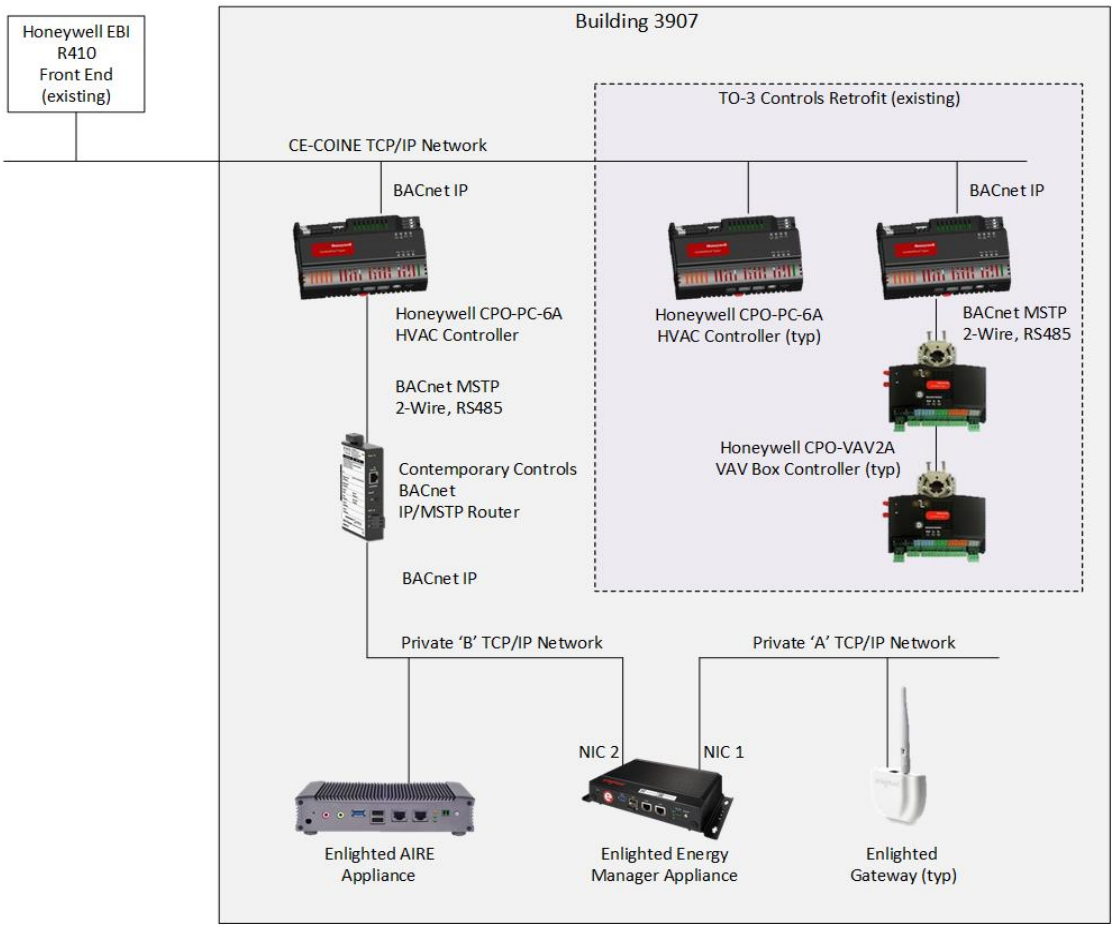


Figure B.9: Interface with HVAC System

6 Plug-Load Controllers (15 units)

Plug-load devices save energy by cutting power to controlled outlets after hours when no occupants are detected in the area. The controlled outlets turn off non-critical, unnecessary electronic equipment such as computer monitors, printers, task lighting (desk lamps), coffee makers, vending machines, small personal fans, space heaters, water-coolers, or other small appliances.

The Enlighted Plug-Load Controller transforms receptacles in 20A circuits to controlled and metered smart receptacles for energy-efficient and code-compliant plug-load control. The controller features two sets of wires to separately power controlled and uncontrolled outlets, so that energy consumption on both uncontrolled and controlled circuits are separately measured.

Plug-load devices were installed within the demonstration areas, in close proximity to the occupancy sensors (in the lighting fixtures). Appendix G shows the approximate installation locations of the plug-loads in the office area. Plug-load controllers will be used to turn non-critical plug-loads ON/OFF in response to occupancy status of the space. The Enlighted Plug-load Controllers communicate with the Enlighted Gateways (Described in Section B.2) via an encrypted IEEE 802.15.4 wireless link.

While we envisioned that we would install plug-load control devices in both the office and high-bay demonstration areas, we identified areas for budget reduction to help offset the added installation cost of comparing the two new lighting designs in consecutive, rather than simultaneous, fixture installations. We therefore installed plug-load controls only in the office area (Appendix G). The office area was identified for plug-loads because it contained more non-critical, discretionary outlets and devices, and because the high-bay sections are production areas with not as many non-critical electronic devices.

Note that we had no ability to control which outlets workers chose to use.

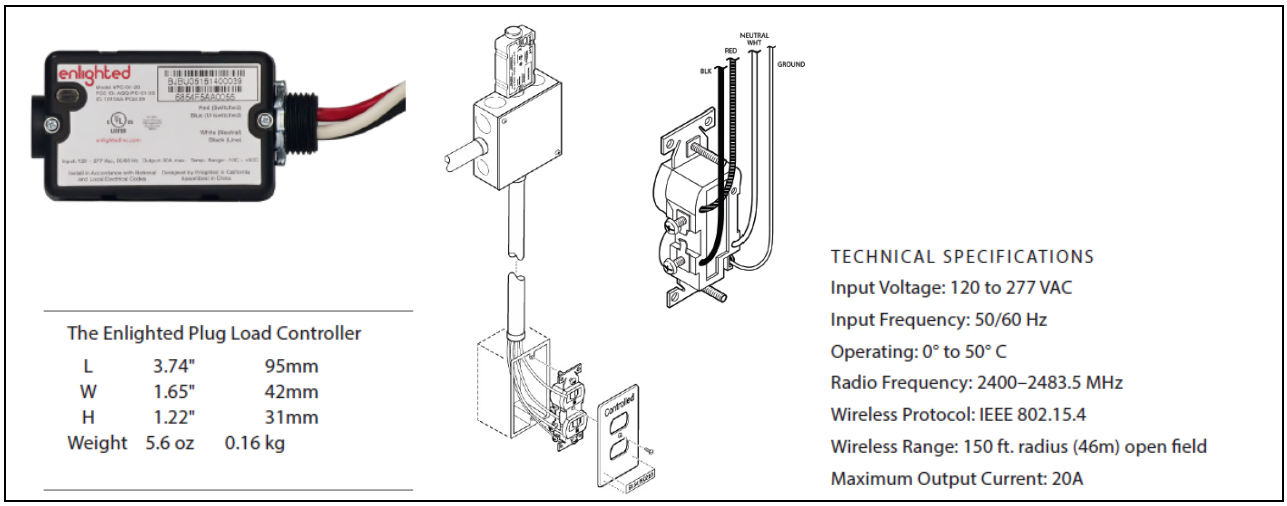


Figure B.10: Plug-load Device

7 Power over Ethernet (PoE) Managed Network Switch – LGS308P (1 unit)

The PoE Switch provides power to the Enlighted Gateways and facilitates data transfer between the Enlighted Gateways and the Energy Manager. The standard RJ-45 Ethernet Ports allow for standard Cat5e or Cat6 cables to be plugged into one of the PoE Switch's many ports. Ports dedicated specifically for PoE capabilities were used to connect Enlighted Gateways to the Switch. The PoE switch uses a 120v outlet to power the device. The installed switch was configured and managed from within the network and secured through port authentication and MAC-based port security, utilizing advanced DHCP snooping and IP-MAC binding functions to ensure network integrity.

Figure B.11: PoE Managed Switch: Linksys LGS308P

8 BTU Meters for Air Handler Units (AHU)

Four total BTU Meters were installed: Two (2) BTU meters per each of the two (2) AHUs (AHU 101 and AHU 202).

The BTU Meters installed were Onicon F-3500 & System 10 BTU Meter Package, shown in Figure B.12, the left arrow highlights the BTU meter for hot water, and the right arrow highlights the BTU meter for chilled water.

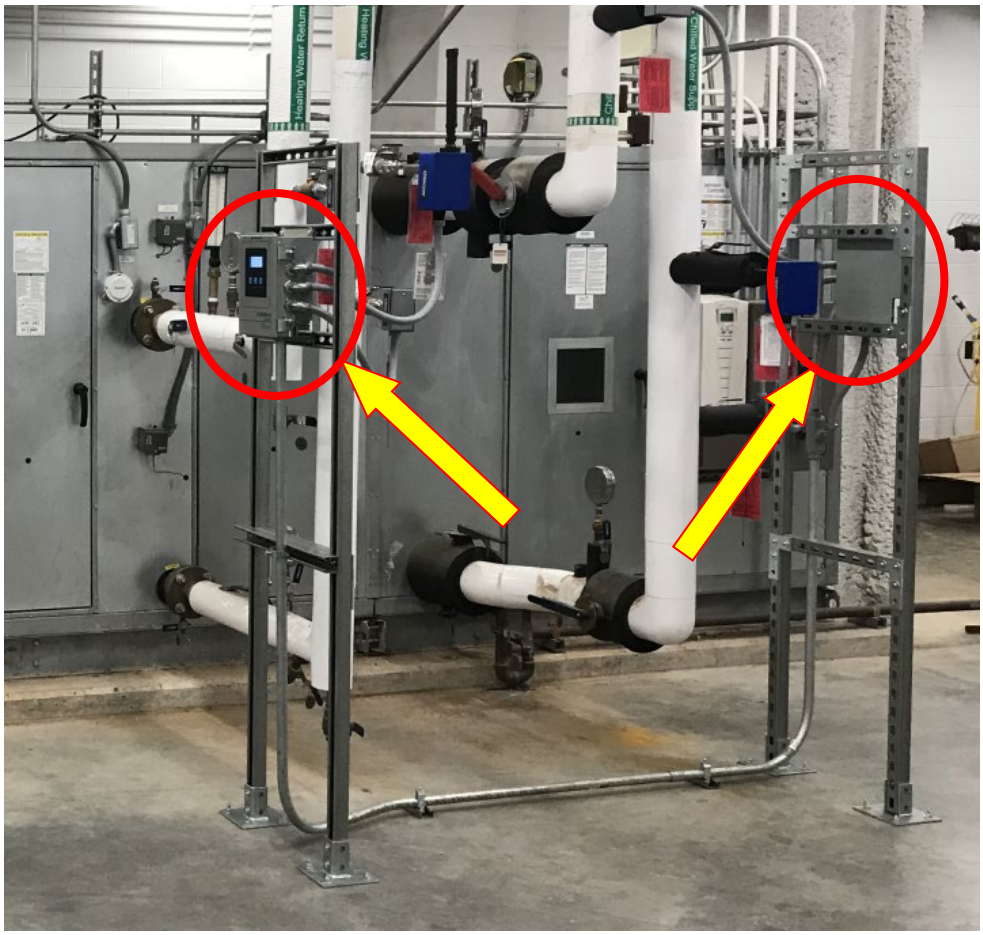


Figure B.12: BTU Meters installed for AHU 202.

9 Energy Meters / Data Loggers for Electrical Circuit Panels (6 devices)

Data loggers monitored energy consumption from lighting for the demonstration areas.

Six Dent Instruments energy meters (Elite Pro energy logger version) were installed in four electrical panels to collect energy consumption data. Data collected from these meters include kWh, power factor, kW, amps, volts and timestamp, sampled at 15-minute intervals.

Table B.2 lists the electric panels and locations where the lighting energy meters were installed.

Table B.2: Electrical Panels for Lighting Circuits

Panel	Location	Volts	Fed By:	Feeds:
HB11	Main Elec Room 123	480/277	Switchboard BMSB	Various lighting circuits, transformers and Panel LUPS
HB21	Main Elec Room 223	480/277	Switchboard BMSB	Various lighting circuits, VAV, etc.
LE12	Machine Room 135	208/120	Panel HE12, Section 2	Mostly receptacles
LUPS	Main Elec Room 123	277	Panel HB11, Circuit 32	Various lighting circuits, and emergency lighting

Figure B.13: Dent Instrument Energy Meters

10 Enlighted Room Control (ERC) Light Switches (9 units)

The Enlighted Room Control provides all the functions of a standard wall switch with override control capabilities, all without additional wiring. Occupants can manually adjust lighting levels to save energy, increase comfort or tailor illumination for specific tasks. Users can choose from pre-programmed settings through the browser-based software interface or customize settings with a few clicks of a mouse.

Enlighted Room Control Switches were installed only in private offices and conference rooms within the office area. Appendix G shows the installation locations of the Enlighted Room Control (ERC) units.

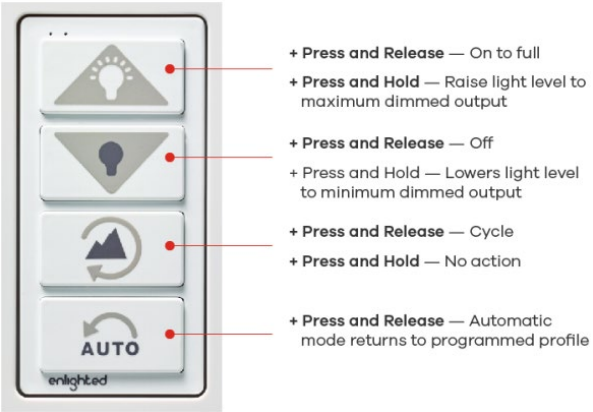


Figure B.14: Enlighted Room Control (ERC)

In those locations where ERC units were installed, existing light switches were covered with wall plates. The ERCs provide full control of the lighting. Note that covering existing light switches prevents interruptions in the power supplied to the occupancy sensors, which receive power from the lighting circuits. Minimizing power interruptions to the occupancy sensors maximize the energy savings realized by the occupancy-based HVAC control feature of the holistic lighting solution.

APPENDIX C NETWORK CONNECTIVITY

Based on extensive discussions between Honeywell, Enlighted, and Tinker AFB staff, the demonstration system operated stand-alone, on an isolated private network, interfacing only with Honeywell's Enterprise Building Integrator (EBI) through a BACnet MSTP Twisted Pair RS-485 protocol.

With this configuration, the lighting data and the lighting controls reside only in the Enlighted Energy Manager. The interface from the Enlighted AIRE module to the existing HVAC controls transmit only the occupancy setback signal per zone directly to the HVAC controllers.

Operating on a stand-alone, isolated private network eliminates many cyber risks and thus facilitated the approval process and allowed achievement of project objectives.

Figure C.1 shows our system architecture overview, and Figure C.2 shows our facility related control systems (FRCS) architecture, based on the UFC-4-010-06 standard. This diagram illustrates our system architecture. The Enlighted Energy Manager (EEM) has two IP network interfaces, Private-A and Private-B, but the packets from the Enlighted Gateway (EGW), on the Private-A network, do not go upstream from the EEM. The messaging between the EGW and the EEM is different from the messaging that the EEM provides upstream. Between the EGW and EEM is a proprietary messaging protocol that sits within the TLS connection. The EEM offers an HTTPS interface for APIs and the Web-GUI client, a TLS connection with a proprietary messaging protocol (different than the one between the EGW and EEM) for communication with AIRE, and an SSH interface.

As an additional safeguard, IP routing was disabled between the two network interface cards (NIC) on the EEM. To prevent a rogue device or actor from sending packets through the EEM from one network to the other, we disabled IP routing in the EEM. The EEM device does not take messages from Network Private-A and route them along on Network Private-B.

A drawback of this isolated private network approach is that the Enlighted Energy Manager (EEM) GUI dashboard for configuring and managing the Enlighted system was accessible only from a physical connection to the private network.

Tinker Point-of Contact Joseph Cecrle provided written approval for our project network.

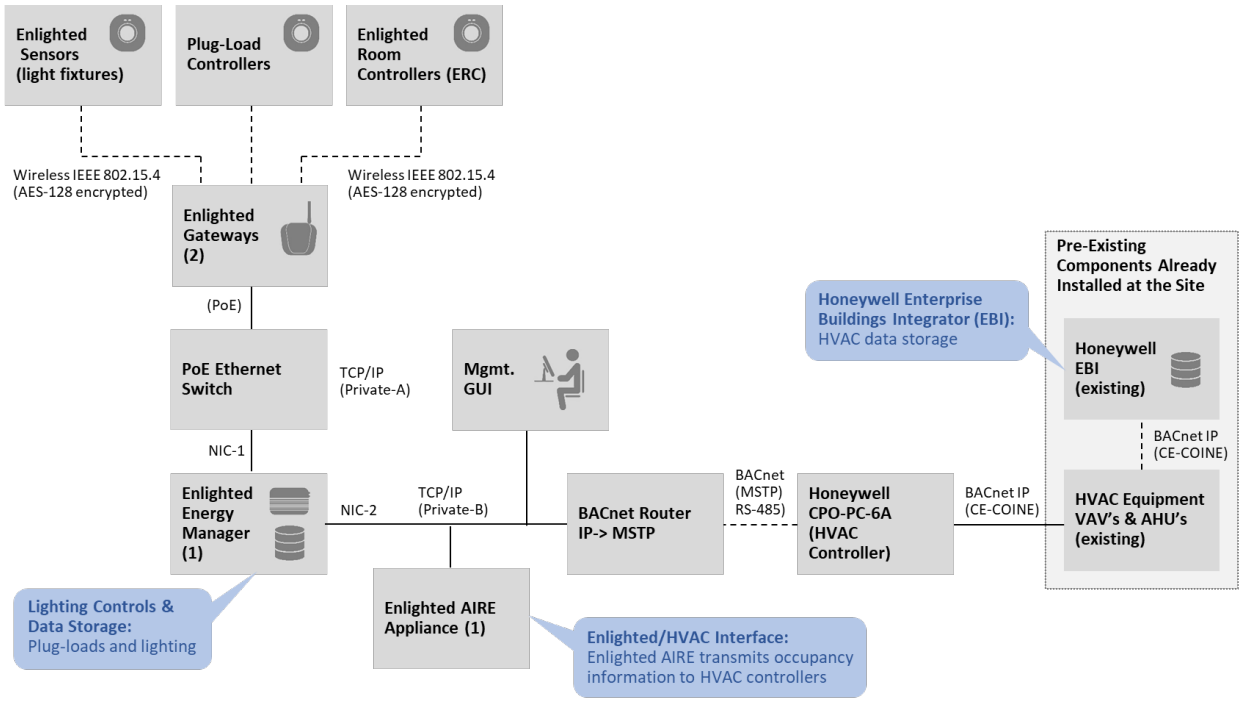


Figure C.1: ESTCP System Architecture

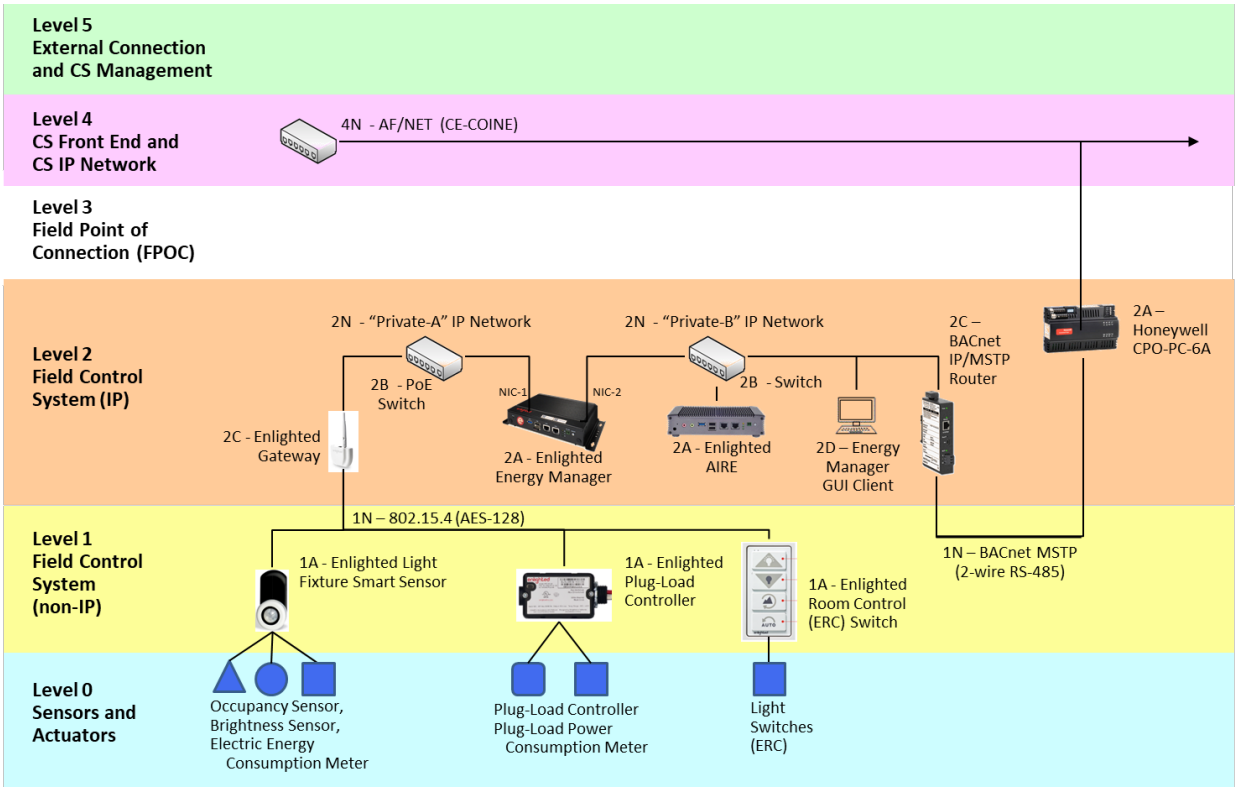


Figure C.2: Facility Related Control Systems (FRCS) Architecture

The following system characteristics addressed known cyber security vulnerabilities and minimized the possible attack vectors.

- Internet/Network - The system is isolated behind several layers of protection: AFNET, ICS/COINE, EBI, CPO Controller, Enlighted Energy Manager Device, encrypted wireless link, and finally, the Enlighted gateway controlling the fixture. This architecture presents a minimal attack surface.
- EBI - Accessed only via ICS workstations requiring CAC login.
- Physical network - Tinker AFB AFNET/COINE is maintained on a secure, port-locked topology which precludes access via foreign computers (e.g. sneaking in and plugging into a switch).
- Physical attack via RS485 at the CPO controller - The physical devices are secured within locked cabinets and protected by login and password.
- Wireless - The system utilizes AES-128 encryption on traffic between the Enlighted gateways to the Enlighted Energy Manager device. This minimizes, as much as possible, the likelihood of an on-premise compromise via injection into the endpoint control.

Furthermore, the system is resilient to power outages by design. Table C.1 describes the impact of power loss for each system component.

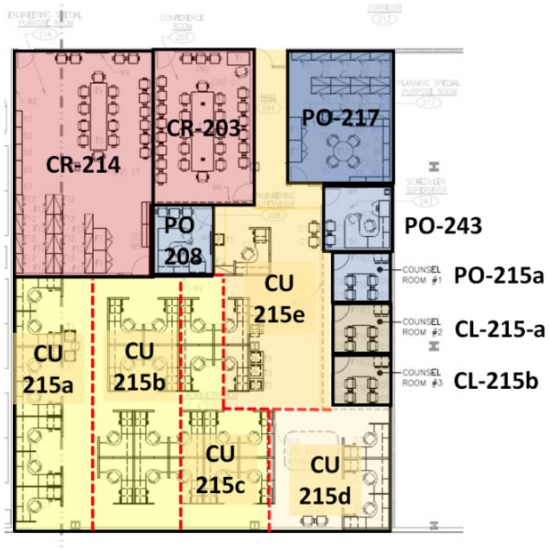
Table C.1: Impact of Power Loss for Each System Component

System Component	Impact of Power Loss
Enlighted AIRE Module	• No impact to lighting. • No impact to plug-loads. • No setbacks will be applied to any HVAC zones. The standard operating procedure (SOP) would apply.
Enlighted Energy Manager	• Lighting and plug-loads will continue to operate. Configuration changes will not be possible, and historic usage data will not be saved. • No setbacks will be applied to any HVAC zones. The SOP would apply.
Network Switches	• Lighting and plug-loads will continue to operate. Configuration changes will not be possible, and historic usage data will not be saved. • No setbacks will be applied to any HVAC zones. The SOP would apply.
Enlighted Gateway	• Lighting and plug-loads will continue to operate. Configuration changes will not be possible, and historic usage data will not be saved. • No setbacks will be applied to any HVAC zones. The SOP would apply.
Enlighted Smart Sensors (at each light fixture)	• If the lighting circuits lose power, emergency lighting would be in place. • No setbacks will be applied to any HVAC zones affected by the lighting power loss.
Enlighted plug-loads	• Same impact as any power loss to the receptacle circuits.

APPENDIX D SYSTEM CONFIGURATION

Office Area Lighting (Phase 2):

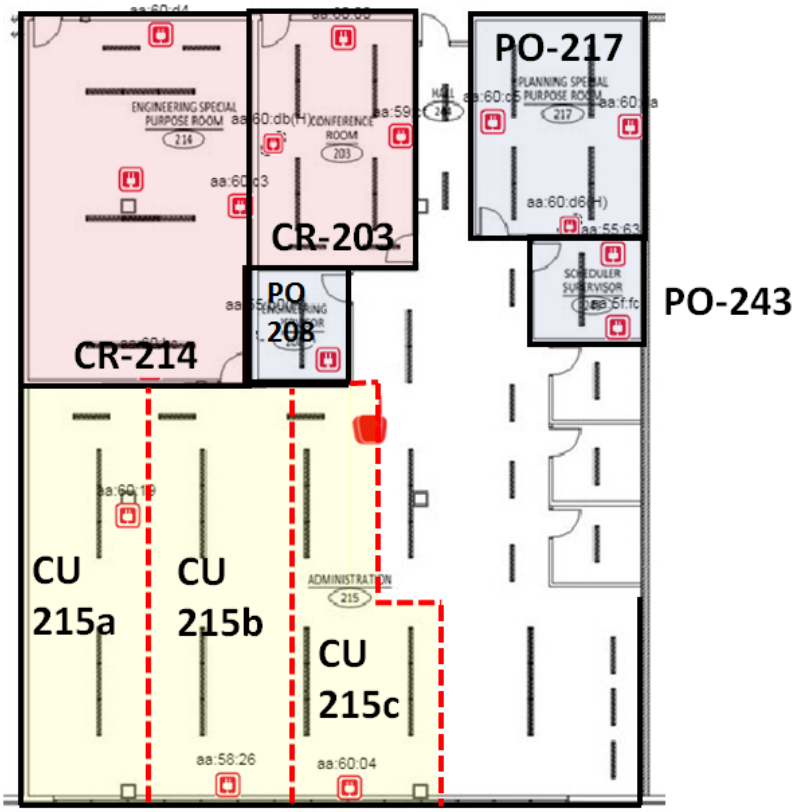
Office Area Lighting	Settings	Office Hours 5am-5pm	After Hours and weekends
Office Area: Cubicle Zones (5)	Occupied Light Level	On (9am-9pm: 60%) / (9pm-9am: 50%)	
	Occupancy Time Delay	15 min	5 min
	Vacant Light Level	Dim (10%)	Off
	Daylight Harvesting?	Yes	
Private Offices (4)	Occupied Light Level	On (40%) / (Office PO-217: 60%)	
	Occupancy Time Delay	15 min	5 min
	Vacant Light Level	Off	
	Switch Configuration	On/Off/Dim 0-100. Two scenes at 20% and 70% dim. Overrides in effect while space is occupied. (Return to Normal after 'Occupancy Time Delay')	
Conference Rooms (2)	Occupied Light Level	On (60%)	
	Occupancy Time Delay	10 min	5 min
	Vacant Light Level	Off	
	Switch Configuration	On/Off/Dim 0-100. Four Presentation Mode scenes. Overrides in effect while space is occupied. (Return to Normal after 'Occupancy Time Delay')	
Closets (2)	Occupied Light Level	On (75%)	
	Occupancy Time Delay	5 min	
	Vacant Light Level	Off	



Lighting Zones in the Office Area

Office Area Controlled Plug-Loads:

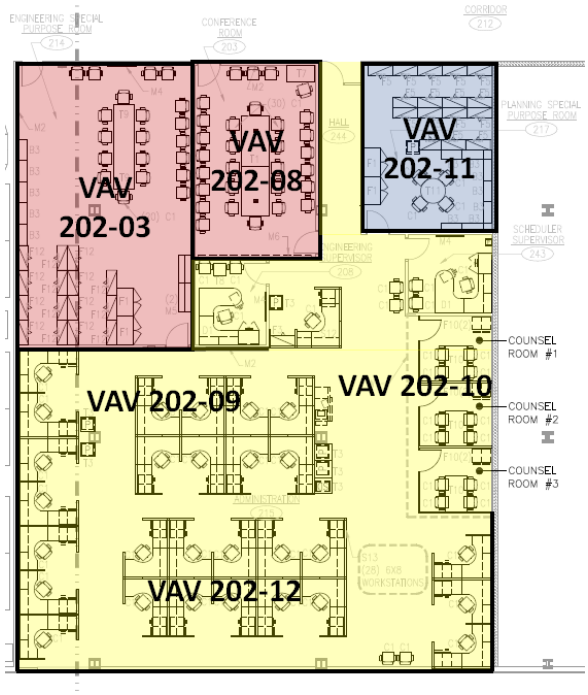
Office Area Plug-Loads	Settings	Office Hours 6am-5pm	After Hours and weekends
Controlled Outlets (15 controlled plug-loads)	Control Setting	Always on	On (when zone is occupied)
	Occupancy Time Delay	N/A	30 min
Uncontrolled Outlets	Control Setting	Always on	



Plug-Load Locations in the Office Area

Office Area HVAC:

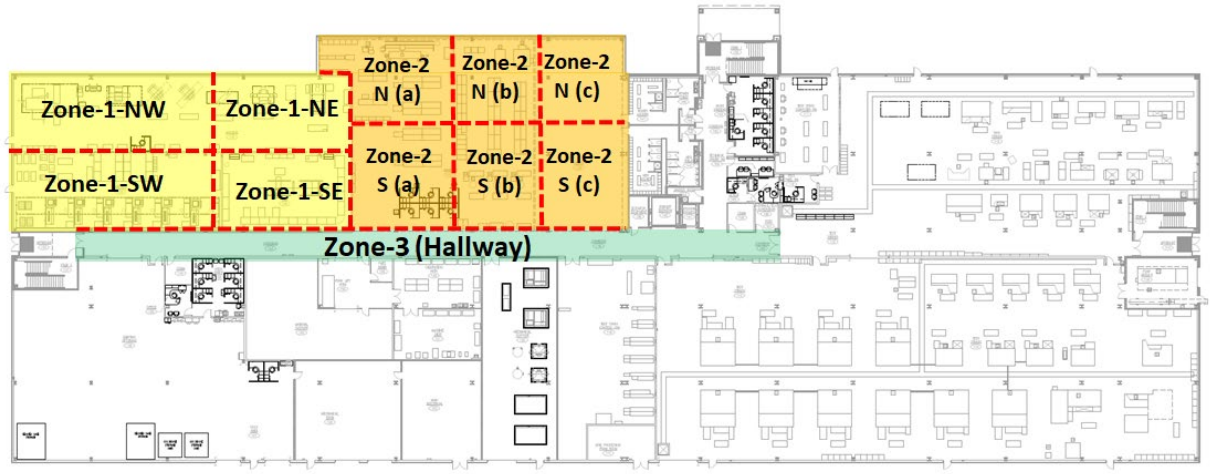
Office HVAC Zones (2)	Occupancy Control Days (Demo Project Control Setting)	Non-Control Days (Baseline Control Setting)
Occupied	Normal	Normal
Vacant	Occupancy Time Delay: 30 Min Vacant: Setback 2 degrees	Normal



Four (4) HVAC Zones in the Office Area

High-Bay Area Lighting:

High-Bay Lighting	Settings	Office Hours (Mon-Sat) 3:30am-4pm	After Hours and Sundays
High-Bay Zones (11)	Occupied Light Level	On (70%)	
	Occupancy Time Delay	15 min	5 min
	Vacant Light Level	Dim (20%)	Off



Five (5) Lighting Zones in High-Bay Area

High-Bay Area HVAC:

High-Bay HVAC Zones (2)	Occupancy Control Days (Demo Project Control Setting)	Non-Control Days (Baseline Control Setting)
Occupied	Normal	Normal
Vacant	Occupancy Time Delay: 30 Min Vacant: Setback 2 degrees	Normal

APPENDIX E LIGHTING QUALITY OCCUPANTS' SURVEY

Light Right Survey

Privacy Statement

This Survey is being conducted to determine occupant preferences about office and industrial lighting for the Department of Defense ESTCP Research Program. The information gathered will be used for the ESTCP research to make recommendations about lighting and lighting controls for Department of Defense buildings, and to improve the state of knowledge about lighting and worker satisfaction.

About This Survey

Responses are anonymous--- Your responses to this on-line survey will be sent directly to the survey administration company server which is not associated with and cannot be accessed by your employer. This ensures that your specific responses will never be available to the organization or individual that you work for. Your responses will only be available as aggregated group information. Participation is Voluntary --- This survey is entirely voluntary, and you are free to choose at any time whether or not to provide responses to the survey or individual questions.

General

1. **Which of the following best describes the type of work that you do?**
   Mark only one oval.
   - ( ) People management, leadership, and/or training
   - ( ) Computer aided design, engineering, or software development
   - ( ) Combination of computer work, paper tasks, phone calls and meetings
   - ( ) Facility management
   - ( ) Industrial work such as, welding, machining, assembly, etc.
   - ( ) Other: _____

2. **What is your age?**
   Mark only one oval.
   - ( ) 30 or under
   - ( ) 31 - 40
   - ( ) 41 - 50
   - ( ) Over 50

3. **What is your gender?**
   Mark only one oval.
   - ( ) Female
   - ( ) Male
   - ( ) Prefer not to say

Personal Work Space Information

Your personal works space is the area where you spend the majority of the time at work.

4. **Which of the following best describes your personal work space?**
Mark only one oval.

- Industrial area: work bench
- Industrial area: machine work
- Office area: enclosed private office
- Office area: cubicles with partitions above standing eye level
- Office area: cubicles with partitions below standing eye level
- Other: _____

5. **What type of computer screen do you have?**
Mark only one oval.

- Laptop
- Flat Panel Screen
- Traditional Screen (CRT)
- Other: _____

6. **On a typical day, how long are you in your personal work space?**
Mark only one oval.

- More than 6 hours
- 4-6 hours
- 2-4 hours
- Less than 2 hours

7. **Are you able to see out a window while sitting in your work space?**
Mark only one oval.

- Yes
- No

8. **Do you like the view?**
Mark only one oval.

- Yes
- No
- NA

9. **Do you sit adjacent to the window?**
Mark only one oval.

- Yes
- No
- NA

Task Lighting

Task lighting, or directional lighting, provides extra lighting to a specific area, in addition to the lighting from light fixtures in the ceiling. Desk lamps and under-cabinet lights are good examples of task lights.

10. **Do you have task lighting? (such as desktop lamps or under-cabinet lights)**
Mark only one oval.

- ( ) Yes
- ( ) No

11. **If you have task lighting, which of the following types of lighting fixtures most closely resembles the task lighting in your personal work space?**
Check all that apply.

- [ ] Under cabinet task light
- [ ] Desktop task light
- [ ] Other: _____

12. **What type of control do you have for your task lighting?**
Mark only one oval.

- ( ) On/Off switch
- ( ) Dimmer switch
- ( ) Does not apply
- ( ) Other: _____

13. **To what extent do you agree or disagree with the following statements about the lighting in your personal work space?**
Mark only one oval per row.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Does Not Apply
I am satisfied with my ability to control my overhead lighting	( )	( )	( )	( )	( )	( )
I am satisfied with my ability to control my task lighting	( )	( )	( )	( )	( )	( )
I am satisfied with my ability to control my window shades or blinds	( )	( )	( )	( )	( )	( )

14. **To what extent do you agree or disagree with the following statements about the lighting in your general office area?**
Mark only one oval per row.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Does Not Apply
The lighting fixtures in the general office area around my work space are nice looking.						
The lighting helps create a good image for the organization.						
The room surfaces (walls, ceilings) have a pleasant brightness.						
My work surface is evenly lighted without very bright or dim spots						
The lights flicker throughout the day						
My skin is an unnatural tone under the lighting						

15. **How would you rate the lighting in your work space for each of the following tasks?**
Mark only one oval per row.

	Much Too Bright	Too Bright	Just Right	Too Dim	Much Too Dim	Does Not Apply
Paper Tasks (reading and writing)						
Reading from a computer screen						
Typing on a keyboard						
Filing or locating papers						
Face to face conversations						
Industrial tasks such as welding, machining, assembly, etc.						

16. **How often do you experience any of the following conditions when in your personal work space during an average day? For the purpose of answering these questions, consider the definition of glare to be unwanted lighting, i.e., loud noise is to sound, as glare is to light.**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always	Does Not Apply
Glare reflected from your work surface						
Glare from the light fixtures reflected on your computer screen						
Glare from the window reflected on your computer screen						
Glare from the overhead lighting in your immediate work space (usually experienced as discomfort)						
Direct glare from the light fixtures beyond your immediate work space (the light fixtures appear too bright)						
Glare from your task lighting						
Direct glare from a window						

17. **Lighting comes in a range of colors, from a "warm" white to "cool" white. "Warm" light is often described as slightly yellow in appearance, and "cool" light is often described as slightly blue in appearance. Using the indicated color range, please indicate:**
Mark only one oval per row.

	Very Warm	Somewhat Warm	Neutral	Somewhat cool	Very Cool	Do Not Know
What is the color appearance of the lighting in your personal work space?						
What would you prefer for the color appearance of the lighting in your personal work space?						

18. **If you could change the lighting in your office, what would you do? Please check all that apply.**
Check all that apply.

- [ ] Change the location of the overhead lighting fixtures relative to your workstation
- [ ] Make the overhead lighting fixtures produce more light
- [ ] Make the overhead lighting fixtures produce less light
- [ ] Make the overhead lighting fixtures less glary
- [ ] Change the aesthetic appearance of the lighting fixtures
- [ ] Change the color appearance of the light produced by the lighiting fixtures
- [ ] Add a task light
- [ ] Be able to control the brightness/light output of the overhead lighting fixtures with a dimmer or high/low switch
- [ ] Get better access to the window view
- [ ] Get better access to daylight
- [ ] Have light bulbs replaced faster when they burn out and fixtures repaired faster when they break
- [ ] I would not change anything
- [ ] Other: _____

Temperature

19. **The temperature in my work area generally feels**
Mark only one oval.

- ( ) Very cold
- ( ) Somewhat cold
- ( ) Just right
- ( ) Somewhat warm
- ( ) Very warm

Comments

20. **Please feel free to submit any other comments about your lighting below:**

_____
_____
_____
_____
_____

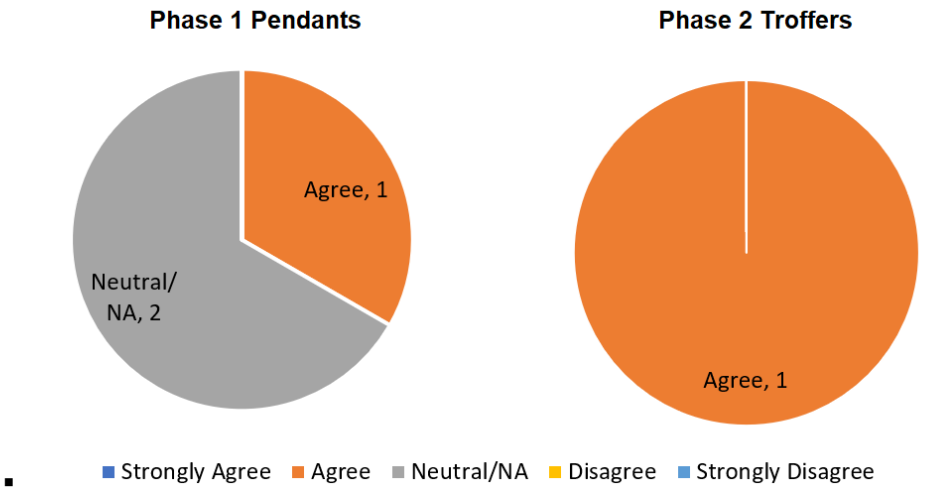
21. **Please feel free to submit any other comments about this survey below:**

Powered by
Google Forms

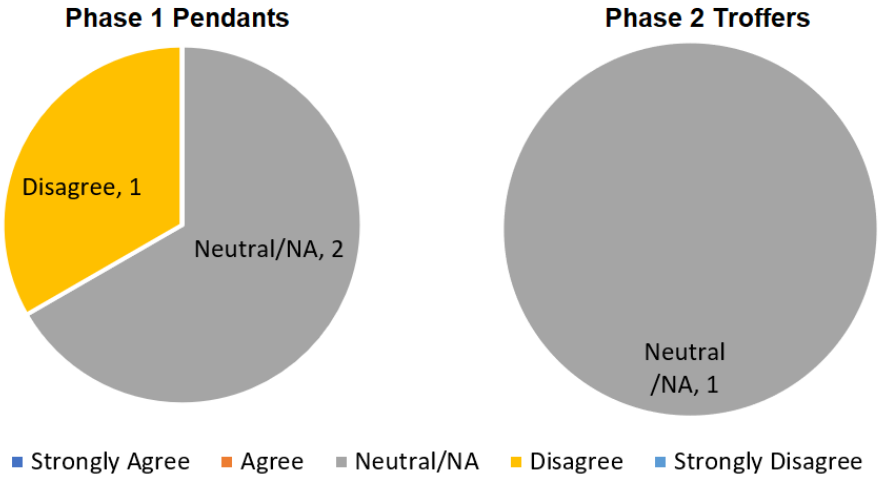
APPENDIX F LIGHTING SYSTEM INSTALLER AND OPERATOR SURVEY

INSTALLING ADMINISTRATIVE OFFICE AREA LIGHTING:

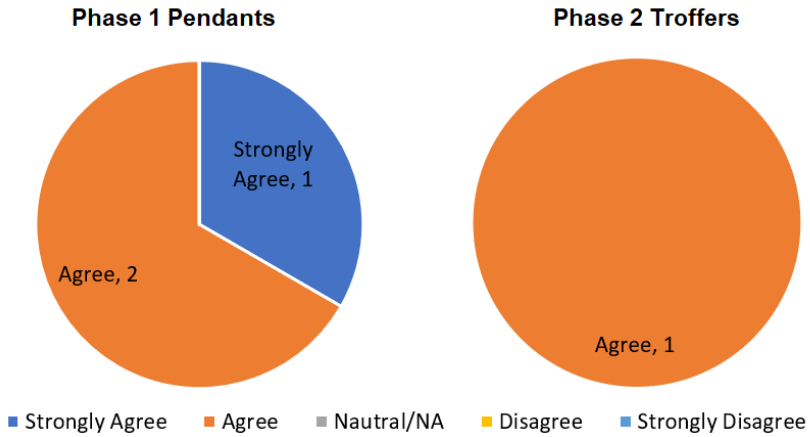
1- Compared to traditional lighting systems, installing the Enlighted smart system was easier than normal.



2- In the administrative area, compared to traditional hardwired lighting controls, the Enlighted lighting control system was easier to install?

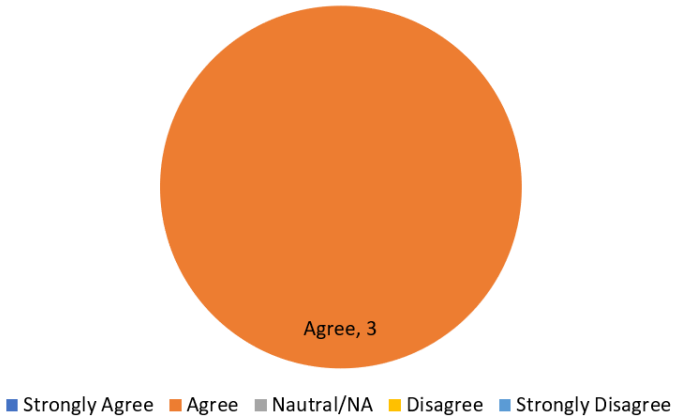


3- In the administrative area, compared to traditional hardwired lighting controls, the Enlighted lighting control system was easier to install?

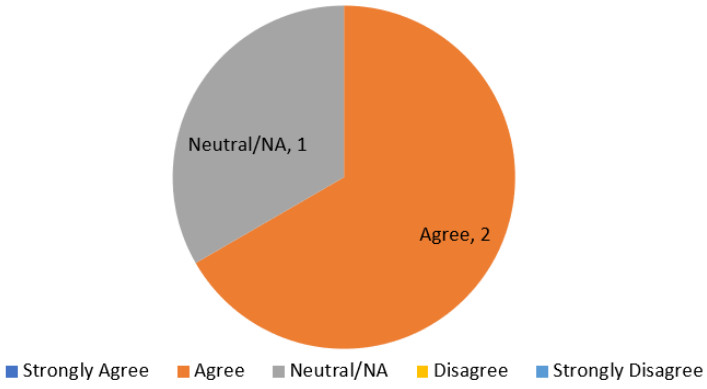


INSTALLING INDUSTRIAL HIGH-BAY AREA LIGHTING:

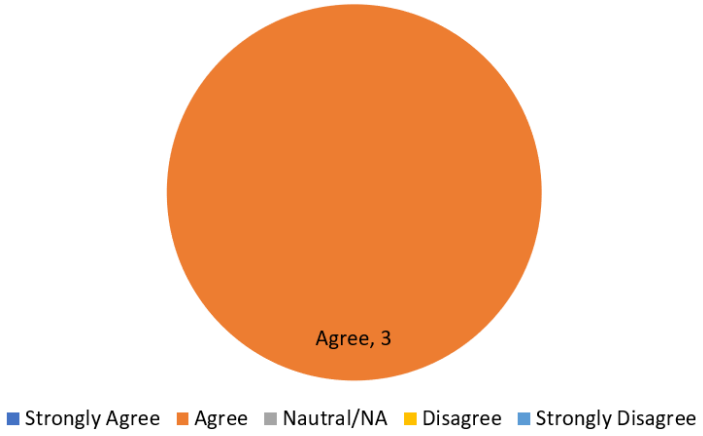
4- Compared to traditional lighting systems, installing the Enlighted smart system was easier than normal.



5- In the high-bay area, compared to traditional hardwired lighting controls, the Enlighted lighting control system was easier to install?



6- In the high-bay area, compared to traditional hardwired lighting controls, the Enlighted lighting control system was easier to install?



ANALYSIS

Administrative Office Area:

- Phase 1: There were three surveys filled out by the installers for phase 1. The installers thought that the system was easy to install, but not as easy as other systems. Installers thought that the wireless control system was much easier to install than a wired control system.
- Phase 2: There was one survey filled out by the installers for phase 2. The installer though that the system was easy to install and was neutral on whether it was easier to install than other systems. The installer thought that the wireless control system was much easier to install than a traditional wired control system.

Industrial High-Bay Area:

- There were three surveys filled out by the installers for the industrial area. The installers agreed that the system was easy to install and 66% thought that this system was easier to install than other systems. All installers thought that the wireless control system was easier to install than a wired control system.

APPENDIX G OFFICE AREA FLOOR PLAN

Building 3907 – 2nd floor, administrative office space area is shown in Figure G.1. It includes 15 plug-load controllers and 9 Enlighted room controllers (ERC) installation locations.

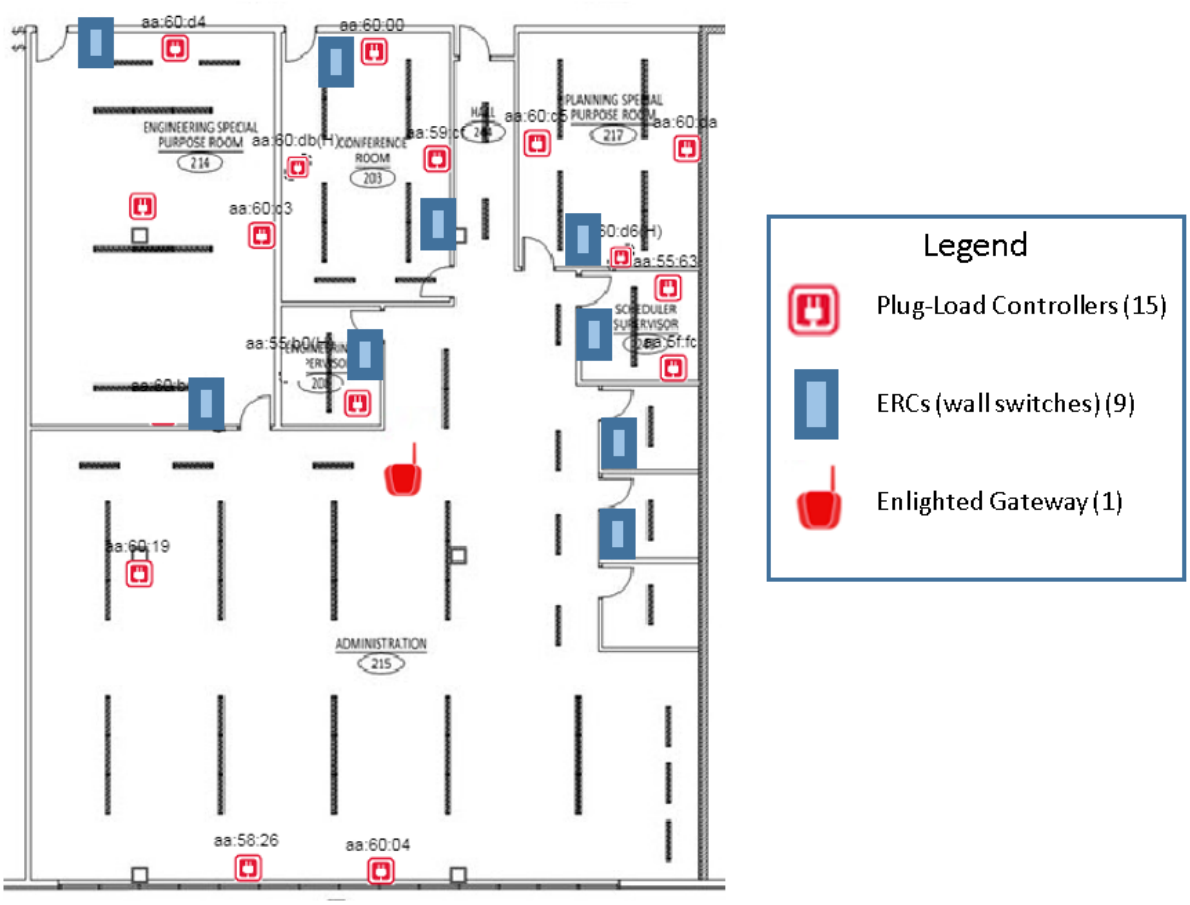


Figure G.1: Building 3907 – 2nd floor, Office Area. Installation location of plug-load controllers, Enlighted room controllers (ERCs) / wall switches, and the Enlighted Gateway.