

FINAL REPORT

LED Fixtures and Integrated Controls for Advanced Holistic
Lightning Solutions

ESTCP Project EW-201722

SEPTEMBER 2020

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Slipstream

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 09/30/2020		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) Sep 2017 - Sep 2020	
4. TITLE AND SUBTITLE LED fixtures and integrated controls for advanced holistic lighting solutions				5a. CONTRACT NUMBER W912HQ-17-C-0024	
				5b. GRANT NUMBER n/a	
				5c. PROGRAM ELEMENT NUMBER n/a	
6. AUTHOR(S) Schuetter, Scott, D				5d. PROJECT NUMBER EW-201722	
				5e. TASK NUMBER n/a	
				5f. WORK UNIT NUMBER n/a	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Slipstream Group, Inc. 431 Charmany Drive Madison, WI 53719				8. PERFORMING ORGANIZATION REPORT NUMBER EW-201722	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive Suite 16F16 Alexandria, VA 22350				10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) EW-201722	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution A: Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The availability of LED fixtures with integrated sensors and embedded controls is relatively new and not implemented at scale in DoD facilities. The increased use of LED lighting, with the addition of integrated controls, will help DoD reduce energy use and energy costs. The goal of this project was to demonstrate, and accelerate the deployment of, an innovative holistic lighting retrofit system in DoD facilities. The project evaluated the demonstrated lighting system in terms of the installation and commissioning process, measured energy and demand savings, light levels, installed cost, system economics, and occupant satisfaction. The project results showed 69% lighting energy savings and 70% peak demand savings. Light levels were brought into closer agreement with UFC recommendations. Occupant, installer and facility staff satisfaction with the system was high. The main barrier to further adoption is the relatively high cost and associated economics (~20 year payback). However, a trend in decreasing system costs will help.					
15. SUBJECT TERMS Light emitting diode; lighting; integrated controls					
16. SECURITY CLASSIFICATION OF: n/a			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 154	19a. NAME OF RESPONSIBLE PERSON Scott Schuetter
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (include area code) 608-210-7149

FINAL REPORT

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ACRONYMS AND ABBREVIATIONS

A	Amps
AES	Advanced Encryption Standard
AMY	Actual Meteorological Year
ANSI	American National Standards Institute
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BLCCA	Building Life-Cycle Cost Analysis
BTU	British Thermal Unit
CT	Current Transducer
CO ₂	Carbon Dioxide
DoD	Department of Defense
EO	Executive Order
ESTCP	Environmental Security Technology Certification Program
EUI	Energy Use Intensity
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GHz	Gigahertz
F	Fahrenheit
fc	Footcandle
ft ²	Square feet
hr	Hour
HVAC	Heating, Ventilation and Air Conditioning
IES	Illuminating Engineering Society
K	Kelvin
kBTU	Thousands of British Thermal Units
kHz	Kilohertz
kW	Kilowatt
kWh	Kilowatt-hour
LED	Light-Emitting Diode
LPD	Lighting Power Density
LWD	Low Occupancy Weekdays
mm	Millimeter

NIST	National Institute of Standards and Technology
NWD	Normal Occupancy Weekdays
POC	Point of Contact
PVAV	Packaged Variable Air Volume
RMF	Risk Management Framework
SIR	Savings-to-Investment Ratio
TMY	Typical Meteorological Year
TRN	Training Days
UFC	Unified Facilities Criteria
U.S.	United States
U.S. DOE	United States Department of Energy
U.S. EIA	United States Energy Information Administration
V	Volts
VAC	Voltage Alternating Current
VAV	Variable Air Volume
W	Watt
WEH	Weekends and Holidays
yr	Year

ACKNOWLEDGMENTS

Slipstream staff who contributed to this project include Dan Cautley, Allie Cardiel, John Dyreby, Scott Hackel, Maddie Koolbeck, Jennifer Li, Andy Lick, Melanie Lord, Greg Marsicek, Leith Nye, and Xiaohui Zhou.

Kris Evans of Cree provided significant technical support throughout the project.

The authors would also like to acknowledge the facilities staff and occupants at both Truax and Selfridge Air National Guard Bases for their time throughout this project. Without their assistance and insight, this project would not have been possible.

ABSTRACT

INTRODUCTION AND OBJECTIVES

The availability of LED fixtures with integrated sensors and embedded controls is relatively new and not implemented at scale in DoD facilities. The increased use of LED lighting, with the addition of integrated controls, will help DoD reduce energy use and energy costs. The goal of this project was to demonstrate, and accelerate the deployment of, an innovative holistic lighting retrofit system in DoD facilities. The project evaluated the demonstrated lighting system in terms of the installation and commissioning process, measured energy and demand savings, light levels, installed cost, system economics, and occupant satisfaction.

TECHNOLOGY DESCRIPTION

The demonstrated lighting system employs LED luminaires available in typical form factors. Each fixture is equipped with a passive-infrared occupancy sensor, a light sensor for daylight harvesting control, and a communications and control module. Switches use a wireless network protocol to communicate with fixtures. Luminaires in the group respond together to both switch operation and to occupancy signals. Each fixture adjusts for available daylight independently. Additional savings may be realized by trimming the high-end output of each luminaire.

PERFORMANCE AND COST ASSESSMENT

Performance Objective	Success Criteria	Result	Met?
Electric energy consumption	Minimum 50% reduction in EUI-lighting	69%	Yes
Peak demand	Minimum 40% reduction in peak demand	70%	Yes
Greenhouse gas emissions	Minimum 50% reduction in GHG emissions	69%	Yes
Light Levels	Net reduction in deviation from UFC recommendations	Truax 510: 2% to -17% Selfridge 124/127: 50% to 18% Selfridge 303: 33% to -13%	Partial
Cost Effectiveness	Maximum 11 year simple payback	Truax 510: 25.6 Selfridge 124/127: 31.3 Selfridge 303: 14.7	No
HVAC energy consumption	Net reduction in EUI-HVAC	Demonstration sites: Increase Reference models: Decrease in climate zones 1-3	Partial
Occupant Satisfaction	Improved overall satisfaction scores	Pre-Retrofit: 2.5 Post-Retrofit: 1.6	Yes
Installation, commissioning and operation	Installers and facility staff report no major difficulty	No reported difficulties	Yes

IMPLEMENTATION ISSUES

The major barrier to significant scaling is first cost. The general trend is decreasing installed cost for these systems which will improve system simple payback and life cycle cost.

EXECUTIVE SUMMARY

INTRODUCTION

The United States Department of Defense (DoD) has around two billion square feet of existing building space, with an annual electric energy use of about 30 billion kWh. [D&R International 2012, U.S. EIA 2020] This is approximately 0.8% of total electricity retail sales in the United States.¹ Because lighting accounts for 18% of electricity use [U.S. EIA 2012] in a typical commercial building, energy efficient lighting retrofits can have a significant impact on DoD's building energy use and expenditures. Reduced energy use through lighting retrofits can also contribute significantly to meeting the 2.5% annual reduction in energy intensity called for in 2015 under Executive Order (EO) 13693. [Executive Order 13693]

This demonstration project used LED lighting technology with integrated occupancy and daylight sensors and embedded controls. LED lighting is readily available on the commercial market and has been used in a significant number of DoD facilities, both as a retrofit and in new construction. The availability of LED fixtures with integrated sensors and embedded controls is relatively new and has not to our knowledge been used in significant numbers in DoD facilities. The increased use of LED lighting, with the addition of integrated and properly functioning controls, will help DoD reduce energy use and energy costs, reduce loads and capacity requirements on both existing power grids and alternative power systems. As such, this technology will help attain energy savings goals set out in EO 13693 and other directives.

OBJECTIVES

The goal of this project was to demonstrate, and accelerate the deployment of, an innovative holistic lighting retrofit system in DoD facilities. The objectives in meeting this goal were to evaluate and report on the demonstrated lighting system in terms of the installation and commissioning process, measured energy and demand savings, light levels, installed cost, system economics, and occupant satisfaction. This project additionally accelerated deployment through various technology transfer activities as well as undergoing the Risk Management Framework (RMF) review process.

This project validated the performance of the technology by monitoring energy use of the existing lighting system prior to retrofit, and the replacement lighting after retrofit. Light levels were measured and compared to UFC recommendations, and qualitative feedback was gathered from occupant surveys and interviews with facility staff and installers. A life-cycle cost analysis demonstrated the cost effectiveness of this system.

TECHNOLOGY DESCRIPTION

The demonstrated lighting system employs LED luminaires available in typical configurations including 2 ft × 2 ft, 2 ft × 4 ft, and 1 ft × 4 ft troffers, linear suspended fixtures, and several size or type of downlights. For this demonstration, the 2 ft × 2 ft and 2 ft × 4 ft were used.

¹ <https://www.eia.gov/energyexplained/us-energy-facts/>

Each fixture has a driver allowing operation at 120 to 277 VAC. The efficacy varies with fixture type, with approximately 130 lumens per watt. With the demonstrated lighting system's controls, each fixture is equipped with a passive-infrared occupancy sensor, a light sensor for daylight harvesting control, and a wireless communications and control module. Additional savings may be realized by trimming the high-end output of each luminaire, or the low-end output under occupancy and daylight control, through settings on the configuration tool.

Once installed, the fixtures are powered, and a handheld configuration tool is used to start an automated wireless network formation and commissioning process. When this process is complete, the configuration tool can also be used to identify specific components (luminaires or switches) and change the grouping (often referred to as zoning) arrangement if needed. Switches use the demonstrated lighting system's wireless network protocol to communicate with fixtures. Fixtures require device AC power and switches require a neutral connection for operation, but hard-wired connections between fixtures and switches are not required. Multiple switches can be used to control a single group.

Once commissioned, the fixtures in the lighting group maintain wireless connectivity with other group members. Luminaires in the group respond together to both switch operation and to occupancy controls; when any occupancy sensor in the group is triggered, all the fixtures operate until a timeout period has expired. Calibration of daylighting controls is included in the automated commissioning process. Each fixture goes through a sequence of varying light output, allowing the controller in each fixture in the group to determine how the output from other fixtures affects its observed light level. Once calibrated, each fixture adjusts for available daylight independently, automatically adjusting for available daylight as well as the light output of other members of the group.

PERFORMANCE ASSESSMENT

The results associated with each performance objective are outlined subsequently.

Table ES 1 summarizes the calculated electric energy consumption reduction for each site.

Table ES 1. Annual Electric Energy Savings for Each Site.

Building	Annual electricity consumption (kWh/ft ²)		Annual electric savings	
	Pre-Retrofit	Post-Retrofit	kWh/ft ²	Percentage
Truax 510	2.0	0.7	1.3	67%
Selfridge 124/127	2.9	1.1	1.8	63%
Selfridge 303	5.1	1.4	3.6	71%
<i>All</i>	<i>3.7</i>	<i>1.2</i>	<i>2.6</i>	<i>69%</i>

Note that the All row represents an area-weighted average of the sites. The success criteria was whether the post-retrofit lighting system achieves a minimum 50% electric energy consumption reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 63% and 71%. The annual electric savings for all sites taken together was 69%.

Table ES 2 summarizes the calculated measured peak demand reduction for each site.

Table ES 2. Measured Peak Demand Savings for Each Site.

Building	Peak Demand (W/ft ²)		Peak Demand Savings	
	Pre-Retrofit	Pre-Retrofit	W/ft ²	Percentage
Truax 510	1.00	0.30	0.70	70%
Selfridge 124/127	1.47	0.55	0.92	62%
Selfridge 303	1.64	0.43	1.22	74%
<i>All</i>	<i>1.45</i>	<i>0.44</i>	<i>1.01</i>	<i>70%</i>

Note that the All row represents an area-weighted average of the sites. The success criteria was whether post-retrofit lighting system achieves a minimum 40% measured peak demand reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 62% and 74%. The savings for all sites taken together was 70%.

Table ES 3 summarizes the calculated greenhouse gas emissions reduction for each site.

Table ES 3. Greenhouse Gas Emissions Savings for Each Site.

Building	Greenhouse gas emissions savings	
	lbCO ₂ e/ft ²	Percentage
Truax 510	2.1	67%
Selfridge 124/127	2.3	63%
Selfridge 303	4.6	71%
<i>All</i>	<i>3.3</i>	<i>69%</i>

Note that the All row represents an area-weighted average of the sites. The success criteria was whether the post-retrofit lighting system achieved a minimum 50% GHG reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 67% and 71%. The greenhouse gas emissions savings for all sites taken together was 69%.

Table ES 4 summarizes the UFC recommended and measured pre-retrofit, post-retrofit and adjusted light levels for each site. The percent difference with respect to UFC recommendations are also included in brackets.

Table ES 4. UFC Recommended and Measured Pre-retrofit, Post-retrofit and Adjusted Light Levels.

Building	Illuminance (fc)			
	Ave UFC Recommendation ²	Pre-Retrofit	Post-Retrofit	Adjusted
Truax 510	30	29 [2%]	16 [-45%]	26 [-17%]
Selfridge 124/127	24	36 [50%]	28 [18%]	28 [18%]
Selfridge 303	30	40 [33%]	25 [-16%]	26 [-13%]
<i>All</i>	<i>28</i>	<i>36 [29%]</i>	<i>24 [-14%]</i>	<i>26 [-6%]</i>

² This column is an area-weighted average of UFC recommendations including 30 fc for offices and conference rooms and 5 fc for corridors.

Note that the All row represents an area-weighted average of the sites. The success criterion was whether the post-retrofit average illuminance percent difference was less than the pre-retrofit average illuminance percent difference. Put another way, the light levels of a given space were brought into closer agreement with the UFC recommendations.

Table ES 5 summarizes the modeled HVAC energy savings for each site.

Table ES 5. Site-specific HVAC Modeling Savings Results.

Building	Annual HVAC Electric		Annual HVAC Natural Gas		Annual HVAC Energy		Annual HVAC Utility Cost	
	kWh/ft ²	%	therm/ft ²	%	kBtu/ft ²	%	\$/ft ²	%
Truax 510	0.02	1%	-0.04	-3%	-3.8	-3%	-\$0.03	-2%
Selfridge 124/127	-0.01	-1%	-0.06	-11%	-5.6	-10%	-\$0.05	-9%
Selfridge 303	0.30	23%	-0.09	-21%	-8.4	-17%	-\$0.05	-9%
All	0.13	10%	-0.07	-10%	-6.5	-9%	-\$0.04	-6%

Note that the All row represents an area-weighted average of the sites. The success criteria was whether the post-retrofit system achieved a minimum 0% HVAC energy consumption reduction as compared to the pre-retrofit system. This is the same as saying that the lighting retrofit reduced the HVAC energy consumption. Taken together, the total HVAC energy consumption increased at all buildings as the cooling season savings were not large enough to offset the heating season penalty.

Figure ES 1 illustrates the commercial reference building modeling results for each of the building types and climate zones.

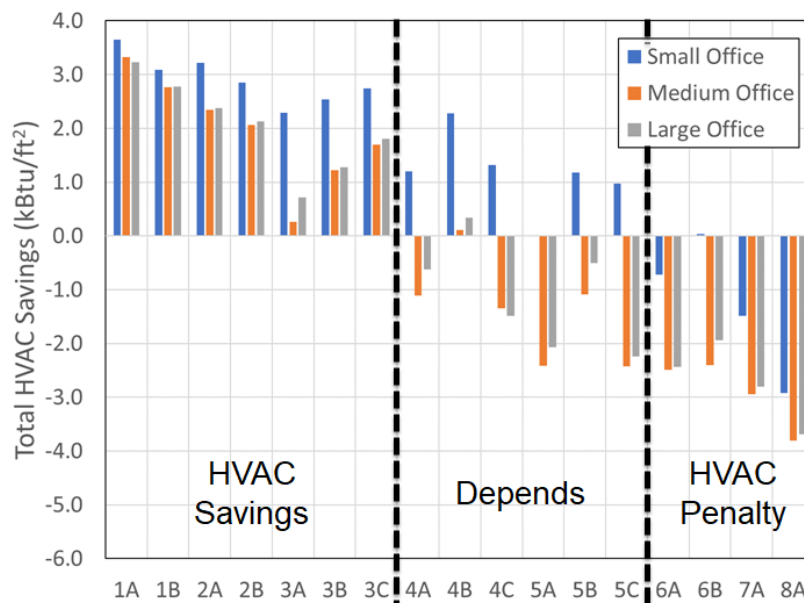


Figure ES 1. Commercial Reference Building Modeling Total HVAC Savings Sorted by Climate Zone.

Note that for hot climate zones (1-3) the reduced lighting load resulted in HVAC savings for each of the building types. Similarly, for cold climates (6-8) the reduced lighting load resulted in an HVAC penalty for each of the building types. However, in temperate climate zones (4-5) the HVAC impact depended on the building type and associated HVAC system type. Since the HVAC system energy consumption is reduced only in hot climates, this performance objective was only partially met.

Table ES 6 summarizes the Likert scores for each of the level of satisfaction questions (1 = Extremely Satisfied, 5 = Extremely Dissatisfied)

Table ES 6. Occupant Survey Likert Score Summary.

Period	Sample Size	Average Likert Score		
		Amount of light in workspace	Ability to control overhead lighting	Visual comfort of the lighting
Pre-Retrofit	23	2.5	2.8	3.1
Post-Retrofit	27	1.6	1.7	1.7

The success criteria was whether the post-retrofit system achieved a minimum 0% Likert scale score reduction as compared to the pre-retrofit system. This is the same as saying that the lighting retrofit improved occupant satisfaction as lower scores are better than higher scores. Note that the Likert score decreased (improved) for each of the categories.

The results of the installer and facility staff survey were largely qualitative. The success criteria were whether no major difficulties were encountered in the installation, commissioning, and operating of the demonstrated lighting system. In fact, no major difficulties were encountered throughout the demonstration project.

The electrical contractors reported that the fixture installation was like a traditional fluorescent lighting system. However, they noted that the switches required an additional neutral conductor, which added time to the installation.

The electrical contractors reported that system commissioning was longer and more complex than a traditional fluorescent lighting system due to the additional control settings. One contractor reported that the printed instructions provided were unclear. However, they were able to access manufacturer support and video tutorials, which were helpful.

Facility staff reported that the day-to-day operation was similar to a traditional fluorescent lighting system, with minimal to no interventions required. One operator mentioned that replacing a faulty fixture or switch (when it occurred) would be more complex due to the programming involved.

COST ASSESSMENT

The results associated with the Life-Cycle Cost Analysis are outlined subsequently.

Table ES 7 summarizes the simple payback for each site, as well as the total all sites taken together.

Table ES 7. Simple Payback at Each Site.

	Truax 510	Selfridge 124/127	Selfridge 303	All
Building Area (ft ²)	1,532	2,175	3,370	7,145
Energy Saved (kWh/ft ²)	1.3	1.8	3.6	2.6
Lighting Energy Saved (%)	67%	63%	71%	69%
Simple Payback (yr)	25.6	31.3	14.7	20.2

Note that none of the sites met the performance objective of under 11-year payback (set by preliminary estimates). It was clear that the installed costs for each site were higher than expected. This was driven than longer installation times, higher fixture density, and higher contractor markups.

Using the NIST Building Life Cycle Cost Analysis program, version 5.3, and methodology [Fuller 1995], we calculated the NPV and SIR related to the demonstrated lighting system installation at each building.

We completed the analysis for four different timeframes: 5 year, 10 years, 20 years, and 33 years. We included 33 years as it represents the full lifetime of the demonstrated lighting system, assuming 100,000 hours of system life [Cree 2019] and 3,000 hours of use annually. While 100,000 hours is related to lumen depreciation, there are other factors that may shorten the system life such as driver failure. This estimate may therefore be considered an upper bound of system life, in addition to the shorter timeframes.

Table ES 8. Lifecycle Cost Analysis Results

Site	5 Years		10 Years		20 Years		33 Years	
	NPV	SIR	NPV	SIR	NPV	SIR	NPV	SIR
Truax 510	-7,505	0.18	-5,652	0.38	-3,174	0.65	-805	0.91
Selfridge 124/127	-20,695	0.11	-17,110	0.26	-12,758	0.45	-8,585	0.63
Selfridge 303	-18,855	0.31	-10,598	0.61	1,351	1.05	12,709	1.47

Only Selfridge 303 has a positive NPR and SIR greater than 1.0 by the end of the rated lifetime of the demonstrated lighting system. This is driven primarily by the high capital costs associated with the three demonstration sites. The positive NPV at Selfridge 303, compared to the other two sites' negative NPV, can be partially explained by its larger annual energy savings.

The capital costs for this project were significantly higher than both our initial estimate for this project and costs for similar installation projects. For that reason, we completed a lifecycle cost analysis using hardware and installation costs from recent demonstration projects of similar lighting systems. The Baseline scenario is defined by area-weighted averaging the 3 sites for this project. The Better scenario is defined by capital costs from General Service Administration (GSA) Proving Ground project. [PNNL 2018]. The Best scenario capital costs come from the Department of Energy LiTES project [Osbourne 2020].

The Better and Best total installation costs are 37% and 60% lower, respectively, than the Baseline scenario. They therefore represent much better economic scenarios. Table ES 9 presents the NPV and SIR for the alternative capital cost scenarios.

Table ES 9. Lifecycle Cost Analysis Results – Alternative Capital Cost

Site	Simple Payback (yr)	5 Years		10 Years		20 Years		33 Years	
		NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)
Baseline	20.2	-6.52	0.23	-4.49	0.47	-1.69	0.80	0.99	1.12
Better	12.6	-3.35	0.36	-1.32	0.75	1.49	1.28	4.17	1.79
Best	7.7	-1.30	0.59	0.73	1.23	3.55	2.11	6.23	2.95

The results show that the NPV and SIR improve considerably when using Better and Best capital cost scenarios. In the 33-year analysis, both the NPV and SIR are significantly higher under the alternatives compared to the DoD project. Furthermore, the lower project costs in the Better scenario result in positive savings within 20 years, while the Best scenario results in positive savings within 10 years. Additionally, the Better and Best alternatives have simple payback periods of 12.6 and 7.7 years, respectively. The Best scenario would therefore meet our economic success criteria of a payback of 11 years or less.

IMPLEMENTATION ISSUES

There were implementation issues with this project that provide insights for future work.

Lessons Learned

Throughout the project, we learned several valuable lessons that would be beneficial to future projects.

The general trend is decreasing installed cost for these systems. As this trend continues, the overall economics of these lighting systems will naturally improve. However, the following may help expedite this within DoD facilities. The installed cost at our demonstration sites was much higher than expected. This involved several factors; installation time, fixture density, and markups. Our higher-than-expected labor hours may be due to the small areas associated with our sites. Fixed costs do not scale with site size, making it more advantageous to pursue lighting retrofit of larger areas (>25,000 ft²). Our sites also had more fixtures per square foot than originally expected. It is our general recommendation is to perform one-for-one lighting replacements. However, in spaces with high existing fixture density (6 ft × 8 ft or closer), photometric modeling should be performed to see if fewer fixtures can adequately light the space. The reduced number of fixtures may offset the additional time spent rewiring. The fixture markup for our demonstration sites was also higher than expected. We recommend that DoD facility staff work closely with their contractor network to develop a trained workforce with experience on integrated lighting control systems. As contractor's become more familiar with these systems, they will perceive less risk in installing them. This will result in more accurate bids and less time spent on projects "getting to know" the systems.

It is important to get facility staff and office managers buy-in. They are valuable resources throughout the retrofit process from coordinating site visits to the retrofit itself, providing relevant information about the spaces and systems to be retrofit (building plans, equipment specifications, schedules...), and communicating information to the space occupants. They also provide valuable feedback about the control setpoints for each space. Obtaining their buy-in may be facilitated by explaining the benefits of the lighting system (energy savings, utility cost savings, increased occupant satisfaction) and how that aligns with their mission.

It is also important to obtain buy-in from the occupants. This similarly involves educating them about the benefits of the system and the basics of its operation. If they understand why the lights are dimming or turning off automatically, they are less likely to complain. We also found that gathering occupant feedback throughout the project was beneficial. The pre-retrofit occupant survey identified areas that needed improvement. This data also informed the extent to which occupants would be comfortable with aggressive versus conservative control setpoints.

Procurement Issues

The demonstrated lighting system is currently commercially available. It is relatively new with limited market penetration. It is therefore new to most electrical contractors and facility staff. The manufacturer provides support through design, installation and commissioning, which is helpful to successful project implementation.

It should be noted that manufacturers may be open to discussing selling their fixtures directly to large entities such as the DoD. Under this approach, the significant markup from contractors and distributors would be bypassed, improving the project's economics. In this scenario, DoD facilities would likely need to use their own facility staff for the installation and commissioning.

Passing the cybersecurity review was slow for this demonstration project. This was due to education and time constraints as opposed to technological reasons. It would be beneficial for future projects to have more than one person trained and authorized to enter information. Another issue was the discrepancy between the eMASS templates we filled out and the actual eMASS entry. Between our filling out the templates and entering the information, the system was updated. Future projects will benefit from a less dynamic process.

1.0 INTRODUCTION

1.1 BACKGROUND

The United States Department of Defense (DoD) has around two billion square feet of existing building space, with an annual electric energy use of about 30 billion kWh. [D&R International 2012, U.S. EIA 2020] This is approximately 0.8% of total electricity retail sales in the United States.³ Because lighting accounts for 18% of electricity use [U.S. EIA 2012] in a typical commercial building, energy efficient lighting retrofits can have a significant impact on DoD's building energy use and expenditures. Reduced energy use through lighting retrofits can also contribute significantly to meeting the 2.5% annual reduction in energy intensity called for in 2015 under Executive Order (EO) 13693. [Executive Order 13693]

This demonstration project used LED lighting technology with integrated occupancy and daylight sensors and embedded controls. The potential energy savings may be estimated by comparing against typical fluorescent lighting installed at a lighting power density of 1.2 W/ft². An LED system would have a lighting power density (LPD) on the order of 0.6 W/ft², reducing energy use by 50%. The additional use of occupancy control and daylight harvesting can cut remaining energy use by 38%, resulting in total savings of about 69% of the original energy use. Proper installation and commissioning are a critical factor in achieving savings with occupancy and daylight controls; the demonstrated lighting system uses fully factory-integrated controls and an automated commissioning process, providing a high degree of certainty of proper operation.

Savings vary with the original lighting design, hours of use, etc., and with the proper installation and commissioning of the controls. In a typical space, with 3,000 hours of annual occupancy, we estimated energy savings at 2.5 kWh/ft². With electricity priced at \$0.10/kWh, this translates to \$0.25/ft² annually, not including associated demand charge savings.

LED lighting is readily available on the commercial market and has been used in a significant number of DoD facilities, both as a retrofit and in new construction. The availability of LED fixtures with integrated sensors and embedded controls is relatively new and has not to our knowledge been used in significant numbers in DoD facilities. The increased use of LED lighting, with the addition of integrated and properly functioning controls, will help DoD reduce energy use and energy costs, reduce loads and capacity requirements on both existing power grids and alternative power systems. As such, this technology will help attain energy savings goals set out in EO 13693 and other directives.

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal of this project was to demonstrate, and accelerate the deployment of, an innovative holistic lighting retrofit system in DoD facilities. The objectives in meeting this goal were to evaluate and report on the demonstrated lighting system in terms of the installation and commissioning process, measured energy and demand savings, light levels, installed cost, system economics, and occupant satisfaction. This project additionally accelerated deployment through various technology transfer activities as well as undergoing the Risk Management Framework (RMF) review process.

³ <https://www.eia.gov/energyexplained/us-energy-facts/>

This project validated the performance of the technology by monitoring energy use of the existing lighting system prior to retrofit, and the replacement lighting after retrofit. More detail on our measurement and analysis plan is included below. Cost of the replacement lighting was estimated from the actual cost of the demonstration installations, and from interviews with installers. A life-cycle cost analysis demonstrated the cost effectiveness of this system.

The project team pursued cybersecurity review of the demonstrated lighting system under the RMF process. We also evaluated the system for compliance with applicable sections of the Unified Facilities Criteria (UFC).

Technology transfer activities included an infographic and a video targeting engineering staff and energy managers which described the demonstration technology, the system installed cost, savings, and other information relevant to prospective users. The intent of these activities was to increase awareness and acceptability of holistic retrofit lighting systems as an energy option, and to provide basic information on project selection and design. We additionally pursued multiple publications and conference presentations. Upon reviewing the UFC, we found no current restrictions to implementing the demonstrated lighting system.

1.3 REGULATORY DRIVERS

The primary drivers for this project were:

- a. EO 13693 (which replaces EO 13423) established increased energy efficiency of Federal agencies as policy and established quantitative targets for reduced energy intensity across agencies of 2.5% per year through 2025.
- b. DoD Directive 4180.01, established DoD Energy Policy guidelines, with language including “Improve the energy performance of ... installations, including both enduring and non-enduring locations”.
- c. DoD Instruction 4170.11 Installation Energy Management, references several implementation steps in achieving energy efficiency, and specifically calling for the use of high efficiency lighting and motion sensor or occupancy controls.
- d. AIR FORCE POLICY DIRECTIVE 90-17 established the framework for energy management within the Air Force. This is relevant since the installations selected for demonstration are Air National Guard bases.
- e. UFC 3-530-1 established requirements for lighting systems, including controls, efficacy, power quality, and network/spectrum approval.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Lighting retrofits have traditionally involved fixture upgrades and/or control upgrades, with little integration of the two. The retrofits have typically required hardwired connections between sensors, switches, and luminaires. The complexity of design, installation and commissioning of these fully wired systems generally results in high costs and reduced flexibility to adapt to changing usage patterns.

The demonstrated lighting system employs LED luminaires available in typical configurations including 2 ft × 2 ft, 2 ft × 4 ft, and 1 ft × 4 ft troffers, linear suspended fixtures, and several size or type of downlights. (Figure 1) For this demonstration, the 2 ft × 2 ft and 2 ft × 4 ft were used.



Figure 1. 2 ft × 4 ft LED Troffer.

Each fixture has a driver allowing operation at 120 to 277 VAC. The efficacy varies with fixture type, with approximately lumens per watt. With the demonstrated lighting system's controls, each fixture is equipped with a passive-infrared occupancy sensor, a light sensor for daylight harvesting control, and a wireless communications and control module. The range of luminaires will allow direct one-for-one replacement in many retrofit situations.

Once installed, the fixtures are powered, and a handheld configuration tool is used to start an automated wireless network formation and commissioning process. When this process is complete, the configuration tool can also be used to identify specific components (luminaires or switches) and change the grouping (often referred to as zoning) arrangement if needed. For example, the lighting near a projection screen in a conference room might be moved to a group that is independent of other lighting. The basic unit of a completed setup process is the "group": a set of lighting fixtures controlled by specific switches.

Switches use the demonstrated lighting system's wireless network protocol to communicate with fixtures. Fixtures require device AC power and switches require a neutral connection for operation, but hard-wired connections between fixtures and switches are not required. Multiple switches can be used to control a single group, e.g., switches near each of four doors to a room can all control one group.

Once commissioned, the fixtures in the lighting group maintain wireless connectivity with other group members. Luminaires in the group respond together to both switch operation and to occupancy controls; when any occupancy sensor in the group is triggered, all the fixtures operate until a timeout period has expired. (Figure 2)

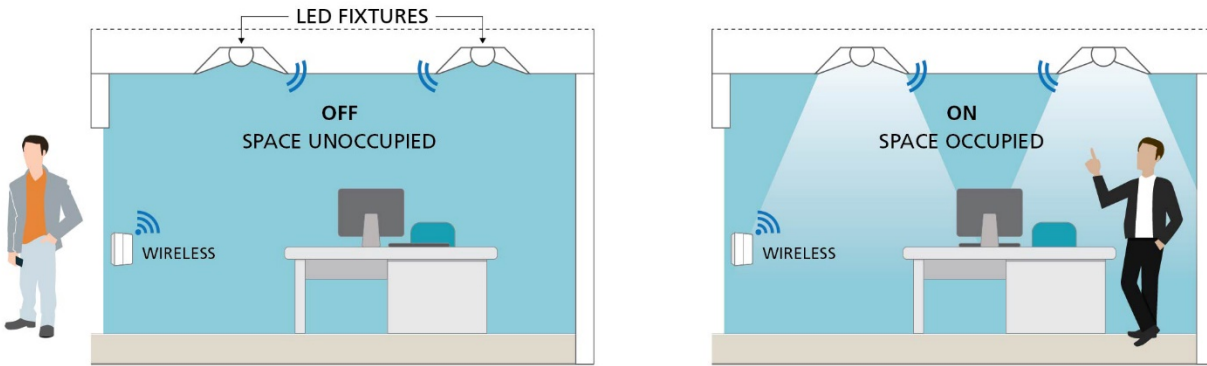


Figure 2. Lighting Fixtures Turning Off During Periods of No Occupancy.

Calibration of daylighting controls is included in the automated commissioning process. Each fixture goes through a sequence of varying light output, allowing the controller in each fixture in the group to determine how the output from other fixtures affects its observed light level. Once calibrated, each fixture adjusts for available daylight independently, automatically adjusting for available daylight as well as the light output of other members of the group. (Figure 3)

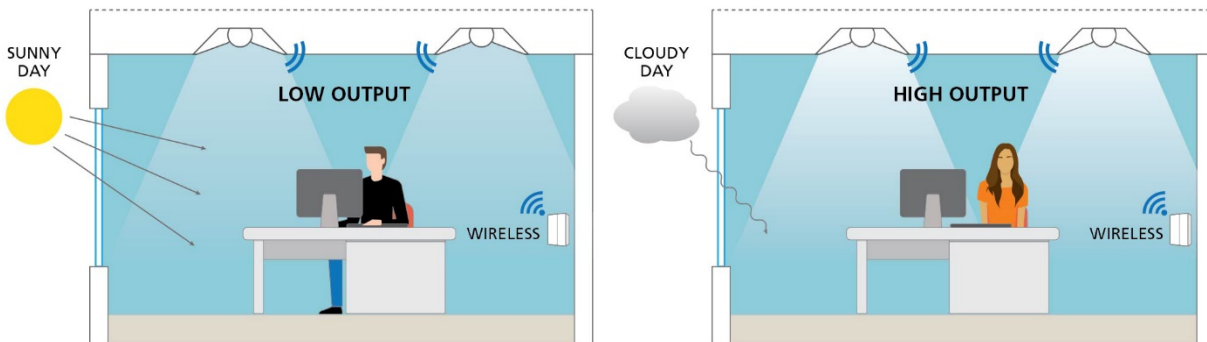


Figure 3. Lighting Fixtures Reducing Output During Periods of Sufficient Daylight.

Additional savings may be realized by trimming the high-end output of each luminaire, or the low-end output under occupancy and daylight control, through settings on the configuration tool.

This project used primarily troffer fixtures (2 ft × 2 ft and 2 ft × 4 ft fixtures in dropped ceilings).

2.2 TECHNOLOGY DEVELOPMENT

No technical development of the Cree SmartCast system was undertaken as part of this ESTCP project.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The proposed technology has significant advantages over typical incumbent lighting systems in the categories of energy efficiency, flexibility of use, and maintenance. The most typical incumbent lighting system is assumed to be fluorescent troffers in an office environment. The quantitative value of benefits vary with the type of incumbent lighting and with the specific application and occupancy.

Energy efficiency: The potential energy savings may be estimated by comparing against typical fluorescent lighting installed at a lighting power density of 1.2 W/ft². An LED system would have a lighting power density (LPD) on the order of 0.6 W/ft², reducing energy use by 50%. The additional use of occupancy control and daylight harvesting can cut remaining energy use by 38% [Williams 2011], resulting in total savings of about 69% of the original energy use.

The demonstrated lighting system has integrated occupancy and daylight controls and uses an automated commissioning process. This offers a distinct benefit compared to systems using third-party controls, as prior research shows that add-on lighting controls are often poorly commissioned and do not yield the expected energy savings. [Hackel 2013]

Total energy savings were estimated for a hypothetical DoD building, a 6,000 square foot office with typical weekday occupied hours, resulting in lighting usage of 3,000 hours annually. Total annual lighting energy savings for this typical building would be 14,904 kWh or 2.5 kWh/ ft². Based on a national average cost of electric energy of \$0.1025/kWh, the estimated utility cost savings would be \$1,528 or \$0.25/ft².

The total cost (labor and materials) of installing the lighting system in a retrofit application was originally estimated at \$3.00/ft², yielding a simple payback of 11.8 years, though this would of course vary across applications.

Flexibility of use: The demonstrated lighting system uses wireless controls between all the fixtures and switches in a designated group. The controls can be configured to group any set of luminaires with any switch or switches, providing flexibility to re-design lighting control plans during retrofitting or later. The lighting fixtures will operate on typical commercial building lighting circuits and will generally draw much less power than existing fixtures, so electrical circuits will not usually require modification.

Maintenance: Fluorescent tubes have a life expectancy of about 25,000 hours, while LEDs have a much longer life, often exceeding 50,000 hours. Several fluorescent tube replacements would be expected within the lifetime of LED fixtures. In addition, fluorescent tubes fail suddenly, and as a result, most facilities have some burned out tubes at any given time. This can reduce lighting effectiveness, and failure to maintain egress lighting could create a hazard. The long life and low maintenance requirements of LED lighting are benefits of the demonstrated system.

Barriers to acceptance: The main general barrier to acceptance of this technology is its installed cost. LED luminaires are becoming increasingly cost competitive with traditional fluorescent lighting technologies. However, a cost premium remains. Although the utility cost and maintenance savings make this technology attractive, the capital cost may be too great for a given facility. Although some training is required on the system, the system's simplicity helps minimize this learning curve.

Less general barriers that may appear in specification applications include the following. Where light fixtures are installed in permanent ceiling systems rather than dropped ceilings, the cost of ceiling work to accommodate the replacement fixtures may make retrofitting unattractive. The requirement for a neutral wire at each switch location may be a slight impediment to installation in some buildings.

3.0 PERFORMANCE OBJECTIVES

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

The project team identified seven quantitative performance objectives and one qualitative performance objective (Table 1).

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Reduce lighting system's electric energy consumption	Lighting Energy Use Intensity (EUI-lighting) in kWh/ft ² /yr	Monitored electricity use of lighting system during pre- and post-retrofit; area of retrofit spaces	Minimum 50% reduction in EUI-lighting
Reduce peak demand	Measured peak demand in W/ft ²	Measured maximum watts used by lighting system during pre- and post-retrofit; area of retrofit spaces	Minimum 40% reduction in peak demand
Reduce lighting system's greenhouse gas (GHG) emissions	Direct fossil fuel GHG emissions for the retrofitted fixtures in metric tons of CO ₂ equivalent/ft ² /yr	Estimated release of GHG based EUI reduction	Minimum 50% reduction in GHG emissions compared with pre-retrofit period
Light Levels	Workplane illuminance in footcandles	Measured illuminance during pre and post-retrofit	Net reduction in percent difference from UFC requirements between pre and post-retrofit
Cost Effectiveness	Simple Payback in years	Data on installed cost including equipment and labor costs, and operating costs	Maximum 11 year simple payback
Reduce HVAC energy consumption	Modeled effect of the lighting system on HVAC energy use	Pre and post-retrofit lighting energy consumption, typical inputs into DOE2.2 model	Net reduction in EUI-HVAC
Occupant Satisfaction	Level of satisfaction among occupants on the performance of lighting system	Likert scale survey of occupant comfort and satisfaction with lighting system	Improved overall satisfaction scores
Qualitative Performance Objectives			
Ease of installation, commissioning and operation	Ability of installers to efficiently install and commission lighting system; facility staff to operate lighting system	Installer and facility staff interviews regarding system installation, commissioning, and operation	Installers and facility staff report no major difficulty in installation, commissioning and operating

The energy savings and other metrics of success vary depending on the specific attributes of each site and lighting system. As such, the quantitative performance objectives in the table above are minimum objectives.

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

The following provides a high-level overview of the performance objectives. Please see the *BASELINE CHARACTERIZATION* and *PERFORMANCE ASSESSMENT* sections for more detail on the data gathered and the analysis approach used in determining whether the performance objectives were met.

3.2.1 Electric Energy Consumption and Lighting Power Density Reduction

EO 13693 established 2.5% annual reduction in energy use intensity of DoD buildings, and energy savings is the primary objective of this demonstration. We monitored electric energy use in pre- and post-retrofit periods to calculate energy savings, with results presented as Energy Use Intensity for Lighting (EUI-lighting) in units of kWh/ft²/yr. Analysis considered four typical days; normal occupancy weekdays, low occupancy weekdays, weekends and holidays, and training days. We adjusted results to reflect an annual mix of day types. We used assumptions of when occupancy and photosensors are active, to differentiate savings between LEDs, task tuning, occupancy and photocontrols. The expected contribution of daylight harvesting in a year was estimated from data collected over about 6 months representing approximately the full range of incident solar angles at each site. Our success criterion was a minimum 50% reduction in EUI-lighting with the retrofit system.

We additionally measured the maximum power draw of the systems pre- and post-retrofit. Comparison of measured peak demand between the pre- and post-retrofit systems was an indicator of the fractional savings attributable to the change in lighting technology (i.e. fluorescent to LED) combined with controls savings. Our success criterion was a minimum 40% reduction in peak demand with the retrofit system.

Note that we used this data to estimate the utility bill impact of consumption and peak demand reductions between the pre- and post-retrofit systems.

3.2.2 Greenhouse Gas Emission Reduction

EO 13693 established reduction in greenhouse gas emissions as policy for federal facilities. We estimated greenhouse gas emissions for the lighting systems in this project by multiplying annualized energy use by an emissions factor. This factor is regionally specific, considering the local mix of electric generation fuels. [eGRID 2016] Results were expressed on a per square foot basis reduction in greenhouse gas emissions for each system.

3.2.3 Light Levels

Adequate and spatially consistent illumination can affect worker productivity and satisfaction, and a primary objective of this lighting retrofit was to ensure light levels agree with UFC requirements. We gathered illuminance data by manual measurement during site visits per Illuminating Engineering Society (IES) procedures. [DiLaura 2011] Repeating these measurements with lights on and off allowed separation of daylight and electric lighting components.

This information was used to verify design illuminance levels before and after retrofit. Our success criterion was a net reduction in the variation between average occupied illuminance and UFC standards.

3.2.4 Cost Effectiveness

Economic performance is clearly a part of most energy efficiency improvement efforts, and calculation of cost effectiveness was a primary objective of the project.

The direct cost of replacement lighting installation contracts provided the base cost of the retrofits, with supplemental information gathered through interviews with the manufacturer, installers, and facilities staff to inform the scaled cost of this technology. Annualized energy cost savings were calculated by applying local utility rate structures to the electricity consumption and demand reduction estimates. The analysis included information on any available utility rebates.

The success criteria for economic performance was a simple payback of 11 years or less. This criteria was arrived at through preliminary estimates of system cost and savings. We also calculated the Net Present Value (NPV) and Savings-to-Investment Ratio (SIR) over a 5, 10, 20 and 33-year period (system lifetime assuming 3,000 hours per year⁴), using the NIST Building Life Cycle Cost Analysis (BLCCA) methodology [Fuller 1995] and assuming a general price inflation of 0.1%, a nominal discount rate of 3.1% and fuel cost inflation rates. [Lavappa 2015]

Sensitivity of the economic performance indicators to electric rates and rebates were also explored.

3.2.5 Reduce HVAC Energy Consumption

As lighting loads are reduced in a space, the HVAC system experiences decreasing cooling loads and increasing heating loads, and consideration of these effects is part of evaluating the overall net energy effect of a lighting retrofit. In commercial buildings, the net effect is typically an overall reduction in HVAC energy consumption. We used energy modeling to estimate the approximate effect of the retrofits on HVAC energy consumption expressed as Energy Use Intensity for HVAC (EUI-HVAC) in units of kBtu/ ft²/yr. A simplified energy model was built in DOE2.2 using eQuest for each facility, including facility-specific inputs such as geometry, envelope properties, scheduling, internal loading and HVAC characteristics. We additionally used measured lighting power for the pre- and post-retrofit periods to approximate the lighting load in the studied spaces. These models predicted the HVAC energy consumption associated with both the pre- and post-retrofit lighting systems. The difference between the predicted pre- and post-retrofit HVAC energy consumption represented the net increase or decrease associated with the retrofit.

We expanded our analysis beyond the demonstration sites using the U.S DOE's prototype building models. This analysis included the most applicable DoD facility types for this lighting technology. It additionally included all major U.S. climate zones. Through this expanded analysis, we understood the effect of the lighting system on HVAC energy consumption in a wide range of DoD applications.

⁴ The annual operating hours for the demonstration sites were approximately 2,600 hours. We reviewed other data sources, including the Department of Energy's building prototype models and multiple state Technical Reference Manual, to determine that 3,000 hours of annual operation was a reasonable value for a typical office.

The success criteria was a net reduction in HVAC energy consumption at each site.

3.2.6 Occupant Satisfaction

Occupant satisfaction with lighting systems is a key factor in minimizing the frequency of control overrides and assuring the persistence of energy savings. User satisfaction may also be a significant factor in decisions by facility staff to pursue additional lighting retrofits. We evaluated occupant satisfaction based on the results of pre- and post-retrofit surveys of staff working at each demonstration facility. The survey instrument used a Likert scale approach, a standard approach in which responses express the strength of agreement or disagreement with statements about lighting quality and comfort. Survey administration were anonymous and voluntary to ensure unbiased results. The criterion for success was a net improvement in Likert scale score.

3.2.7 Ease of Installation, Commissioning and Operating

Ease of installation, commissioning and operating may have an impact on future decisions by engineering managers to pursue similar lighting retrofits, and on installer enthusiasm for, and pricing of, such retrofits. We interviewed both installing contractors and base engineering staff about time, effort, learning curve, specific problems encountered, and the ultimate success of retrofitting using the demonstrated lighting system. We did not have specific criteria for success under this objective but evaluated the results in terms of the difficulty reported by installers and facility staff in installation, commissioning and operating of the demonstrated lighting system as compared to other systems offering similar functionality and translated identified issues with retrofitting to recommendations for improved processes.

4.0 FACILITY/SITE DESCRIPTION

Our criteria for site selection included:

- The existing lighting should be primarily T8 or T12 fluorescent troffer fixtures. Fluorescent lighting is almost certainly the most common incumbent lighting type in DoD office space, making it a prime candidate for demonstration. Standard 2 ft × 2 ft or 2 ft × 4 ft troffer fixtures in dropped ceilings are very common and ideal candidates for replacement. Some mix of other lighting types was acceptable, and the demonstrated lighting fixtures are available in suspended linear and recessed downlight types.
- Occupancy should be as office space or similar usage, occupied a minimum of approximately 40 hours per week. Regularity in occupied hours is a benefit since it reduces variability in lighting use from day to day but is not a firm requirement.
- A lack of existing daylight and occupancy controls was preferred. The presence of automatic controls complicates data analysis and is a less interesting study since most existing systems do not have controls.
- Some availability of daylight is strongly preferred in at least part of the space under study. Daylight availability will allow quantification of energy savings by daylight harvesting controls. This criterion need not apply to all the studied space.
- Test facilities should allow for easy access by our team. Limited access by the project team will simply complicate work and could reduce project quality if for example the team is unable to gain access to download data on a timely basis.

These criteria mean that any selected facility would be reasonably representative of a large fraction of DoD facility space. The climate zone of the sites was not a primary selection criterion. We planned to estimate HVAC energy effects of the lighting retrofit, but did so through modeling, not direct measurement in a specific climate zone.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

We identified two DoD installations that have facilities suitable for the demonstration and agreed to participate in the project (Figure 4).



Figure 4. DoD Facilities Participating In This Project.

The main activity in these areas was typical office work. The demonstration minimally interacted with military operations. The main interaction with occupants was a short survey both before and after the retrofit to understand user satisfaction. Additionally, the office work was only disrupted during the retrofit itself. To the greatest extent possible, we scheduled the retrofits during periods of minimal occupancy to minimize this disruption.

Through site visits and plan review, the project team completed a compilation of the following characteristics of each demonstration site:

- Architecture
 - Building area
 - Floor plan; area of each space and orientation
 - Window-to-wall ratio
 - Window properties
 - Interior properties; surface reflectance, partition geometry
- Operation
 - Space type and tasks performed
 - Number of occupants
 - Schedule of occupancy
- Lighting
 - Lighting types, counts, and fixture power
 - Controls; photosensor, occupancy, manual switching, timeclock
 - Workplane illuminance

- HVAC
 - System type
 - Equipment age

4.1.1 Truax Field

Truax Field is an Air National Guard base located in Madison, WI and comprises facilities for the 115th Fighter Wing. The facility selected for the demonstration is Truax 510, a 39,784 square-foot office and warehouse building originally built in 1986 (Figure 5).



Figure 5. Satellite Imagery (a) South Façade (b) and Interior (c) of Truax 510.

As highlighted in Figure 6, we studied 3 spaces in Truax 510; 2 private offices and 1 open office.

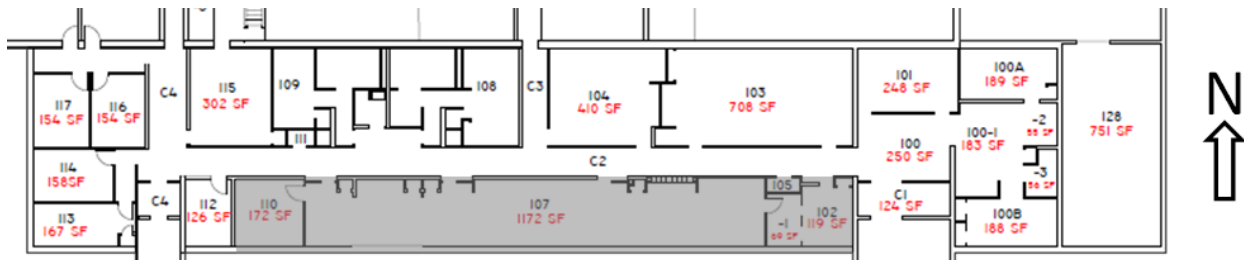


Figure 6. Floor Plan Highlighting Studied Area (in grey) of Truax 510.

The spaces were primarily occupied Monday thru Thursday from 6:00 am to 4:00 pm. Additionally, there was weekend occupancy from 8:00 am to 5:00 pm approximately once each month for training.

The lighting fixtures in the space are 2 ft × 4 ft lensed fluorescent troffers in a dropped ceiling. There was a mix of 2-lamp and 3-lamp T8 fixtures. Note the LPDs of each space in Table 2 range from a minimum of 1.11 W/ft² in the open office to a maximum of 1.50 W/ft² in one of the private offices. The area-weighted average LPD across all retrofit spaces was 1.18 W/ft². These estimates assume a ballast factor of 0.88. All lighting in the studied spaces was controlled by manual wall switches with no automatic occupancy controls.

All spaces had significant daylight availability, with no photosensor controls. Each space was on the south wall of the building with significant glazing area and a short perimeter depth from the windows.

The estimated window-to-wall ratio of the spaces was 40% and the depth of daylight penetration is about 12 feet at maximum.

Truax 510 was served by a variable air volume overhead air distribution system with cooling and heating produced by air-cooled chillers and atmospheric gas boilers, respectively. Table 2 summarizes the lighting installed in Truax 510.

Table 2. Truax 510 Lighting Summary

Room Number	Approximate Area (ft²)	Number of Light Fixtures	Installed Lighting Power Density (W/ft²)	Number of Occupants
107 Open Office	1,172	22	1.11	12
110 Private Office	172	4	1.31	2
102 Private Office	188	4	1.50	1
Total	1,532	30	1.18	15

4.1.2 Selfridge Air National Guard Base

Selfridge is a large Air National Guard base located northeast of Detroit in Harrison Township, MI, and is home of the 127th Wing of the Michigan Air National Guard.

We selected Selfridge 303 (Figure 7) and Selfridge 124/127 (Figure 8) for demonstration.



Figure 7. Satellite Imagery (a) South Façade (b) and Interior (c) of Selfridge 303.

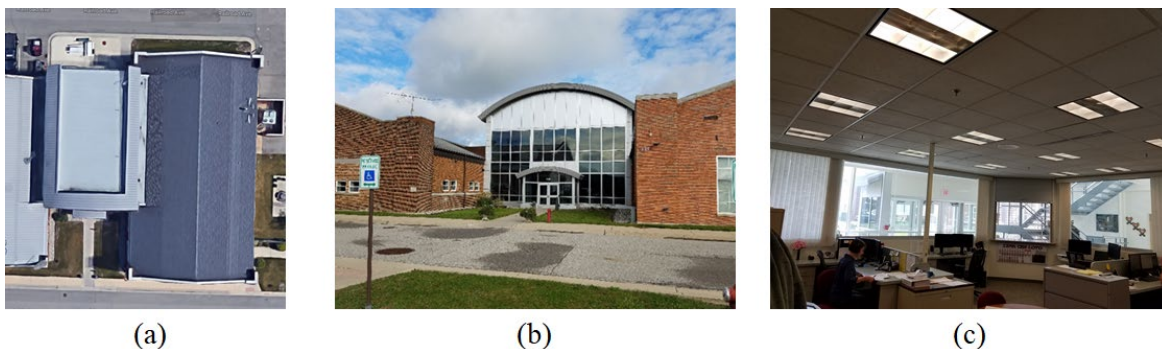


Figure 8. Satellite Imagery (a) South Façade (b) and Interior (c) of Selfridge 124/127.

Selfridge 303 was a brick structure built in the 1930s, and houses administrative functions including a finance group in the north wing of the first floor, the area selected for demonstration. The spaces we studied (Figure 9) included a significant open office area, 7 private offices, and one conference room.

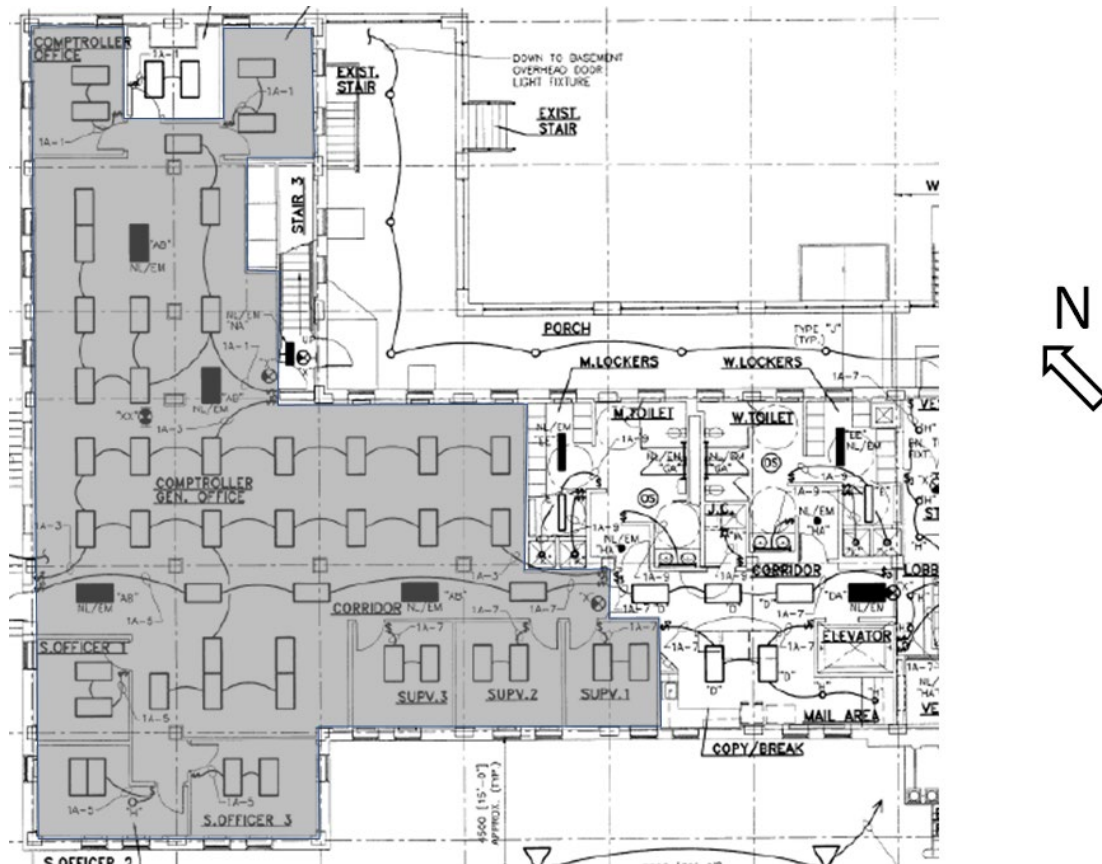


Figure 9. Floor Plan Highlighting Studied Area (In Grey) of Selfridge 303.

The spaces were primarily occupied Monday thru Friday from 7:00 am to 4:00 pm.

The lighting fixtures in the space were 2 ft × 4 ft lensed fluorescent troffers in a dropped ceiling. All fixtures to be retrofit were 3-lamp T8 fixtures. Note the LPDs of each space in Table 3 range from a minimum of 1.16 W/ft² in one of the private offices to a maximum of 2.43 W/ft² in one of the open offices. The area-weighted average LPD across all retrofit spaces was 1.63 W/ft². These estimates assume a ballast factor of 0.88. All lighting in the studied spaces was controlled by manual wall switches with no automatic occupancy controls.

All private offices and portions of the open office spaces had significant daylight availability, with no photosensor controls. These spaces had an estimated window-to-wall ratio of 24% and the depth of daylight penetration is about 15 feet at maximum.

Selfridge 303 was served by residential style split air conditioner units with condensing furnaces. Table 3 summarizes the lighting installed in Selfridge 303.

Table 3. Selfridge 303 Lighting Summary

Room Number	Approximate Area (ft ²)	Number of Light Fixtures	Installed Lighting Power Density (W/ft ²)	Number of Occupants
140	117	2	1.44	1
141	136	2	1.24	1
142	128	2	1.32	1
144	146	2	1.16	1
145	138	2	1.22	1
146	116	2	1.46	1
151	138	2	1.22	1
Conference 149	144	2	1.17	0
Office NW	410	11	2.27	5
Office SW	386	8	1.75	6
Office Central	313	9	2.43	6
Office E	186	3	1.36	2
Office S	206	4	1.64	4
Corridor NS	449	9	1.69	0
Corridor EW	357	5	1.18	0
Total	3,370	65	1.63	30

Building 124 was constructed in 2006 and acts as a connector between Building 127 and another older structure. Buildings 124 and 127 are attached structures that house base civil engineering functions. The studied spaces (Figure 10) included a large and a small open office area, 2 private offices, associated corridor spaces and one conference room.

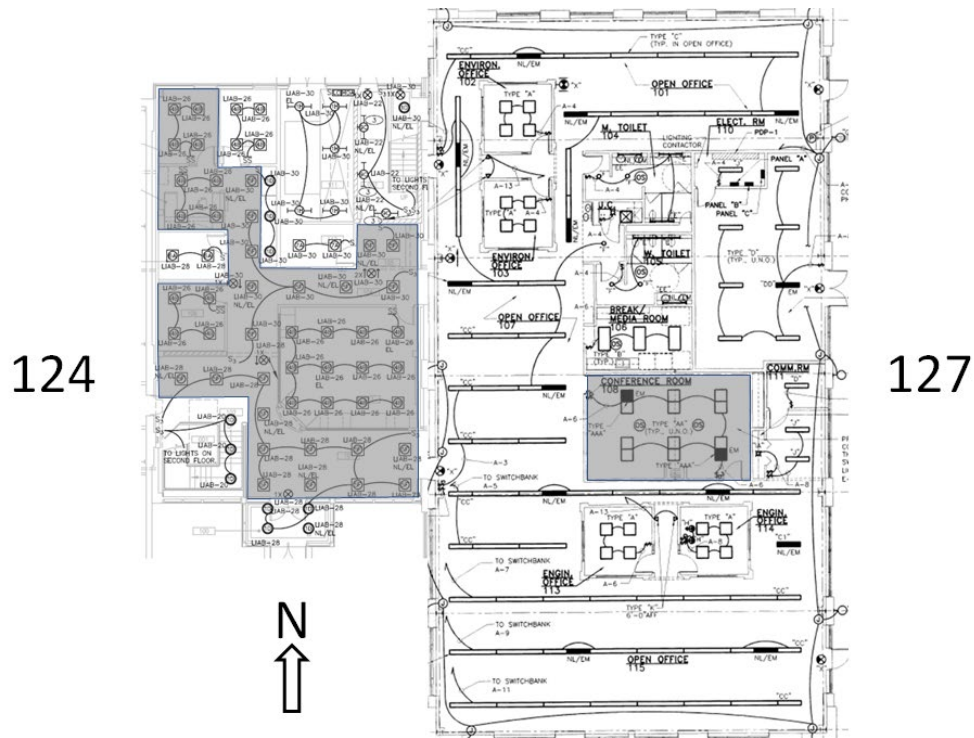


Figure 10. Floor Plan Highlighting Studied Area (In Grey) of Selfridge 124/127.

The building was primarily occupied Tuesday thru Friday from 6:00 am to 4:30 pm.

The lighting fixtures in the space were 2 ft × 2 ft lensed fluorescent troffers in a dropped ceiling. The retrofit fixtures were a mix of 2, 3 and 4-lamp T8 fixtures. Note the LPDs of each space in Table 4 range from a minimum of 1.32 W/ft² in the larger open office to a maximum of 2.21 W/ft² in the conference room. The area-weighted average LPD across all retrofit spaces was 1.6 W/ft². These estimates assume a ballast factor of 0.88. All lighting in the studied spaces were controlled by manual wall switches. A single automatic occupancy sensor controlled the north corridor space.

The south corridor and adjacent space in the large open office had significant daylight availability. However, no photosensor controls existed in any spaces to be retrofit. The south corridor had an estimated window-to-wall ratio of 100% and the depth of daylight penetration extends into the adjacent open office via a window in the internal, adjoining wall.

Selfridge 124/127 were served by a variable air volume overhead air distribution system with cooling and heating produced by air-cooled chillers and atmospheric gas boilers, respectively. Table 4 summarizes the lighting installed in Selfridge 124/127.

Table 4. Selfridge 124/127 Lighting Summary

Room Number	Approximate Area (ft²)	Number of Light Fixtures	Installed Lighting Power Density (W/ft²)	Number of Occupants
103	407	12	1.32	4
106	131	4	1.37	1
108	125	4	1.44	1
109	127	4	1.41	1
Corridor N	370	10	1.62	0
Corridor S	506	12	1.42	0
Conference B127	509	16	2.21	0
Total	2,175	62	1.54	7

Note that more information about the retrofit system is provided in the *DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS* section.

4.2 FACILITY/SITE CONDITIONS

There are no additional relevant facility or site conditions beyond those described in Section 4.1.

5.0 TEST DESIGN

This section describes the research design and testing procedure to address the performance objectives described in Section 4.0.

Fundamental Problem

LED lighting saves considerable energy as compared to conventional lighting technologies. Associated controls, such as occupancy sensing and photocontrol, can provide additional savings. However, these controls have historically been external to the lighting fixture, leading to overcomplicated installation and commissioning. Combining this with their historically high cost, these systems have not achieved high market penetration to date. This means that significant energy savings are not being realized. The demonstrated lighting system minimizes installation, commissioning and operational complexity by integrating lighting controls within each fixture and providing one-button commissioning. The continually decreasing cost of this system further enhances its value by improving the system's economics.

Demonstration Question

How much lighting energy can be saved by replacing existing lighting systems with the demonstrated lighting system? What are the associated system economics? How does the retrofit lighting system impact occupant satisfaction?

5.1 CONCEPTUAL TEST DESIGN

This section provides an overview of the test design we used to evaluate the performance objectives.

5.1.1 Hypothesis

The demonstrated lighting system will save significant lighting energy with improved occupant satisfaction compared to existing lighting systems.

5.1.2 Independent Variable

Existing building lighting systems retrofit with the demonstrated lighting system.

5.1.3 Dependent Variables

All variables used in meeting performance objectives including:

- Monitored electricity use of lighting system during pre- and post-retrofit
- Area of retrofit spaces
- Measured maximum power used by lighting system during pre- and post-retrofit
- Measured illuminance during pre and post-retrofit
- Data on installed cost including equipment and labor costs, and operating costs

- User survey results
- Installer survey results

5.1.4 Controlled Variables

- Number of DoD buildings for similar demonstration building types
- Electricity rates
- Discount rate
- Local weather data
- Building occupancy schedule

5.1.5 Test Design

The approach that was used to test the hypothesis in this demonstration is sequential testing, and the demonstration was conducted at three facilities in two DoD installations (Truax Field Air National Guard base and Selfridge Air National Guard base.) The comparisons were between the existing lighting systems and the post-retrofit new lighting systems, focusing on the retrofit area lighting energy use reduction, occupant comfort (indicated by the results of the occupant survey) and the retrofit costs and simple paybacks/life-cycle cost analysis. All dependent and independent variable data used to evaluate the quantitative performance objectives were collected during the demonstration period. These data included electricity use of existing and the new lighting systems, space illuminance, and costs for equipment and hiring contractors to perform the new lighting system retrofit and commissioning. Local weather and solar data were also be collected for the normalization of pre- and post-retrofit data for fair comparison. Approximately 6 months of pre- and post-retrofit data were collected to cover the range of typical weather and lighting condition. See *APPENDIX D: EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES* for more information on the period lengths. Qualitative performance objective evaluation was accomplished through occupant and contractor/installer interviews.

5.1.6 Test Phases

This project had four main test phases: pre-retrofit phase, retrofit phase, post-retrofit phase, and data analysis phase.

The pre-retrofit phase was mainly to collect data on lighting energy use and light levels at the existing buildings before the lighting retrofit.

- The first step was pretest preparation, which included facility data/document collection, lighting energy and light level monitoring system design, monitoring instrument procurement and calibration (if needed,) and site visit coordination with installation managers. Facility basic information and engineering drawings (architectural and electrical drawings were the most relevant in this demonstration) were collected and reviewed, and the most suitable building and space were selected for lighting retrofit. Energy and light level monitoring system design were based on existing lighting design and layout of the selected spaces.

- The second step was site visits to these demonstration sites to conduct monitoring instrument installation as well as illuminance measurements in the retrofit spaces at the current conditions. For power monitoring instrument installation, we hired local certified electrical contractors to help us connect high-voltage wires as necessary. Data generated was checked onsite to make sure we could collect and monitor data remotely via a cellular connection. Beside continuous light level measurements at multiple representative locations, a one-time light level measurement throughout the retrofitted spaces was conducted during the visits to record existing lighting conditions. We additionally measured illuminance and power of the pre-retrofit lighting system to establish its performance curve.
- The final step included pre-retrofit data collection and monitoring. During this phase, pre-retrofit data was continuously collected and monitored periodically. In the case of missing data or observed questionable data, we contacted local facility staff to investigate the situation. A short occupant survey was administered to gather data pertaining to the occupant satisfaction with the pre-retrofit lighting system.

The retrofit phase included lighting retrofit design, lighting retrofit contractor selection, lighting retrofit and commissioning, installer interview, and a thorough light level field measurement at the three demonstration sites.

- The first step was lighting retrofit design. This step involved working with the demonstrated lighting system manufacturer to develop engineer drawings and specifications. These documents will be presented to each facility's staff for comment and approval.
- The second step was selecting the contractor to perform the lighting retrofit. This step involved first sending the design documents to several qualified local contractors at each base. A list of approved contractors was gathered from each base's facility staff. We organized a walkthrough of each facility with interested contractors and conducted a Request for Information period during which questions were answered and shared with all interested contractors. At the end of this period, bids were acquired from multiple contractors, and a selection of the winning bid was made.
- The third step was conducting the retrofit and associated commissioning. The lighting retrofits were implemented by the selected contractors at each demonstration sites, and the lighting systems were fully commissioned based on manufacturer requirements to make sure all functions work properly.
- The fourth step was a brief installer and facility staff interview. The lighting installers and facility were interviewed to evaluate their experiences in installing and commission the lighting systems.
- At the end of the retrofit phase, one-time post-retrofit light level field measurements was conducted by the Slipstream staff throughout the retrofitted spaces.

In the post-retrofit phase, post-retrofit lighting power and space illuminance data was continuously collected and monitored. In the case of missing data or observed questionable data, we contacted local facility POC immediately to investigate the situation. Electronic surveys were conducted to assess the overall user experience and satisfaction level of the retrofit lighting system. Monitoring equipment was removed from the facility once enough post-retrofit data was collected.

In the data analysis phase, pre- and post-retrofit data was reviewed and cleansed, followed by data normalization, before final performance metrics was calculated/evaluated based on data collected.

- The first step was data cleansing. Pre- and post-retrofit data was first be reviewed (automatically using software and manually by visual inspection) to detect incomplete, incorrect, or inaccurate data, and then cleansed by correcting (or removing) corrupt or inaccurate data from dataset. This was to make sure data used in analysis were all valid.
- The second step was data normalization. Pre- and post-retrofit data were normalized to a typical annual period using local weather and solar intensity information. Datasets were also sub-categorized by normal weekday (normal occupancy), low weekday (low occupancy), weekend and holiday (almost no occupancy), and training (high occupancy) during the normalization process. The pre- and post-retrofit data were extrapolated to annual performance for the same year.
- The final step was calculation of performance metrics for lighting electric energy use reduction, lighting power density reduction, GHG reduction, and reduction of HVAC energy use (based on simulation model outputs,) the annual performance differences after normalization between pre- and post-retrofit equal savings. Light level changes were compared based on two one-time comprehensive field light level measurements. Simple payback and other cost effectiveness metrics were calculated using NIST Building Life Cycle Cost Analysis method and based on actual costs of lighting fixtures and installation and projected annual lighting and HVAC energy savings. Qualitative occupant satisfaction and installer experience evaluation were based on electronic surveys and interviews, respectively.

5.2 BASELINE CHARACTERIZATION

5.2.1 Reference Conditions

The following data were collected to assess each performance objective during the baseline period.

- Electric energy consumption and peak demand reduction:
 - General: typical occupied period, area served
 - Existing lighting system characteristics: lighting type, number of fixtures, fixture power, color temperature, delamping or burned out lamps, existing lighting system controls and associated settings (i.e. time out period and minimums),
 - Energy: electrical power at the circuit panel, and electrical current at each switched circuit
 - Normalization: general horizontal irradiance from nearby weather stations, continuous illuminance in at least one representative location in each switched circuit
- Greenhouse gas emission reduction: No data was acquired, but rather simple factors were applied to energy savings estimates.
- Light levels: space type, typical occupant tasks, occupant demographics, point-in-time illuminance at locations corresponding to IES methodology, continuous illuminance in at least one representative location in each switched circuit
- Cost effectiveness: Lamp replacement schedule
- Reduce HVAC energy consumption: HVAC system type, building area and building type

- Occupant satisfaction: number of occupants, occupant survey results
- Ease of installation and commissioning: No data was acquired for existing lighting system.

5.2.2 Baseline Collection Period

We collected baseline data for approximately 6 months. This length allowed us to establish typical occupancy patterns. It further captured seasonal variations in lighting usage due to shorter and longer days and corresponding variability in available daylight.

5.2.3 Existing Baseline Data

This project did not utilize any existing baseline data.

5.2.4 Baseline Estimation

We used the following approaches to calculate the baseline performance for each subsequent objective.

Electric energy consumption reduction

To quantify electric energy savings, we first calculated the baseline or pre-retrofit lighting system's annual electricity consumption. Figure 11 is a flowchart of the steps involved in calculating the baseline electric energy consumption.

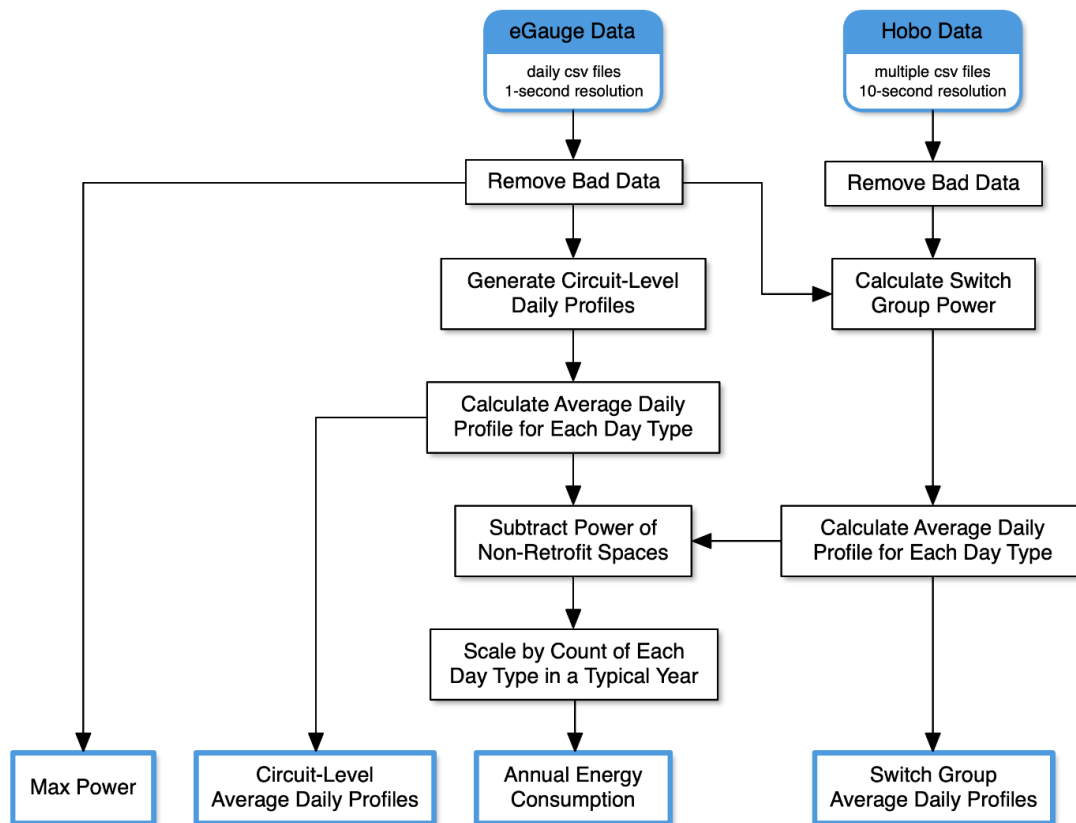


Figure 11. Flow Chart of Baseline Electric Energy Consumption Calculation.

There are two data sources for this calculation (described in more detail in the *Data Collection Equipment* section). eGauge data included lighting true power, power factor and voltage of the lighting circuits associated with the retrofit. eGauge data is recorded on a 1 second interval throughout the pre- and post-retrofit periods. However, to save on computational intensity, we only used data on a 10 second interval. Hobo data included lighting current of individual lighting switch groups associated with the affected lighting circuits. A lighting switch group was defined as one or more lights that are controlled by a manual light switch. Hobo data was recorded on a 10 second interval throughout the pre- and post-retrofit periods.

The eGauges monitor true power, while the Hobos do not. In order to calculate the true power associated with the Hobo on each lighting switch group, we started with the Hobo's recorded current. We then found the voltage and power factor from the eGauge serving the switch group's lighting circuit. We then used this data to convert electrical current to electrical power:

$$P_{sg,i} = I_{sg,i} \cdot V_{lc,i} \cdot PF_{lc,i}$$

Where:

$P_{sg,i}$ is the calculated power at a given switch group at time interval i in W,

$I_{sg,i}$ is the measured current at a given switch group at time interval i in A,

$V_{lc,i}$ is the voltage of the associated lighting circuit at interval i in V, and

$PF_{lc,i}$ is the power factor of the associated lighting circuit at interval i .

The next step was to create hourly power profiles for each switch group and lighting circuit. These profiles contained the average power for each of the 24 hours in a typical day. To generate the hourly averages, data were binned into each hour of the day for each day type (discussed subsequently) and the hourly average was assumed to be the mean of all these values.

$$P_{sg,j} = \frac{\sum_{i=1}^n P_{sg,i}}{n}$$

$$P_{lc,j} = \frac{\sum_{i=1}^n P_{lc,i}}{n}$$

Where:

$P_{sg,j}$ is the calculated lighting power for a given switch group at hour j in W,

$P_{lc,j}$ is the calculated lighting power for a given lighting circuit at hour j in W,

$P_{lc,i}$ is the monitored power at a given lighting circuit at time interval i in W, and

n is the number of data points for hour j .

We considered 4 day types; normal occupancy weekdays (NWD), low occupancy weekdays (LWD), weekends and holidays (WEH), and training days (TRN). Note that the LWD were Mondays for Selfridge ANGB and Fridays for Truax ANGB.

Table 5 summarizes the training days at each base during the pre and post-retrofit periods.

Table 5. Training Days at Each Base During the Pre- and Post-retrofit Periods.

Site	2018											2019					
	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Selfridge	3, 4, 5, 6	3, 4	7, 8	3, 4, 5, 6	9, 10	28, 29			13, 14	3, 4	1, 2	5, 6	2, 3	9, 10	6, 7	4, 5	6, 7, 8, 9
Truax	1, 2, 3, 4	3, 4	7, 8	5, 6	2, 3		18, 19	8, 9	13, 14	3, 4	1, 2	5, 6	2, 3	2, 3	5, 6	4, 5	1, 2

Not all lighting on any given lighting circuit were retrofit as part of this demonstration. Unfortunately, we did not monitor the pre-retrofit lighting power for switch groups that were not planned to be retrofit but were on affected circuits. Upon realizing that we would need this data, we installed Hobos to monitor the post-retrofit lighting power for these switch groups. We subsequently assumed that the lighting consumption in these un-retrofit spaces was the same for the pre-retrofit and post-retrofit periods. This as a reasonable assumption since the lighting and space usage did not change appreciably in these spaces between periods.

The next step was therefore to develop circuit level daily profiles that represented only the retrofit spaces. The circuit level daily profiles were adjusted by subtracting the associated un-retrofit switch group average profiles.

$$P_{lc,retrofit,j} = P_{lc,j} - \sum_{k=1}^m P_{sg,unretrofit,k,j}$$

Where:

$P_{lc,retrofit,j}$ is the calculated lighting power for the retrofit portion of a lighting circuit at hour j in W,

$P_{sg,unretrofit,k,j}$ is the calculated lighting power for an un-retrofit switch group k at hour j in W, and

m is the number of un-retrofit switch groups on a given lighting circuit.

The final step was to calculate the pre-retrofit annual electricity consumption of the baseline lighting system according to:

$$Q_{pre} = \left(n_{NWD} \sum_{j=1}^{24} P_{lc,retrofit,j,NWD} + n_{LWD} \sum_{j=1}^{24} P_{lc,retrofit,j,LWD} + n_{WEH} \sum_{j=1}^{24} P_{lc,retrofit,j,WEH} + n_{TRN} \sum_{j=1}^{24} P_{lc,retrofit,j,TRN} \right) \left(\frac{1 \text{ Wh}}{1000 \text{ kWh}} \right) \left(\frac{1}{A_{retrofit}} \right)$$

Where:

Q_{pre} is the pre-retrofit lighting system's annual electricity consumption in kWh/ft²,
 n_{NWD} is the number of normal occupancy weekdays in a typical year,
 $P_{lc,retrofit,j,NWD}$ is the calculated lighting power for the retrofit portion of a lighting circuit at hour j for the normal occupancy weekday in W,
 n_{LWD} is the number of low occupancy weekdays in a typical year,
 $P_{lc,retrofit,j,LWD}$ is the calculated lighting power for the retrofit portion of a lighting circuit at hour j for the low occupancy weekday in W,
 n_{WEH} is the number of weekends and holidays in a typical year,
 $P_{lc,retrofit,j,WEH}$ is the calculated lighting power for the retrofit portion of a lighting circuit at hour j for the weekend and holidays in W,
 n_{TRN} is the number of training days in a typical year,
 $P_{lc,retrofit,j,TRN}$ is the calculated lighting power for the retrofit portion of a lighting circuit at hour j for the training days in W, and
 $A_{retrofit}$ the retrofit area of a given lighting circuit in ft².

Peak demand reduction

The measured peak demand for each space was calculated by:

$$D_{pre} = \frac{\max(P_{pre,retrofit})}{A_{retrofit}}$$

Where:

D_{pre} is the measured pre-retrofit peak demand in W/ft²,
 $P_{pre,retrofit}$ is the measured lighting power dataset for the pre-retrofit period in W,
 $A_{retrofit}$ the retrofit area in ft².

Greenhouse gas emission reduction

The greenhouse gas emissions for each space was calculated by:

$$GHG_{pre} = f_{GHG} Q_{pre}$$

Where:

Q_{pre} is the pre-retrofit lighting system's annual electricity consumption in kWh/ft²,
 GHG_{pre} is the greenhouse gas emissions of a given space in metric tons of CO₂ equivalent/ft², and
 f_{GHG} is a conversion factor in metric tons of CO₂ equivalent/kWh [eGRID 2016].

Note that the greenhouse gas conversion factor is representative of a given region's mix of power generation. Each region encompasses multiple states and is thus not specific to the utilities serving each demonstration site.

Light levels

We collected data for calculating average illuminance through manual measurements. To minimize disruptions to occupants, we scheduled these measurements during periods of low occupancy. We worked with facility staff to identify these periods and notify facility staff and occupants of potential disruptions.

One method for calculating average illuminance would be to take readings on a 2' × 2' grid throughout the entire space and then average the measurements. However, this method is time-intensive, requiring many readings for even relatively small spaces. We therefore followed the IES Lighting Handbook's procedure for calculating average illuminance. [DiLaura 2011] This procedure is more focused, defining key positions for illuminance readings based on a given lighting system's luminaire configuration type. The location of these key positions was recorded in the pre-retrofit period and duplicated in the post-retrofit period. Care was taken to eliminate any daylight from these measurements. We drew any blinds that were present. If significant daylight was still present, we took a reading at a given location with the lights on followed immediately by a reading with the lights off. The difference between these readings was the electric-only illuminance and was used for calculating the average illuminance. Figure 12 shows one luminaire configuration type: Regular Area with Single Row of Continuous Luminaires.

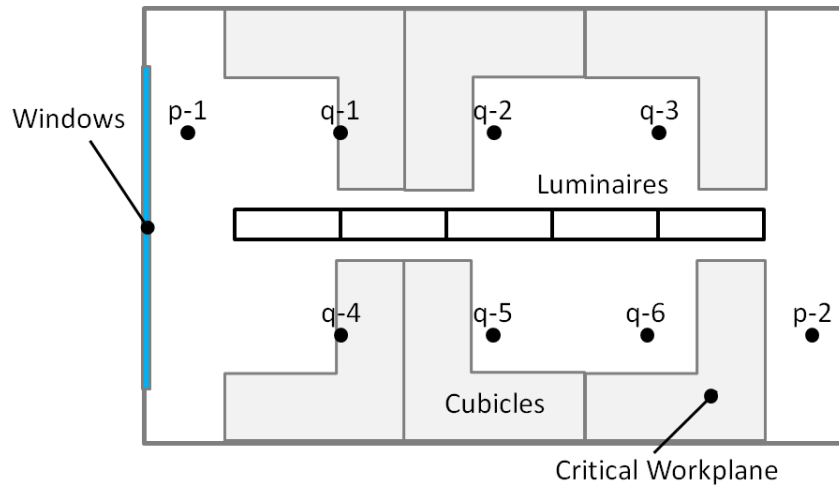


Figure 12. Light Meter Measurement Points for Regular Area with Single Row of Continuous Luminaires.

Note that the measurement points (i.e. p-1, p-2, q-1...) were specific to the luminaire configuration type, and the number of total points was greatly reduced when compared to a regular a 2' × 2' grid. The average illuminance, E_{ave} , for this specific luminaire configuration was given by:

$$E_{pre} = \frac{Q(N - 1) + P}{N}$$

Where:

E_{pre} is the average illuminance in a given space in fc,

N is the number of luminaires in the space,

Q is the average of the illuminance measurements taken at the q-labeled points in fc, and
 P is the average of the illuminance measurements taken at the p-labeled points in fc.

Other luminaire configurations have different key measurement points and different equations for finding the average illuminance. We calculated the percent difference between the pre-retrofit average illuminance and the UFC recommended illuminance via:

$$E_{\%,pre} = \frac{|E_{pre} - E_{UFC}|}{E_{UFC}}$$

Where:

E_{UFC} is the UFC average illuminance recommendation of a given space in fc, and
 $E_{\%,pre}$ is the lighting system's pre-retrofit average illuminance percent difference with respect to UFC recommendations in %.

Reduce HVAC energy consumption

We built representative building energy models for each building using DOE2.2 as the modeling engine. We will use eQuest (Figure 13) as the graphical user interface.

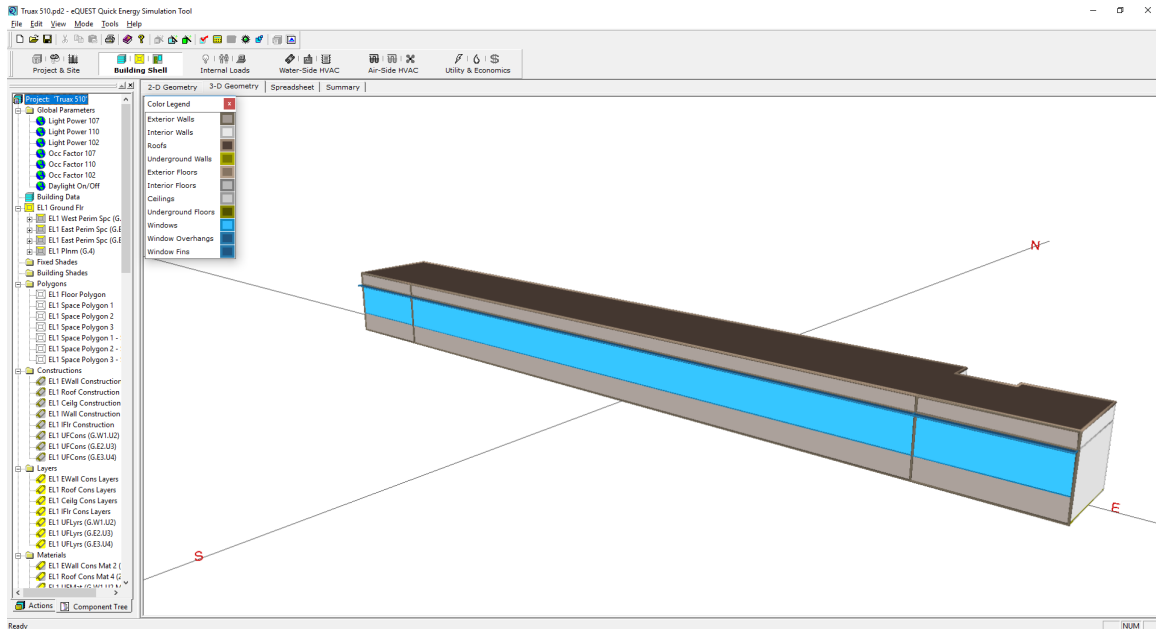


Figure 13. eQuest Model of Simplified Energy Model for Truax 510.

The energy models approximated the geometry of the retrofit portion of the building at each retrofit location and used default modeling inputs for the given building type where site specific inputs are not known. We used measured lighting power for the pre- and post-retrofit periods to approximate the lighting load in the studied spaces. We updated each model from data gathered on-site with inputs regarding envelope properties, occupancy schedules, HVAC system types and typical weather representative of each site. The models predicted the pre-retrofit annual HVAC electricity and natural gas consumption of each building. The total pre-retrofit annual HVAC energy consumption were then calculated according to:

$$Q_{pre,HVAC} = Q_{pre,HVAC,elec} \left(\frac{3.412 \text{ kBTU}}{1 \text{ kWh}} \right) + Q_{pre,HVAC,natgas} \left(\frac{100 \text{ kBTU}}{1 \text{ therm}} \right)$$

Where:

$Q_{pre,HVAC}$ is the pre-retrofit annual HVAC energy consumption in kBTU/ft²,

$Q_{pre,HVAC,elec}$ is the pre-retrofit annual HVAC electricity consumption in kWh/ft², and

$Q_{pre,HVAC,therm}$ is the pre-retrofit annual HVAC natural gas consumption in therm/ft².

The impact of reduced lighting load HVAC system performance is highly dependent on building type, HVAC system type and local climate. The demonstration sites were homogenous across these categories. In order to understand the HVAC impact across a range of DoD applications, we undertook additional modeling. This modeling utilized the Department of Energy commercial reference building models [U.S Department of Energy 2011] to model the HVAC impact on various building types in each of the 17 U.S climate zones. We used the large, medium and small office prototype models, since the building type and range of HVAC system types were the most applicable to this demonstration project. We utilized the ANSI/ASHRAE/IES Standard 90.1-2004 baseline versions, as they were most representative of an existing building. We then substituted the pre- and post-retrofit lighting schedules developed for the site-specific modeling. HVAC energy impacts were calculated using the same methodology as the pre-retrofit period.

Occupant satisfaction

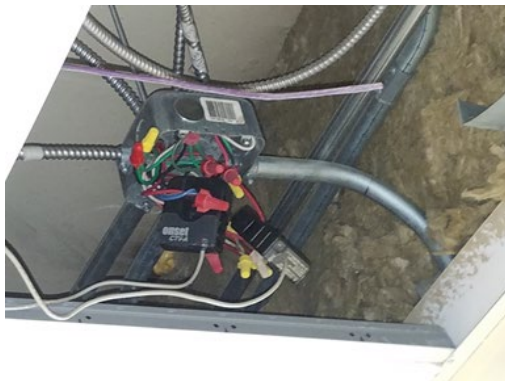
For each survey question, we calculated the average Likert scale score.

5.2.5 Data Collection Equipment

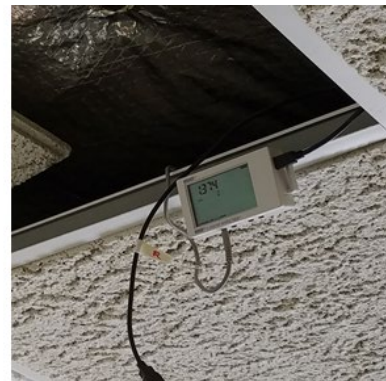
The following monitoring equipment was used for this project.

Electrical Current for Each Lighting Switch Group

We monitored electrical current for each lighting switch group through continuous measurements using Onset's CTV-A CTs and logged on Onset's Hobo UX120-006M 4 channel data loggers (Figure 14).



(a)



(b)

Figure 14. Onset's CTV-A CTs (a) and Onset's Hobo UX120-006M 4 Channel Data Logger (b).

Electrical Power for Each Lighting Circuit

We monitored electrical power for each lighting circuit through continuous measurements using an eGauge power meter and associated CTs (Figure 15). The eGauge meter sampled line voltage via direct connections and current flow via CTs at a rate of about 4 kHz, with the integrated product representing real electric power. CTs were selected to match the capacity of each circuit to maximize accuracy while allowing for near-full loading of each circuit.

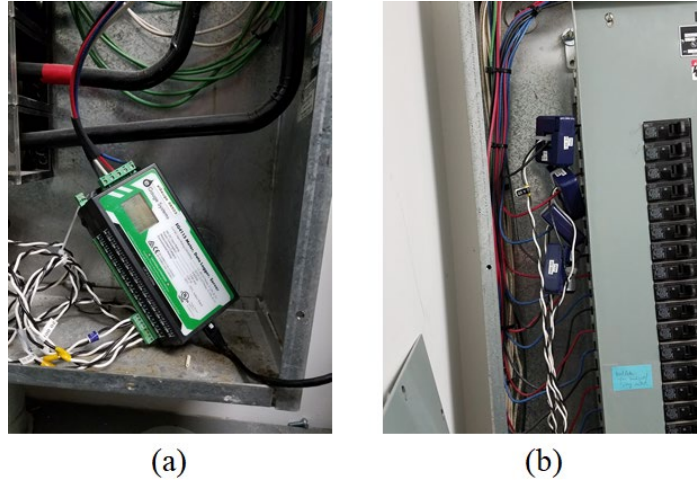


Figure 15. eGauge (a) and Associated CTs (b).

Average Illuminance in Each Space

We measured average illuminance in each space through one-time measurements using an existing Extech EA30 light meter (Figure 16).



Figure 16. Extech EA30 Light Meter.

Illuminance at Key Location

We monitored illuminance at a minimum of one key location in each space through continuous measurements using LI-COR's LI-210R photometric sensors. These measurements were amplified via EME System's Universal Transconductance Amplifier and logged on Onset's Hobo UX120-006M 4 channel data loggers. We used a mix of existing and new photometric sensors.

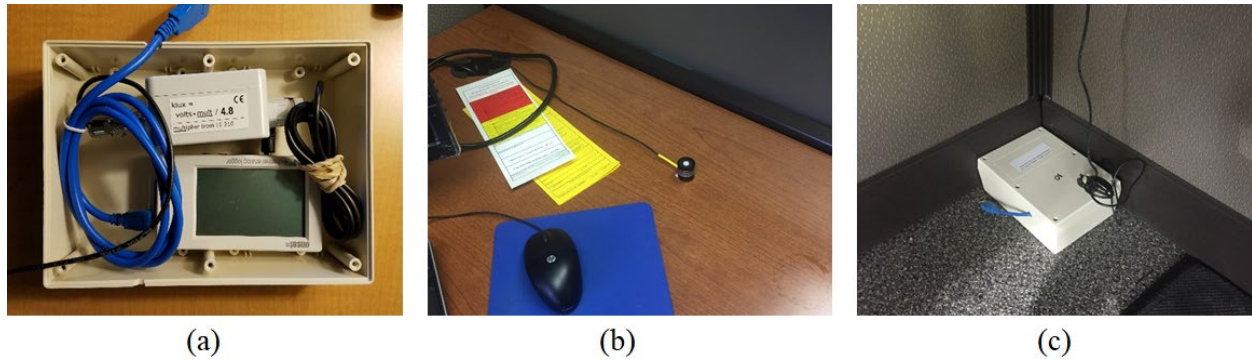


Figure 17. Enclosure with EME System's Universal Transconductance Amplifier and Onset's Hobo UX120-006M 4 Channel Data Logger (a) Installed LI-COR's LI-210R on Desktop (b) and Installed Enclosure Under Desk (c).

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 System Design

Cree SmartCast was the demonstrated lighting system for this project. Table 6 summarizes the quantity of each lighting system component deployed at each site.

Table 6. Quantity of Each Lighting System Component Deployed At Each Site

Equipment	Truax 510	Selfridge 124/127	Selfridge 303
2 ft × 2 ft Troffer	30	62	0
2 ft × 4 ft Troffer	0	0	65
Dimmer Switch	10	13	15
Configuration Tool	1	1	1

At Truax 510, it is important to note that the new 2 ft × 2 ft fixtures are replacing existing 2 ft × 4 ft fixtures. New ceiling tiles that were like the existing ceiling tiles were installed in the created gap.

The fixtures and switches communicated wirelessly to form a networked system. Occupants may manually turn on and off the lighting at the switches, as well as continuously adjust light levels up to the tuned level. Fixture-integrated occupancy sensors and associated controls turn off lights automatically during periods of no occupancy. Fixture-integrated photosensors and associated controls continuously dim lights during periods of sufficient daylight. The configuration tool was used during commissioning to form switch and occupancy groups, as well as adjust other system settings from their defaults.

Photometric analysis of each space was undertaken to quantify the average illuminance of the retrofit lighting system at full power. This analysis then identified the extent to which each space's lighting was tuned to bring it into agreement with UFC illuminance recommendations.

Photometric analysis of each space further quantified the average-to-minimum illuminance ratio between the pre- and post-retrofit lighting systems. We attempted to design a lighting system that agreed with UFC recommendations. However, since we did not have control of the fixture spacing, this was not always possible. In this situation, we designed a system that improves upon the existing system's average-to-minimum illuminance ratio.

For private offices, there was one switch per space. For conference rooms, we designed a switching approach that worked with the space's audio-visual equipment needs. This entailed one switch for the fixtures immediately adjacent to the screen, and another for the rest of the space's fixtures. For open offices, we worked with facility staff to design the best switching approach based on cubicle arrangements and occupant traffic. This entailed switches at entrances/exits controlling fixtures over grouped cubicles.

Existing fixtures with onboard emergency batteries were replaced with fixtures with similar capabilities.

The color temperature of all retrofit fixtures was 4000 K, in agreement with UFC recommendations.

The occupancy controls were set to vacancy mode in both open and private offices, as well as conference rooms. This means that an occupant needs to manually turn the lights on, but the lights shut off automatically. The occupancy controls in corridor spaces were left in their default auto-on setting. The unoccupied level for occupancy controls was left at its default value of 0%. The timeout period for occupancy controls were left at the system default of 20 minutes. Each switch group were controlled as an occupancy group.

The photosensor controls continuously dimmed the light levels based on the amount of available daylight. The minimum daylight level was left at its default value of 5%. Note that this is a percentage of the tuned, not full, power.

5.3.2 Components of the System

Troffers

Table 7 summarizes the characteristics of the troffers used in the retrofits.

Table 7. Troffer Characteristics

Characteristic	ZR22 Troffer	ZR24 Troffer
Dimensions	2 ft × 2 ft	2 ft × 4 ft
Initial Delivered Lumens	3,250 lumens	4,000 lumens
Input Power	25 watts	30 watts
Efficacy	130 lumens/watt	133 lumens/watt
Nominal Power Factor	0.9	0.9
Input Voltage	120-277 V, 60 Hz	120-277 V, 60 Hz
Operating Temperature Range	32-95 °F	32-95 °F
Suitable for Damp Conditions	Yes	Yes
Total Harmonic Distortion	<20%	<20%
Continuous Dimming Range	5-100% of full power	5-100% of full power
Color Rendering Index	80+	80+
Correlated Color Temperature	4000 K (3500 K available)	4000 K (3500 K available)
Integrated Occupancy and Photosensors	Yes	Yes
Wireless Communication	2.4 GHz, AES 128-bit encryption	2.4 GHz, AES 128-bit encryption
Occupancy Sensor Type	Passive-Infrared	Passive-Infrared
Occupancy Sensor Coverage	~100 ft² at 10 ft mounting height	~100 ft² at 10 ft mounting height
Fixture Mounting Height	<12 ft	<12 ft
Limited Warranty	Luminaire: 10 year Emergency Backup Battery: 1 year (if applicable)	Luminaire: 10 year Emergency Backup Battery: 1 year (if applicable)
Design Lights Consortium Qualified	Yes	Yes

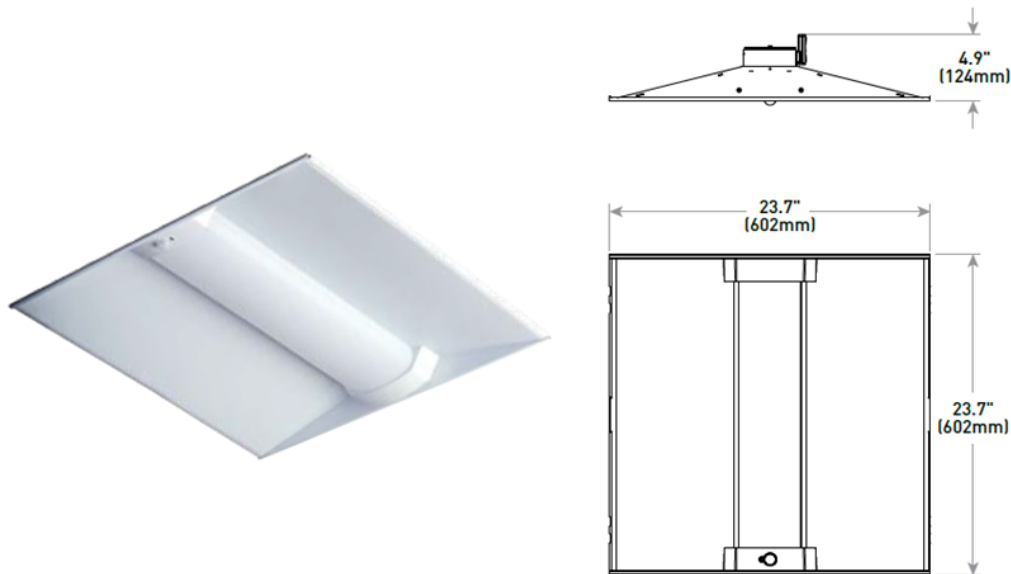


Figure 18. ZR22 LED Recessed Troffer

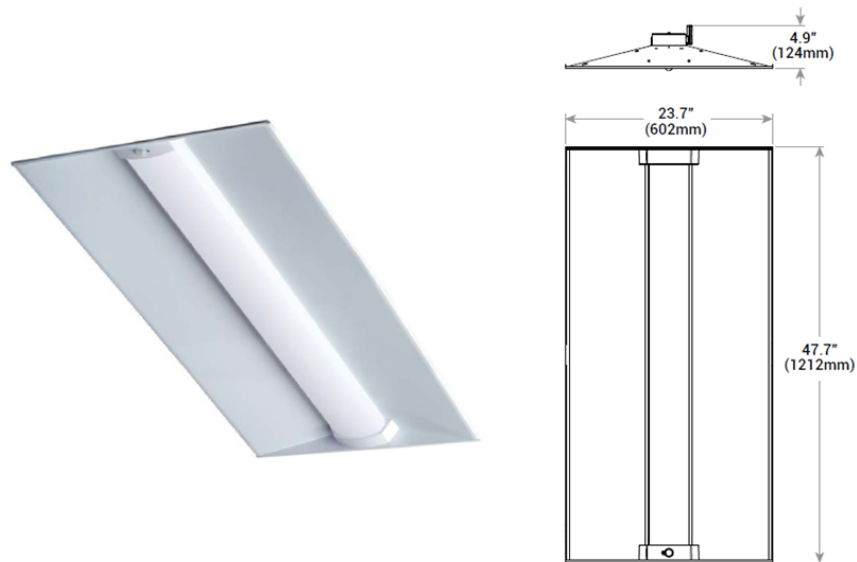


Figure 19. ZR24 LED Recessed Troffer.

Wireless Dimmer Switch

The wireless dimmer switch (Figure 20) provides manual control of associated lighting fixtures. This control includes on/off and continuous dimming over the range of fixture power. It has an input power of 0.7 W at 120 V and 1 W at 277 V. It has an input voltage of 120 – 277 V. It comes with a limited warranty of 5 years and is usable in damp conditions.

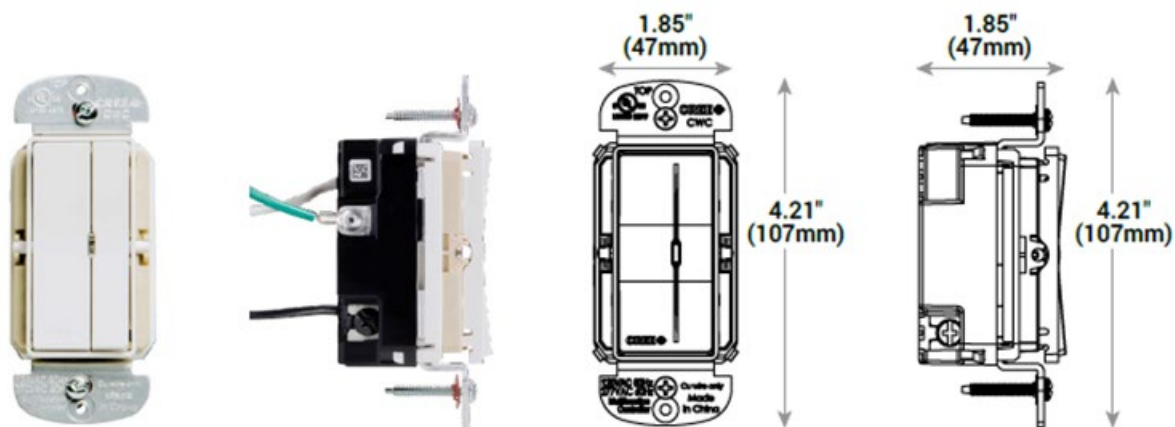


Figure 20. Wireless Dimmer Switch.

Configuration Tool

The configuration tool (Figure 21) is used during commissioning of the demonstrated lighting system. It is used to start the OneButton setup, as well as adjust other system settings from their default values. It is battery powered and comes with a 5-year limited warranty.

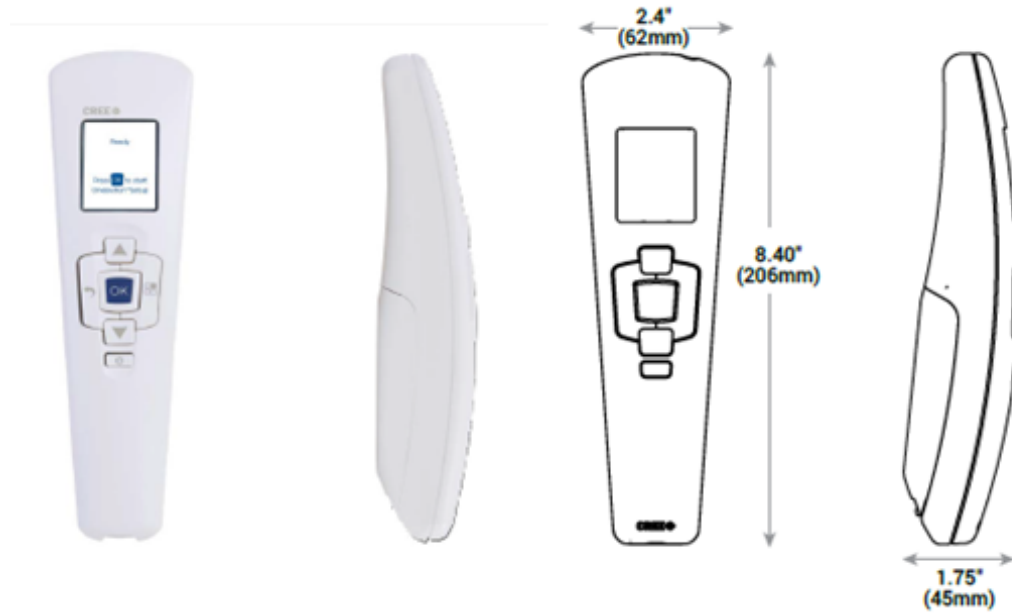


Figure 21. Configuration Tool.

5.3.3 System Depiction

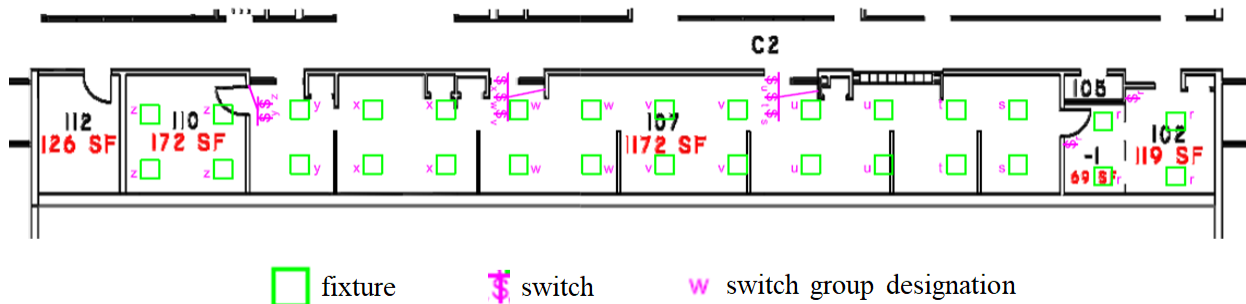


Figure 22. Lighting Plans for Retrofit at Truax 510.

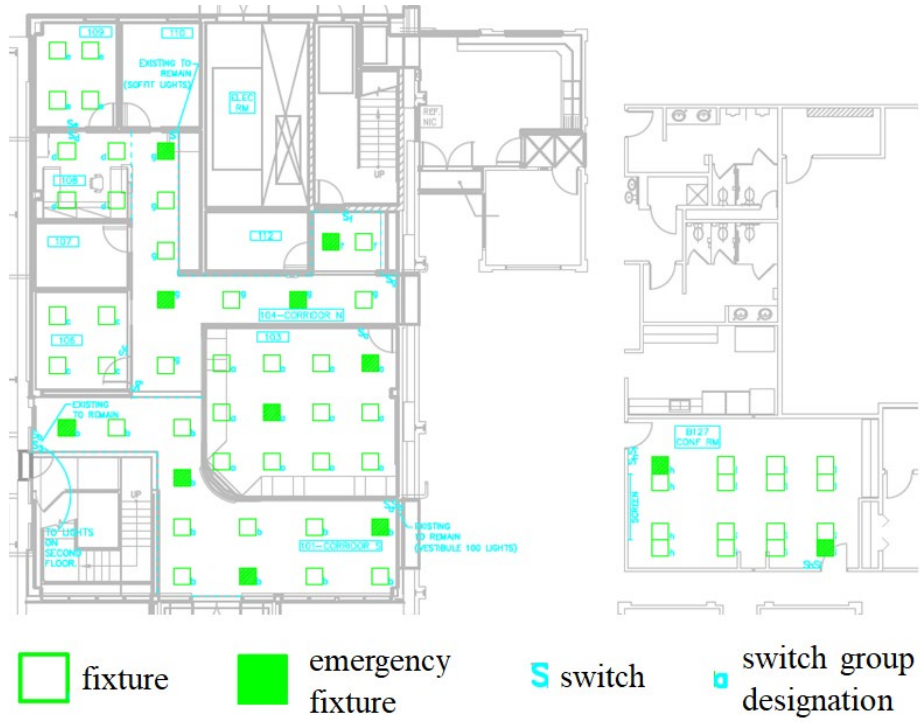


Figure 23. Lighting Plans for Retrofit at Selfridge 124/127.

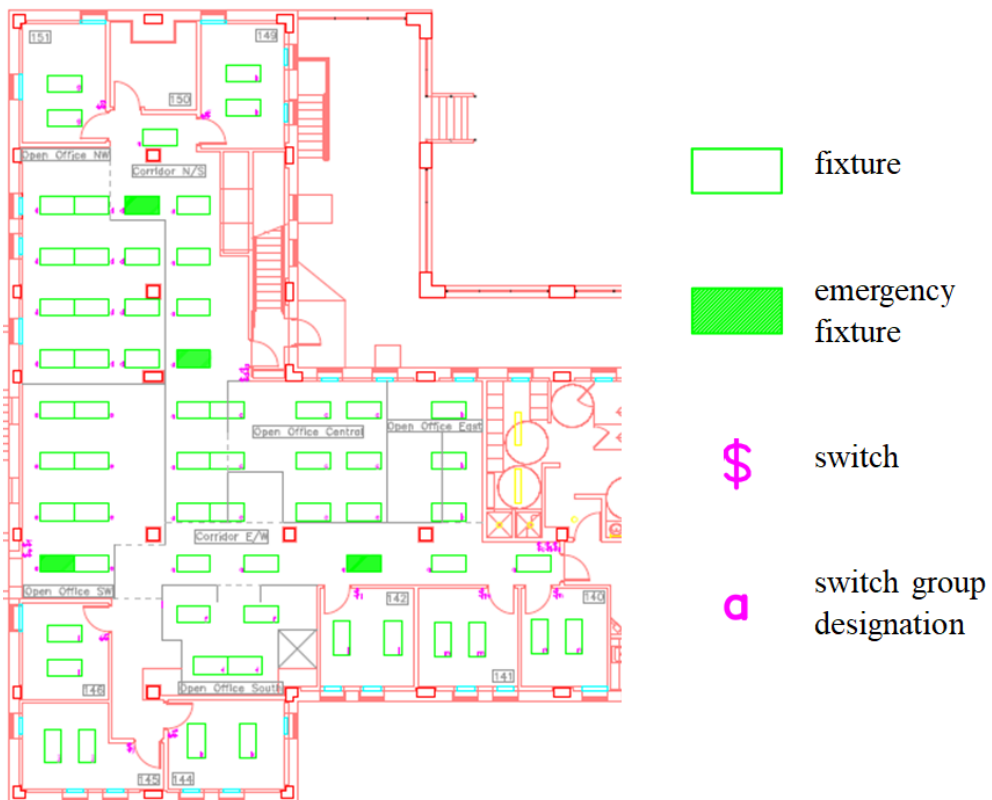


Figure 24. Lighting Plans for Retrofit at Selfridge 303.

5.3.4 System Integration

The demonstrated lighting system replaced the existing lighting system in each space. Existing fixtures were replaced one-for-one with new lighting fixtures. Existing line voltage switches were replaced with wireless switches per the new design's switching arrangement.

The primary failure mode is loss of power. In the event of loss of power, emergency lighting is required to provide enough light for occupant egress. Existing fixtures with emergency battery backup were replaced with new fixtures with emergency battery backup. Other existing emergency lighting remained in its existing condition. These systems provided adequate egress lighting in the event of loss of power.

A secondary failure mode is loss of wireless communication. In the event of loss of wireless communication, lighting fixtures would turn on to the maximum power and illumination levels. Any occupancy, vacancy, daylighting, or task tuning controls would be disabled. Wireless wall switches and associated manual off control would also be disabled. When wireless communication is restored, the lighting system would resume normal operation having maintained the system set up and configuration.

5.4 OPERATIONAL TESTING

5.4.1 Operational Testing of Cost and Performance

The commissioning process for the installed lighting systems complied with the requirements of ANSI/ASHRAE/IES Standard 90.1-2016, including functional testing of occupancy and daylight sensing controls, reporting on commissioning test results, and delivery of an operating manual to the responsible party on base.

During the demonstrated system's installation and commissioning, no continuous illuminance or electric power data was obtained. The monitoring equipment was reconfigured as needed. If the number or location of switched groups changed from the pre- to post-retrofit, we updated the number or location of our electric current meters. Our intent was that the changes to our monitoring equipment be minimal. During commissioning, we repeated our illuminance-to-power performance curve to establish the relationship for the demonstrated lighting system. We collected qualitative data during these phases thru interviews of both installing contractors and base engineering staff about time, effort, learning curve, and specific problems encountered during these periods. At the end of commissioning phase, we repeated our measurements of average illuminance in each space as described in the *Baseline Estimation* section. These results were compared to UFC recommendations and further tuning of the system's light levels was made as necessary.

Most data collection occurred during the retrofit lighting system's steady-state operation. During this phase, we monitored the retrofit lighting system's performance in the same manner as we monitored the existing lighting system's performance. Specifically, we continuously monitored electrical current at each lighting switch group, electrical power at each lighting circuit and illuminance at a minimum of one key location in each space.

5.4.2 Modeling and simulation

There was no modeling or simulation associated with operational testing our demonstrated system. Building energy modeling was conducted to quantify the effect of the lighting retrofit on HVAC energy consumption, and photometric modeling was conducted during the design to determine post-retrofit illuminance.

5.4.3 Timeline

Table 8. Operational Testing Plan Timeline

Phase	Truax 510		Selfridge 124/127 and 303	
	Start Date	End Date	Start Date	End Date
Install retrofit lighting	12/6/2018	12/6/2018	12/7/2018	12/12/2018
Commissioning	12/7/2018	12/7/2018	12/13/2018	12/13/2018
Steady State Data Collection	2/16/2019	6/27/2019	1/16/2018	6/9/2019

5.5 SAMPLING PROTOCOL

The following sampling protocol resulted in the collection of relevant and sufficient data to validate the demonstrated lighting system's cost and performance under real-world conditions. Since normal operation of lighting were expected to include the full range of occupancy and daylight availability at any specific site, and the effects of both daylight harvesting, and occupancy control could be isolated from the data, data collection involved a single baseline period and a single post-retrofit period at each facility. We did not enable daylight and occupancy controls sequentially, as this would not have allowed us to study and report on the ease of commissioning that is one of the main differentiators between the demonstrated lighting system and other similar lighting systems. However, we quantified the proportional savings between the LEDs, task tuning, occupancy and photocontrol via a post-data acquisition analysis.

5.5.1 Data Collector(s)

Lighting power, illuminance and other space-related data were collected by the Slipstream team at each site. Occupant surveys were created by the Slipstream team and distributed electronically by each base's contact. The data was collected electronically via the online survey instrument. Installer and facility staff surveys were administered by the Slipstream team.

5.5.2 Data Recording

Electrical Current for Each Lighting Switch Group

Data recording of electrical current for each lighting switch group occurred automatically at ten second intervals throughout the pre- and post-retrofit monitoring periods by Onset's CTV-A CTs. This data was stored on Onset's Hobo UX120-006M 4 channel data loggers. We ensured that the battery life and logger memory were sufficient to cover the duration of the monitoring periods. Batteries were checked, and data downloaded to Slipstream laptops during site visits both during and after the pre- and post-retrofit periods. The data was saved to Slipstream servers once a network connection was available.

Electrical Power for Each Lighting Circuit

Data recording of electrical power for each lighting circuit occurred automatically at one second intervals throughout the pre- and post-retrofit monitoring periods by eGauge devices. Slipstream used an automated, hourly query process over cellular connections to save data to Slipstream servers.

Average Illuminance in Each Space

Data recording of illuminance in each space was taken manually once during both the pre- and post-retrofit monitoring periods by an Extech EA30 light meter. The data was recorded at key locations according to the IES Lighting Handbook's procedure as outlined in the *Baseline Estimation* section. The recorded data was manually input into summary spreadsheets. Both the spreadsheets and scanned electronic copies of field downs were saved on Slipstream servers. This data was then used to calculate average illuminance in each space.

Illuminance at Key Location

Data recording of illuminance at key locations in each space occurred automatically at ten second intervals throughout the pre- and post-retrofit monitoring periods by LI-COR's LI-210R photometric sensors. This data was stored on Onset's Hobo UX120-006M 4 channel data loggers. We ensured that the battery life and logger memory were sufficient to cover the duration of the monitoring periods. Batteries were checked, and data downloaded during site visits both during and after the pre- and post-retrofit periods. The data was then saved to Slipstream servers once a network connection was available.

5.5.3 Data Description

Electrical Current for Each Lighting Switch Group and Illuminance at Key Location

The electrical current for each lighting switch group (Figure 25) and illuminance at key locations (Figure 26) data was downloaded in Hoboware format then exported to comma separated variable file format. The pre- and post-retrofit periods were both on the order of 6 months long. At ten second intervals over an entire year, that is 3,153,600 data points for each switch group.

Plot Title: fourchan_10565274		
#	Date Time, GMT-06:00	Volt, V (LGR S/N: 10565274, SEN S/N: 10565274)
1	2/9/2018 0:00	0.04837
2	2/9/2018 0:00	0.07294
3	2/9/2018 0:00	0.10727
4	2/9/2018 0:00	0.11032
5	2/9/2018 0:00	0.11215
6	2/9/2018 0:00	0.13153
7	2/9/2018 0:01	0.12787
8	2/9/2018 0:01	0.12528
9	2/9/2018 0:01	0.14069
10	2/9/2018 0:01	0.1355
11	2/9/2018 0:01	0.13107
12	2/9/2018 0:01	0.14511
13	2/9/2018 0:02	0.13901
14	2/9/2018 0:02	0.13413
15	2/9/2018 0:02	0.1474
16	2/9/2018 0:02	0.14099
17	2/9/2018 0:02	0.13581
18	2/9/2018 0:02	0.14893
19	2/9/2018 0:03	0.14221
20	2/9/2018 0:03	0.13687

Figure 25. Sample Electrical Current Data from Hobo UX120-006 M 4 Channel Data Logger.

Plot Title: fourchan_10523782		
#	Date Time, GMT-06:00	Volt, V (LGR S/N: 10523782, SEN S/N: 10523782, LBL: 10181)
1	2/9/2018 0:00	0.0013
2	2/9/2018 0:00	0.00126
3	2/9/2018 0:00	0.00126
4	2/9/2018 0:00	0.0013
5	2/9/2018 0:00	0.0013
6	2/9/2018 0:00	0.00126
7	2/9/2018 0:01	0.0013
8	2/9/2018 0:01	0.00126
9	2/9/2018 0:01	0.00126
10	2/9/2018 0:01	0.0013
11	2/9/2018 0:01	0.00126
12	2/9/2018 0:01	0.0013
13	2/9/2018 0:02	0.0013
14	2/9/2018 0:02	0.0013
15	2/9/2018 0:02	0.0013
16	2/9/2018 0:02	0.00126
17	2/9/2018 0:02	0.00126
18	2/9/2018 0:02	0.0013
19	2/9/2018 0:03	0.0013
20	2/9/2018 0:03	0.00126

Figure 26. Sample Illuminance Data from Hobo UX120-006 M 4 Channel Data Logger.

Electrical Power for Each Lighting Circuit

The electrical power for each lighting circuit (Figure 27) data was transmitted and saved in comma separated variable file format. The pre- and post-retrofit periods were both on the order of 6 months long. At one second intervals over an entire year, that is 31,536,000 data points for each circuit.

Eastern	Timestamp	P124_26	P124_28	P124_30	A124_26	A124_28	A124_30	V124_A	V124_B	V124_C
4/1/2018 20:00	1522627259	1	36	405	0.041	1.563	3.593	123.262	123.496	123.357
4/1/2018 20:01	1522627260	2	37	404	0.039	1.563	3.593	123.241	123.499	123.354
4/1/2018 20:01	1522627261	1	37	405	0.04	1.563	3.593	123.233	123.489	123.357
4/1/2018 20:01	1522627262	1	37	405	0.041	1.562	3.594	123.232	123.489	123.362
4/1/2018 20:01	1522627263	2	37	405	0.039	1.562	3.593	123.235	123.489	123.369
4/1/2018 20:01	1522627264	1	37	405	0.039	1.562	3.593	123.239	123.53	123.373
4/1/2018 20:01	1522627265	2	36	405	0.041	1.563	3.593	123.234	123.494	123.383
4/1/2018 20:01	1522627266	1	37	405	0.04	1.563	3.592	123.231	123.496	123.39
4/1/2018 20:01	1522627267	1	37	405	0.038	1.563	3.594	123.215	123.494	123.39
4/1/2018 20:01	1522627268	2	37	405	0.039	1.563	3.593	123.223	123.508	123.391
4/1/2018 20:01	1522627269	1	37	404	0.041	1.562	3.593	123.186	123.482	123.351
4/1/2018 20:01	1522627270	1	37	405	0.04	1.561	3.593	123.196	123.477	123.317
4/1/2018 20:01	1522627271	2	37	405	0.041	1.563	3.593	123.195	123.502	123.365
4/1/2018 20:01	1522627272	1	37	405	0.04	1.564	3.593	123.188	123.489	123.36
4/1/2018 20:01	1522627273	2	37	405	0.042	1.563	3.592	123.215	123.514	123.381
4/1/2018 20:01	1522627274	1	36	405	0.041	1.562	3.593	123.236	123.539	123.404
4/1/2018 20:01	1522627275	2	37	404	0.042	1.562	3.593	123.275	123.53	123.396
4/1/2018 20:01	1522627276	1	38	405	0.041	1.563	3.593	123.239	123.537	123.385
4/1/2018 20:01	1522627277	2	36	405	0.042	1.562	3.592	123.279	123.573	123.418

Figure 27. Sample Electrical Power Data from eGauge.

Average Illuminance in Each Space

The spot illuminance measurements used to calculate average illuminance in each space (Figure 28) were saved in Microsoft Excel file format. Up to 18 measurement locations, each with lights on and lights off measurement, were taken in each space during both the pre- and post-retrofit periods. This equates to a maximum of 72 measurements for each space.

<i>Measured Illuminance Points</i>			
	Lights On (fc)	Lights Off (fc)	Difference
p-1	37	11	26
p-2	34	4	30
p-3			
p-4			
q-1	43	18	25
q-2	64	36	28
q-3	42	6	36
q-4	38	6	32
q-5			
q-6			
q-7			
q-8			
r-1	69	11	58
r-2	72	25	47
r-3	57	17	40
r-4	63	13	50
r-5	46	6	40
r-6	55	7	48
r-7	72	15	57
r-8	54	7	47
t-1	43	11	32
t-2	51	5	46
t-3	43	6	37
t-4	48	5	43

Figure 28. Sample Spot Illuminance Measurements from Extech Photometer.

Note that, although 24 points are shown in Figure 28, only a subset are required for a given space's luminaire configuration.

5.5.4 Data Storage and Backup

Slipstream used a dedicated server for remote data collection from field sites, with automatic database insertion and daily archival. All data were backed up daily to an off-site location with encryption.

Data were stored on dedicated network segments with access limited to individuals who had passed a background check and/or were cleared to work on specific projects. Data were backed up daily to our backup and disaster recovery environment. Slipstream owns and maintains all hardware, operating systems and software in secure facilities. The backup site adheres to the same security standards as our primary environment.

5.5.5 Data Collection Diagram

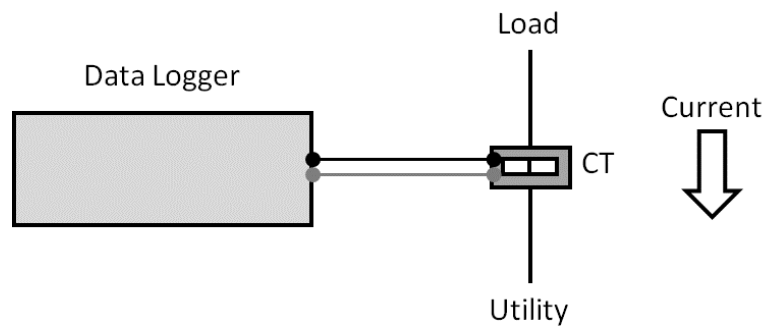


Figure 29. Schematic of Data Logger and CT Used to Monitor Electrical Current for Each Lighting Switch Group.

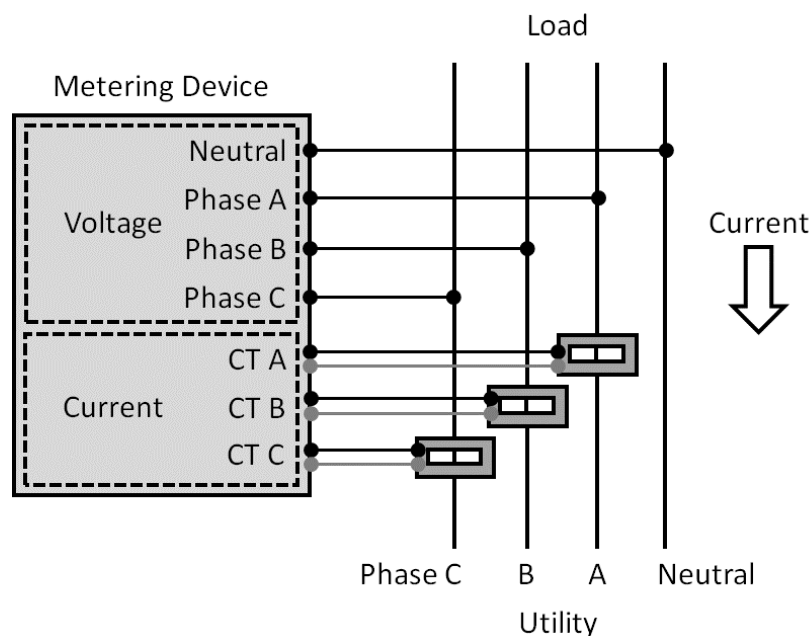


Figure 30. Schematic of Power Meter and CTs Used to Monitor Electrical Current for Each Lighting Switch Group.

5.5.6 Survey Questionnaires

The occupant survey is outlined in *APPENDIX B: OCCUPANT SURVEY*. The occupant survey was reviewed and approved by facility staff at each installation prior to administering it to occupants electronically. It was designed to be as simple as possible, while still capturing the data of interest. This increased the participation rate. The post-retrofit survey were distributed several weeks after commissioning such that occupants could become acclimated to the new lighting system prior to taking the survey. The installer and facility staff survey are outlined in *APPENDIX C: INSTALLER AND FACILITY STAFF SURVEY*.

5.6 SAMPLING RESULTS

The significant size of the data gathered for this project precludes including it in its entirety as part of this report. We therefore summarize the data in terms of the hourly profiles for each of the 4 typical day types for the monitored switch groups and lighting circuits. For the average illuminance in each space, we summarize the one-time spot measurements for each space. These summaries are included in *APPENDIX F: DATA SAMPLING SUMMARY*.

6.0 PERFORMANCE ASSESSMENT

The *Baseline Estimation* section outlines the methods for calculating the baseline performance of the pre-retrofit systems. These same methods were repeated using post-retrofit data to calculate the performance of the post-retrofit systems. Performance objectives were evaluated according to the following.

6.1 ELECTRIC ENERGY CONSUMPTION REDUCTION

The lighting system's electric energy consumption reduction was calculated according to:

$$Q_{\%red} = \frac{Q_{pre} - Q_{post}}{Q_{pre}}$$

Where:

Q_{pre} is the pre-retrofit lighting system's annual electricity consumption in kWh/ft², and
 Q_{post} is the post-retrofit lighting system's annual electricity consumption in kWh/ft², and
 $Q_{\%red}$ is the lighting system's annual electricity consumption reduction in %.

Table 9 summarizes the calculated electric energy consumption reduction for each site.

Table 9. Annual Electric Energy Savings for Each Site.

Building	Annual electricity consumption (kWh/ft ²)		Annual electric savings	
	Pre-Retrofit	Post-Retrofit	kWh/ft ²	Percentage
Truax 510	2.0	0.7	1.3	67%
Selfridge 124/127	2.9	1.1	1.8	63%
Selfridge 303	5.1	1.4	3.6	71%
<i>All</i>	<i>3.7</i>	<i>1.2</i>	<i>2.6</i>	<i>69%</i>

Note that due to rounding the savings is not equal to the difference between the pre- and post-retrofit values. Further, the All row represents an area-weighted average of the sites. The success criteria was whether the post-retrofit lighting system achieves a minimum 50% electric energy consumption reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 63% and 71%. The annual electric savings for all sites taken together was 69%. Note that absolute savings was highest in Selfridge 303, which had a high pre-retrofit LPD and longer hours of operation. Absolute savings were lowest in Truax 510 which had a low pre-retrofit LPD and shorter hours of operation.

Occupancy and Daylight Variability Between Periods

Occupancy patterns and daylight availability were two variables that had a significant impact on the pre- and post-retrofit lighting systems. We wanted to ensure that these variables were consistent between periods such that the calculated energy savings was not affected.

We checked for occupancy variation by comparing the equivalent full load hours (EFLH) between the pre and post-retrofit periods for each of the sites. EFLH was calculated as:

$$EFLH_{pre} = \frac{Q_{pre}}{\max(P_{pre,retrofit})} \left(\frac{1000 \text{ kW}}{1 \text{ W}} \right)$$

$$EFLH_{post} = \frac{Q_{post}}{\max(P_{post,retrofit})} \left(\frac{1000 \text{ kW}}{1 \text{ W}} \right)$$

Where:

$EFLH_{pre}$ is the pre-retrofit equivalent full load hours in hours, and

$EFLH_{post}$ is the post-retrofit equivalent full load hours in hours.

Table 10 outlines the calculated EFLH for each period at each site.

Table 10. Calculated EFLH for Each Period at Each Site.

Building	Equivalent Full Load Hours (hr)		
	Pre-Retrofit	Post-Retrofit	% Difference
Truax 510	1,952	2,137	-9%
Selfridge 124/127	1,953	1,922	2%
Selfridge 303	3,070	3,374	-10%
All	2,557	2,630	-3%

Note that the EFLH were similar between periods for each site. Further, the All row represents an area-weighted average of the sites. This was confirmed by facility staff who noted no major changes in the retrofit spaces. At the sites with the highest variation, the EFLHs increased. This means that the lighting was utilized more often during the post-retrofit period, equating to conservative energy savings estimates.

The demonstrated lighting system includes automatic photosensor control, while the pre-retrofit lighting may be manually turned off by occupants during periods of enough daylight. In order to ensure that daylight availability did not affect our savings calculation, we adjusted the range of days used in our calculations such that daylight availability was similar between our pre and post-retrofit periods.

Table 11 summarizes the unadjusted date ranges available for each site.

Table 11. Unadjusted Analysis Date Range.

Building	Pre-Retrofit			Post-Retrofit		
	First Date	Last Date	Total Days	First Date	Last Date	Total Days
Truax 510	2/10/2018	12/5/2018	294	2/16/2019	6/27/2019	131
Selfridge 124/127	4/6/2018	12/6/2018	242	1/16/2019	6/9/2019	144
Selfridge 303	4/2/2018	12/6/2018	246	3/2/2019	6/9/2019	99

Figure 31 illustrates the hourly global solar radiation from the nearest weather station for each site during the unadjusted periods.

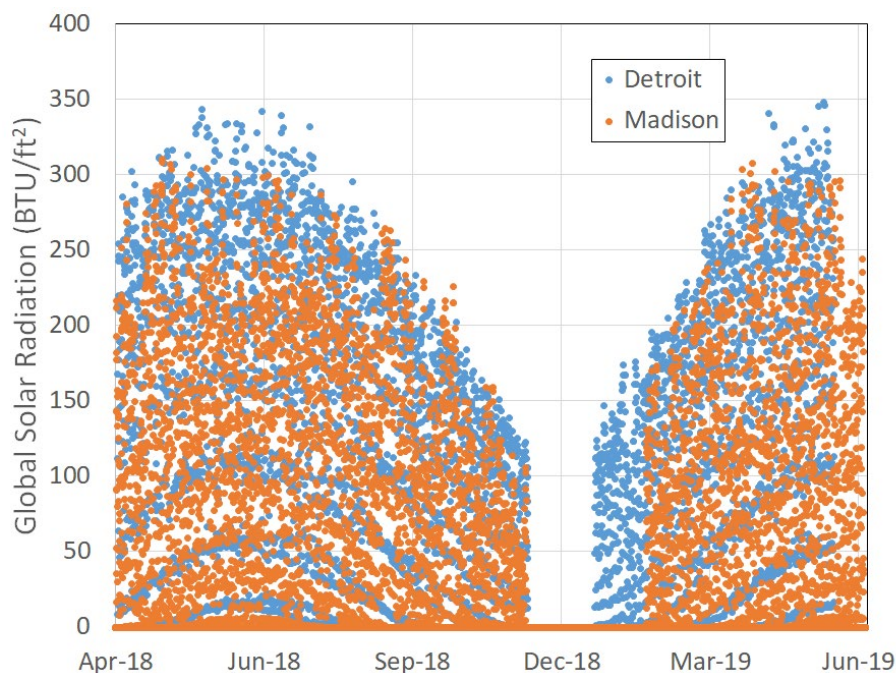


Figure 31. Hourly Global Solar Radiation for Each Site During the Unadjusted Periods.

Note the asymmetry of the unadjusted periods (pre-retrofit to the left of the gap and post-retrofit to the right). This is largely due to the pre-retrofit period including a larger portion of the year and corresponding solar cycle than the post-retrofit period. We subsequently adjusted the periods to include periods that more closely reflected each other. These periods both included low and high global solar radiation from days close to the winter and solar solstices, respectively.

Table 12 summarizes the adjusted date ranges available for each site.

Table 12. Adjusted Analysis Date Range.

Building	Pre-Retrofit			Post-Retrofit		
	First Date	Last Date	Total Days	First Date	Last Date	Total Days
Truax 510	6/21/2018	10/25/2018	126	2/16/2019	6/21/2019	125
Selfridge 124/127	6/21/2018	10/25/2018	126	2/15/2019	6/9/2019	114
Selfridge 303	6/21/2018	10/25/2018	126	3/2/2019	6/9/2019	99

Figure 32 illustrates the hourly global solar radiation from the nearest weather station for each site during the adjusted periods.

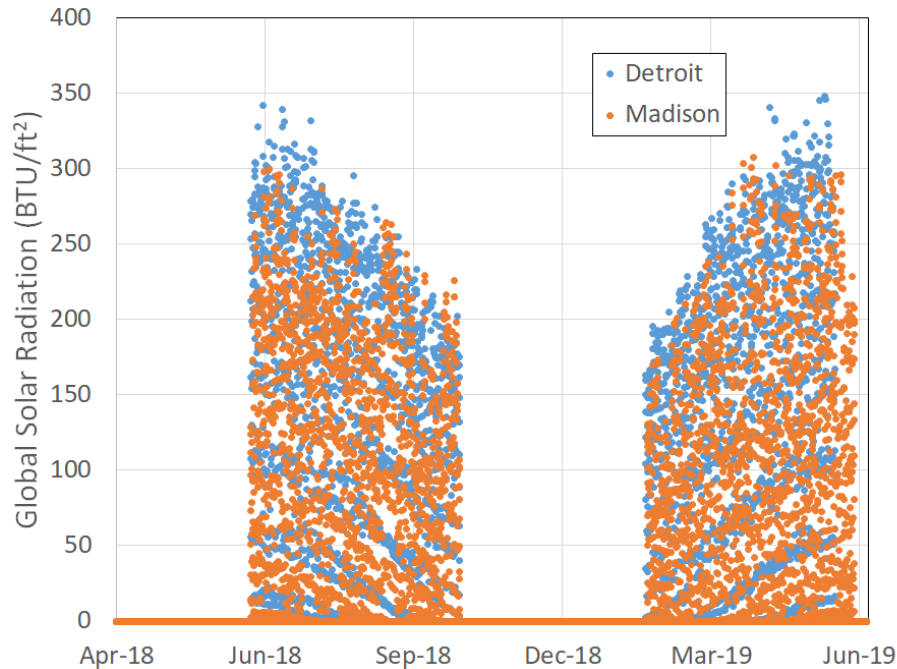


Figure 32. Hourly Global Solar Radiation for Each Site During the Adjusted Periods.

Note the symmetry between the adjusted pre and post-retrofit periods. Table 13 summarizes compares the average global solar radiation in Btu/hr/ft².

Table 13. Average Global Solar Radiation in Btu/hr/ft² for Unadjusted and Adjusted Periods.

Site	Unadjusted			Adjusted		
	Pre-Retrofit	Post-Retrofit	% Difference	Pre-Retrofit	Post-Retrofit	% Difference
Detroit	78.26	70.91	-10%	81.17	81.17	0%
Madison	57.02	62.26	8%	63.85	61.84	-3%

Note that the percent difference between pre and post-retrofit global solar radiation was significantly reduced between the unadjusted and adjusted data periods.

When adjusting the period lengths, we maximized the data used, while minimizing the solar variability between periods. However, we wanted to ensure that reducing the dataset did not affect the results. We therefore calculated the annual energy consumption of the pre and post-retrofit lighting systems with varying amounts of data. This analysis indicated the amount of data needed to achieve a converged result. More specifically, the fewer days of data analyzed, the more day-to-day variations impacted the result. As more days were added, the variability of any given day had less of an impact.

Figure 33 illustrates the calculated lighting energy consumption for each site during the pre-and post-retrofit periods for increasing number of days analyzed.

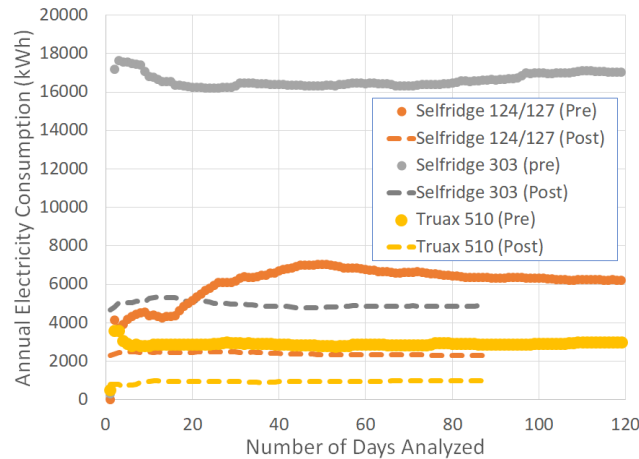


Figure 33. Calculated Lighting Energy Consumption for Each Site During the Pre- and Post-retrofit Periods for Increasing Number of Days Analyzed.

From this analysis, we concluded that approximately 100 days of data to achieve converged results for the pre-retrofit period and 40 days for the post-retrofit period. Since our adjusted periods were longer than these, we conclude that reducing the data analyzed did not have an impact on the calculated energy savings.

6.2 ELECTRIC ENERGY SAVINGS PROPORTIONS

We undertook an additional analysis to calculate the proportion of energy savings attributable to each of the following controls: LEDs, task tuning, occupancy control, and photocontrol. See the *APPENDIX E: SAVINGS PROPORTIONS* section for more detail on the calculation methodology.

Table 14 these results by switch group. The switch groups with 0% of the savings attributable to tuning were programmed to be untuned ($P_{tune} = P_{untune}$). The switch groups with 0% of the savings attributable to photocontrol were spaces where this control was disabled due to occupant feedback.

Table 14. Proportional Savings by Switch Group

Building	Switch Group	LED Savings (%)	Tune Savings (%)	Occupancy Savings (%)	Photocontrol Savings (%)
Truax 510	107-U	68	31	1	0
Truax 510	107-V	64	31	5	0
Truax 510	107-X	72	24	4	0
Truax 510	110	70	19	8	3
Selfridge 124/127	103	63	9	0	28
Selfridge 124/127	106	53	17	3	27
Selfridge 124/127	109	53	10	10	27
Selfridge 303	140	77	14	7	2
Selfridge 303	142	63	18	20	0
Selfridge 303	146	70	18	5	7
Selfridge 303	149	71	15	15	0
Selfridge 303	Office E	78	7	4	11
Selfridge 303	Office SW	70	6	4	21
Selfridge 303	Office S	68	12	4	16
All	All	69	13	4	14

Note that due to rounding, not all rows will sum to 100%. Table 14 includes the aggregated savings proportion results across all the analyzed spaces. Note that these savings are proportions of the total savings and therefore add to 100%. The results show most energy savings (69.8%) came from LEDs. Daylighting controls (13.6%) and task tuning (12.7%) were similar sized components of savings. Occupancy controls (3.9%) were the smallest component of overall savings. Of the switch groups analyzed, a large number were untuned or had low tuning values, which impacted the proportion of savings from tuning. In a building with more tuned fixtures, this percent would be higher.

6.3 PEAK DEMAND REDUCTION

The lighting system's measured peak demand reduction was calculated according to:

$$D_{\%Red} = \frac{D_{pre} - D_{post}}{D_{pre}}$$

Where:

D_{post} is the post-retrofit measured peak demand in W/ft², and

$D_{\%Red}$ is the lighting system's measured peak demand reduction in %.

Table 15 summarizes the calculated measured peak demand reduction for each site.

Table 15. Measured Peak Demand Savings for Each Site.

Building	Peak Demand (W/ft ²)		Peak Demand Savings	
	Pre-Retrofit	Post-Retrofit	W/ft ²	Percentage
Truax 510	1.00	0.30	0.70	70%
Selfridge 124/127	1.47	0.55	0.92	62%
Selfridge 303	1.64	0.43	1.22	74%
<i>All</i>	<i>1.45</i>	<i>0.44</i>	<i>1.01</i>	<i>70%</i>

Note that due to rounding the savings is not equal to the difference between the pre- and post-retrofit values. Further, the All row represents an area-weighted average of the sites. The success criteria was whether post-retrofit lighting system achieves a minimum 40% measured peak demand reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 62% and 74%. The savings for all sites taken together was 70%. The measured peak demand reduction is indicative of the peak demand charge savings from the retrofit as the savings occurred during most utility's peak periods (weekday afternoons).

6.4 GREENHOUSE GAS EMISSION REDUCTION

The lighting system's greenhouse gas emission reduction was calculated according to:

$$GHG_{\%Red} = \frac{GHG_{pre} - GHG_{post}}{GHG_{pre}}$$

Where:

GHG_{post} is the post-retrofit GHG emissions of a given space in metric tons of CO₂ equivalent/ft², and

$GHG_{\%Red}$ is the lighting system's GHG emissions reduction in %.

Table 16 summarizes the calculated greenhouse gas emissions reduction for each site.

Table 16. Greenhouse Gas Emissions Savings for Each Site.

Building	Greenhouse gas emissions savings	
	lbCO ₂ e/ft ²	Percentage
Truax 510	2.1	67%
Selfridge 124/127	2.3	63%
Selfridge 303	4.6	71%
<i>All</i>	<i>3.3</i>	<i>69%</i>

Note that the All row represents an area-weighted average of the sites. The success criteria was whether the post-retrofit lighting system achieved a minimum 50% GHG reduction as compared to the pre-retrofit lighting system. Note that each site achieved this threshold, with savings ranging between 67% and 71%. The greenhouse gas emissions savings for all sites taken together was 69%.

6.5 LIGHT LEVELS

The lighting system's post-retrofit average illuminance percent difference with respect to UFC recommendations will be calculated according to:

$$E_{\%,post} = \frac{E_{post} - E_{UFC}}{E_{UFC}}$$

Where:

E_{post} is the post-retrofit average illuminance of a given space in fc, and

$E_{\%,post}$ is the lighting system's post-retrofit average illuminance percent difference with respect to UFC recommendations in %.

The success criteria was whether the post-retrofit average illuminance percent difference was less than the pre-retrofit average illuminance percent difference. Put another way, the light levels of a given space were brought into closer agreement with the UFC recommendations.

Table 17 summarizes the UFC recommended and measured pre-retrofit, post-retrofit and adjusted light levels for each site. The percent difference with respect to UFC recommendations are also included in brackets.

Table 17. UFC Recommended and Measured Pre-retrofit, Post-retrofit and Adjusted Light Levels.

Building	Illuminance (fc)			
	Ave UFC Recommendation	Pre-Retrofit	Post-Retrofit	Adjusted
Truax 510	30	29 [2%]	16 [-45%]	26 [-17%]
Selfridge 124/127	245	36 [50%]	28 [18%]	28 [18%]
Selfridge 303	30	40 [33%]	25 [-16%]	26 [-13%]
<i>All</i>	<i>28</i>	<i>36 [29%]</i>	<i>24 [-14%]</i>	<i>26 [-6%]</i>

Note that the All row represents an area-weighted average of the sites. Further note that the post-retrofit percent difference of 14% was less than the pre-retrofit percent difference of 29% for the combined sites. Due to the lower than expected post-retrofit illuminances, we revisited both Truax 510 and Selfridge 303. In many spaces, we increased the task tuning setpoints. This adjustment increased the light levels in these spaces, bringing the light levels into closer agreement with UFC recommendations. The adjustments also addressed occupant feedback we received shortly after the commissioning process. This feedback was specific to two private offices. The low sample makes it impossible to draw conclusions about trends within this feedback.

Light loss factor incorporates phenomena, including dirt and lumen depreciation, that reduce the illuminance provided by luminaires over time. Light loss factor is used within photometric models to design lighting systems that will provide recommended levels of illuminance over the system's life. The resulting system therefore provides higher than recommended illuminance shortly after installation, with the illuminance approaching the recommended illuminance over time. Typical light loss factors are approximately 0.9, which translates to installed illuminances 10% higher than recommended. For recommended illuminance of 30 to 50 fc, this would be between 3 and 5 fc. Our adjusted illuminance was 6% below the recommended levels. The adjusted illuminance levels were therefore 2 to 3 fc below the recommended levels and will drift down over time. These light levels received positive feedback from the occupants, despite being lower than the pre-retrofit illuminance. Further, absolute illuminance depreciation will be small and will occur over many years of the fixture life. In addition, there is significant daylight in many of these spaces and task lighting to ensure sufficient light is provided to the work plane if an occupant desires. Finally, facility staff may easily increase the light levels in the future by increasing a space's task tuning setpoint. We therefore felt justified in not making further upward adjustments.

6.6 COST EFFECTIVENESS

In addition to the life-cycle cost analysis outlined in the *COST ASSESSMENT* section, we calculated the simple payback of the lighting system. Simple payback was calculated according to:

$$\text{Simple Payback} = \frac{\text{Installed Costs} - \text{Rebates}}{\text{Utility Cost Savings}}$$

⁵ This column is an area-weighted average of UFC recommendations including 30 fc for offices and conference rooms and 5 fc for corridors.

The success criteria was a simple payback of less than 11 years. This criteria was arrived at through preliminary estimates of system cost and savings. The simple payback results are summarized in the *Simple Payback* subsection of the *COST ASSESSMENT* section.

6.7 REDUCE HVAC ENERGY CONSUMPTION

The HVAC energy consumption reduction was calculated according to:

$$Q_{\%Red,HVAC} = \frac{Q_{pre,HVAC} - Q_{post,HVAC}}{Q_{pre,HVAC}}$$

Where:

$Q_{post,HVAC}$ is the post-retrofit HVAC energy consumption in kBTU/ft², and

$Q_{\%Red,HVAC}$ is the HVAC energy consumption reduction in %.

The success criteria was whether the post-retrofit system achieved a minimum 0% HVAC energy consumption reduction as compared to the pre-retrofit system. This is the same as saying that the lighting retrofit reduced the HVAC energy consumption. Table 18 summarizes the modeled HVAC energy savings for each site.

Table 18. Site-specific HVAC Modeling Savings Results.

Building	Annual HVAC Electric		Annual HVAC Natural Gas		Annual HVAC Energy		Annual HVAC Utility Cost	
	kWh/ft ²	%	therm/ft ²	%	kBTU/ft ²	%	\$/ft ²	%
Truax 510	0.02	1%	-0.04	-3%	-3.8	-3%	-\$0.03	-2%
Selfridge 124/127	-0.01	-1%	-0.06	-11%	-5.6	-10%	-\$0.05	-9%
Selfridge 303	0.30	23%	-0.09	-21%	-8.4	-17%	-\$0.05	-9%
All	0.13	10%	-0.07	-10%	-6.5	-9%	-\$0.04	-6%

Note that the All row represents an area-weighted average of the sites. The energy modeling showed HVAC electric energy savings at Truax 510, Selfridge 303 and all buildings combined. This was due to lower lighting loads resulting in lower cooling and associated fan and pump electric energy consumption. For Selfridge 124/127, fan and pump electricity consumption increased due to the impact of the increased heating load being greater than the decreased cooling load. The energy modeling showed increased HVAC natural gas usage at all buildings. This was due to lower lighting loads resulting in higher heating energy consumption. Taken together, the total HVAC energy consumption increased at all buildings as the cooling season savings were not large enough to offset the heating season penalty.

6.7.1 Commercial Reference Building Modeling

Figure 34 illustrates the commercial reference building modeling results for each of the building types and climate zones.

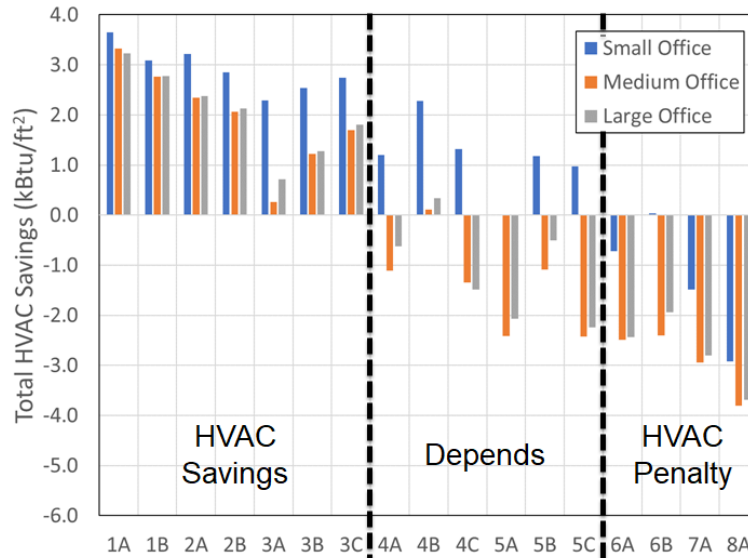


Figure 34. Commercial Reference Building Modeling Total HVAC Savings Sorted by Climate Zone.

Note that for hot climate zones (1-3) the reduced lighting load resulted in HVAC savings for each of the building types. Similarly, for cold climates (6-8) the reduced lighting load resulted in an HVAC penalty for each of the building types. However, in temperate climate zones (4-5) the HVAC impact depended on the building type and associated HVAC system type. These results are mapped to the U.S. in Figure 35.

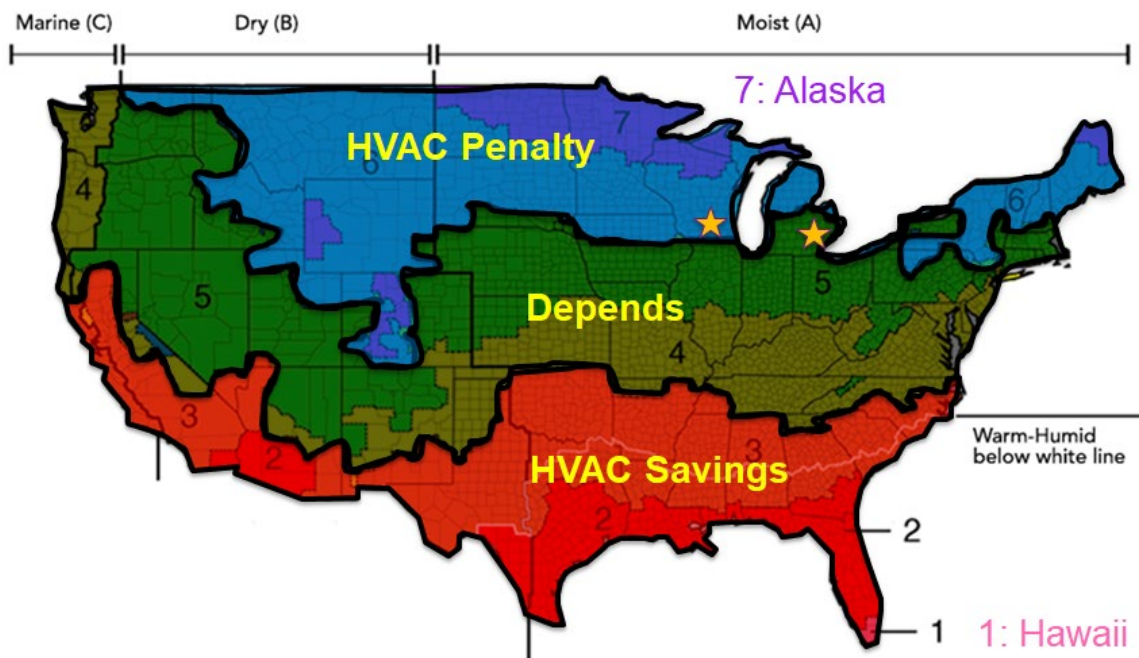


Figure 35. Map of HVAC Impacts.

The commercial reference building modeling results were also sorted by HVAC system type, shown in Figure 36. The Small Office model had an Air Source Heat Pump (ASHP) with natural gas backup. The Medium Office used a Packaged Variable Air Volume (PVAV) system with electric reheat system. Its primary heating coil was natural gas-fired. The Large Office used a Variable Air Volume (VAV) system with hot water reheat from a natural gas-fired boiler.

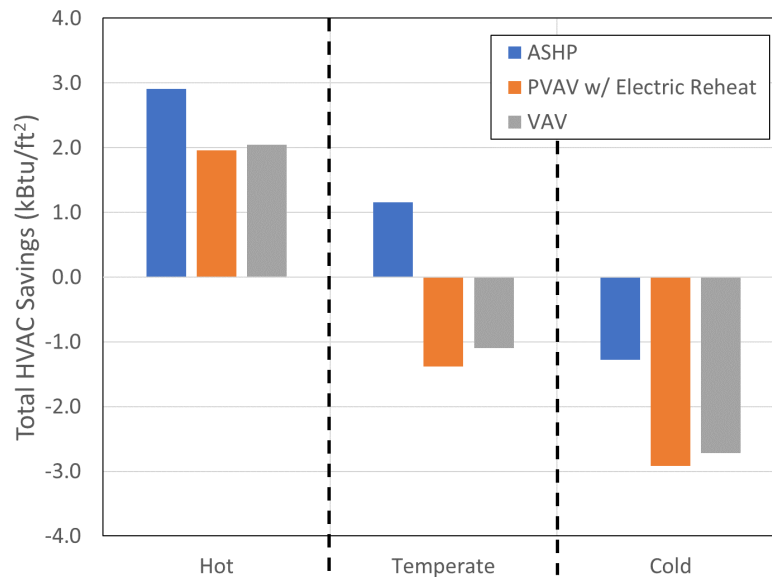


Figure 36. Commercial Reference Building Modeling Results Sorted by HVAC System Type.

Both VAV systems had similar results and only yielded total HVAC savings in warmer climates. The ASHP system had total HVAC savings in the warmer and more temperature climates. All 3 HVAC systems had natural gas penalties across all climates (Figure 35) with more pronounced savings in colder climates. This was due to the decreased heating load from the lighting load reduction.

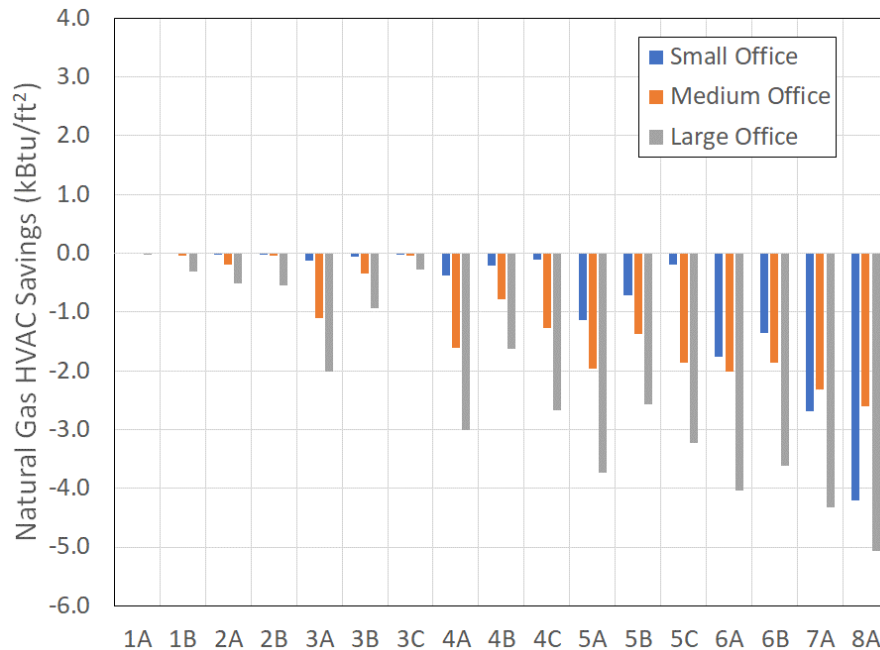


Figure 37. Commercial Reference Building Modeling Natural Gas HVAC Savings Sorted by Climate Zone.

The electric HVAC savings (Figure 38) depended on its primary heating fuel type, and how often any secondary heating was utilized.

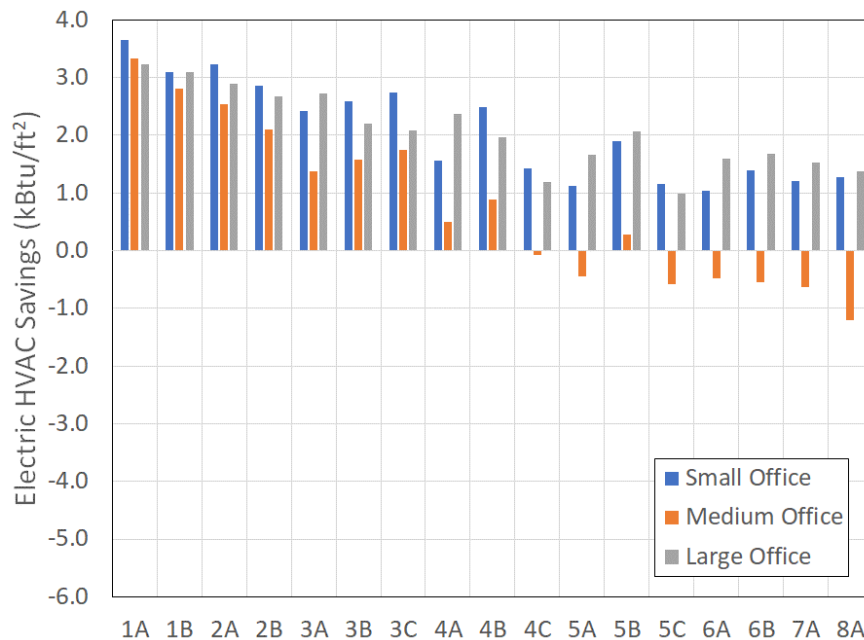


Figure 38. Commercial Reference Building Modeling Electric HVAC Savings Sorted by Climate Zone.

The Small Office electric HVAC savings was always positive, resulting from cooling and fan consumption being larger than any electric heating penalty. The Small Office electric savings were sufficiently large to overcome the natural gas penalty in climate zones 1-5, resulting in net HVAC savings. The Large Office electric HVAC savings was also always positive, resulting from reduced cooling, fan and pump energy and no corresponding electric heating equipment. The net effect was total HVAC savings in climate zones 1-3 for the Large Office's VAV system. The Medium Office electric HVAC savings were positive only in climate zones 1-4. The Medium Office had an electric HVAC penalty in climate zones 5-8 due to the increased electric energy consumption from its reheat. The net effect was total HVAC savings only in climate zones 1-3.

6.8 OCCUPANT SATISFACTION

The Likert scale score reduction for each occupant survey question was calculated according to:

$$L_{\%Red} = \frac{L_{pre} - L_{post}}{L_{pre}}$$

Where:

L_{pre} is the pre-retrofit Likert scale score for a given question,

L_{post} is the post-retrofit Likert scale score for a given question, and

$L_{\%Red}$, is the Likert scale score reduction in %.

The success criteria was whether the post-retrofit system achieved a minimum 0% Likert scale score reduction as compared to the pre-retrofit system. This is the same as saying that the lighting retrofit improved occupant satisfaction as lower scores are better than higher scores. Table 19 summarizes the Likert scores for each of the level of satisfaction questions (1 = Extremely Satisfied, 5 = Extremely Dissatisfied)

Table 19. Occupant survey Likert Score Summary.

Period	Sample Size	Average Likert Score		
		Amount of light in workspace	Ability to control overhead lighting	Visual comfort of the lighting
Pre-Retrofit	23	2.5	2.8	3.1
Post-Retrofit	27	1.6	1.7	1.7

Note that the Likert score decreased (improved) for each of the categories.

Figure 39 summarizes the pre- and post-retrofit occupant satisfaction regarding the amount of light.

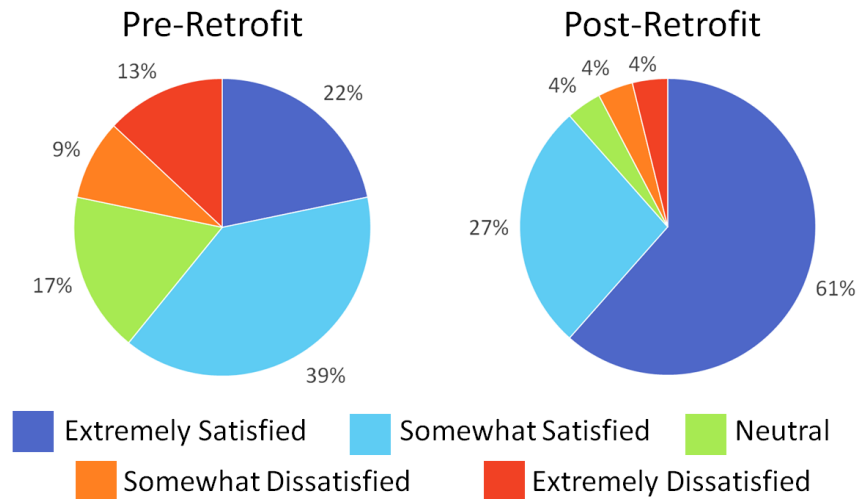


Figure 39. Pre- and Post-retrofit Occupant Satisfaction Regarding the Amount of Light.

Pre-retrofit there was a wide range of satisfaction with their lighting system. In general, the open office occupants had a wide range of satisfaction with their current lighting system, as can be expected since individual preference vary and the lighting provided was uniform across all occupants. In the private offices, the feedback was more positive, but a couple of occupants were very dissatisfied with their lighting, likely due to their having very high light levels with little controllability.

Post-retrofit the high amount of “extremely or somewhat satisfied” respondents increases significantly. The overall score improved from 2.5 to 1.0. The two remaining dissatisfied occupants were in private offices. After this survey, we circled back out to improve their light levels. We did not re-administer the survey, so we are not sure whether this improved the overall occupant satisfaction scores.

The results were similar across the other satisfaction questions.

6.9 EASE OF INSTALLATION, COMMISSIONING AND OPERATING

The results of the installer and facility staff survey were largely qualitative. The success criteria was whether no major difficulty were encountered in the installation, commissioning, and operating of the demonstrated lighting system. In fact, no major difficulties were encountered throughout the demonstration project. The level of satisfaction with the demonstrated lighting system from facility operators was 2.0 or Somewhat Satisfied.

The electrical contractors reported that the fixture installation was similar to a traditional fluorescent lighting system. However, they noted that the switches required an additional neutral conductor, which added time to the installation.

The electrical contractors reported that system commissioning was longer and more complex than a traditional fluorescent lighting system due to the additional control settings. One contractor reported that the printed instructions provided were unclear. However, they were able to access manufacturer support and video tutorials, which were helpful.

Facility staff reported that the day-to-day operation was similar to a traditional fluorescent lighting system, with minimal to no interventions required. One operator mentioned that replacing a faulty fixture or switch (when it occurred) would be more complex due to the programming involved.

6.10 PERFORMANCE OBJECTIVE SUMMARY

Table 20 summarizes whether the success criteria for each performance objective was met.

Table 20. Whether the Success Criteria for Each Performance Objective Was Met.

Performance Objective	Success Criteria	Result	Met?
Quantitative Performance Objectives			
Reduce lighting system's electric energy consumption	Minimum 50% reduction in EUI-lighting	69%	Yes
Reduce peak demand	Minimum 40% reduction in peak demand	70%	Yes
Reduce lighting system's greenhouse gas emissions	Minimum 50% reduction in GHG emissions compared with pre-retrofit period	69%	Yes
Light Levels	Net reduction in deviation from UFC requirements between pre and post-retrofit	<u>Truax 510</u> 2% to -17% <u>Selfridge 124/127</u> 50% to 18% <u>Selfridge 303</u> 33% to -13%	Partial
Cost Effectiveness	Maximum 11 year simple payback	<u>Truax 510</u> 25.6 <u>Selfridge 124/127</u> 31.3 <u>Selfridge 303</u> 14.7	No
Reduce HVAC energy consumption	Net reduction in EUI-HVAC	Demonstration sites: Net increase Reference models: Net decrease in climate zones 1-3	Partial
Occupant Satisfaction	Improved overall satisfaction scores	Pre-Retrofit: 2.5 Post-Retrofit: 1.6	Yes
Qualitative Performance Objectives			
Ease of installation, commissioning and operation	Installers and facility staff report no major difficulty in installation, commissioning and operating	No reported difficulties	Yes

7.0 COST ASSESSMENT

Economic performance is a part of most energy efficiency improvement efforts and a key metric for analyzing project performance. To analyze economic performance, we calculated the simple payback period for each site and performed a detailed life-cycle cost analysis. We additionally repeated these calculations with more typical costs and explored the sensitivity of the economic performance indicators to various factors.

Spreadsheet analysis was used to perform simple payback calculations and the sensitivity analysis and the NIST Building Life Cycle Cost Analysis program, Version 5.3, was used for the life-cycle cost analysis.

7.1 COST MODEL

Table 21 presents the costs related to implementing the demonstrated lighting system, which were used in our project overall cost assessment. The cost estimates come from the installation contracts, with supplemental information gathered through interviews with the manufacturer, installers, and facilities staff.

Table 21. Cost Elements

Cost Element	Truax 510	Selfridge 124/127	Selfridge 303
Building Area (ft ²)	1,532	2,175	3,370
One-Time			
Hardware Capital	\$7,035	\$19,275	\$18,570
Installation Labor	\$2,700	\$4,250	\$9,300
Rebate	\$606	\$300	\$549
Annual			
Maintenance – LEDs (after warranty ends in year 10)	\$4.1	\$10.9	\$10.6
Facility operational cost savings – Energy	\$355	\$740	\$1,855
Facility operational cost savings – fluorescent lamp and ballast replacements	\$58	\$170	\$140

Hardware capital costs are costs related to the installation of the demonstrated lighting fixtures, wireless switches and handheld commissioning tool at each site. Installation labor costs reflect one-time labor costs for the electrical contractor to install and commission the new lighting system at each of the project sites. This cost will vary by site, lighting system design, and selected electrical contractor. The rebate is estimated per the utility efficiency program serving each site. It defers a portion of the hardware capital and installation labor costs. The hardware capital, installation labor and rebate categories occur once at the beginning of the system's life.

Maintenance costs are related to facility staff or electrical contractors troubleshooting and fixing the demonstrated lighting system. They are recurring annual costs. Note that if an occupancy or photosensor were to fail, the entire fixture would need to be replaced. Manufacturer data suggests that 0.5% of fixtures need to be replaced over 10 years and that replacement of one fixture takes around 30 minutes. Since the system's warranty is 10 years, we assumed that starting in year 10, 0.05% (0.5% over 10 years) of fixtures in each building would need to be replaced annually.

We estimated the annual material cost as 0.05% of the upfront hardware cost from our demonstration sites and the labor cost as 30 minutes per fixture multiplied by an \$80 per hour labor rate (average labor rate across the 3 sites) and 0.05% of all LED fixtures. Note that the cost to maintain the demonstrated lighting system (estimated at \$0.004/ft² across all sites) is significantly less than a traditional fluorescent system (estimated at \$0.052/ft² across all sites). Ballast and lamp replacement contribute about equally to the annual maintenance cost for a fluorescent system. Although lamp replacement occurs more frequently, ballasts have both a higher material and labor cost per replacement.

Facility operational cost savings include both the annual electricity cost savings and the annual maintenance savings from avoided fluorescent lamp and ballast replacement. Annualized energy cost savings were calculated by applying local utility rate structures to the reductions in electricity consumption and demand. Table 22 summarizes the electric rates for each site.

Table 22. Electric Rates for Each Site

Electric Rate Element	Truax 510	Selfridge 124/127	Selfridge 303
Electricity Consumption (\$/kWh)	\$0.094	\$0.080	\$0.080
Electric Demand (\$/kW/month)	\$13.2	\$17.8	\$17.8

To calculate avoided fluorescent costs, we assumed a standard lifetime for each lamp and ballast type, estimated the cost to replace all lamps or ballasts, and then spread the replacement costs over the standard lifetime of the lamp (8 years for 2' lamps and 12 years for 4' lamps) [Osram and Sylvania 2012] or ballast (16 years) [McCullough et al. 2016]. The replacement costs for a lamp included the cost of a new fluorescent lamp, the recycling fee to dispose of a lamp, and the labor cost to replace a lamp. Note that a labor rate of \$15/hr was used for lamp replacement to reflect the lower rate of facility maintenance staff as compared to an electrician. The replacement costs for a ballast were the cost of a new ballast and the labor cost for an electrician to replace it. We used the project's invoiced cost for the recycling of fluorescent lamps for the recycling cost, technical resource manuals' (MI and WI) estimates for the cost of a new fluorescent lamp [Cadmus 2019; Michigan Public Service Commission 2019], and secondary literature for the cost of a new ballast and labor cost estimates for the replacement of a lamp or ballast [Current 2018]. Note the \$80/hr labor rate was used for ballast replacement to reflect the higher rate of an electrician.

7.2 COST ANALYSIS AND COMPARISON

7.2.1 Simple Payback

The simple payback was calculated according to the *Cost Effectiveness* subsection of the *PERFORMANCE ASSESSMENT* section where Installed Costs were taken as the Hardware Capital and Installation Labor costs, and the Utility Cost Savings as the Facility operational cost savings – Energy from Table 21. Table 23 summarizes the simple payback for each site, as well as the total all sites taken together.

Table 23. Simple Payback at Each Site.

	Truax 510	Selfridge 124/127	Selfridge 303	All
Building Area (ft ²)	1,532	2,175	3,370	7,145
Energy Saved (kWh/ft ²)	1.3	1.8	3.6	2.6
Lighting Energy Saved (%)	67%	63%	71%	69%
Simple Payback (yr)	25.6	31.3	14.7	20.2

Note that none of the sites met the performance objective of under 11-year payback (set by preliminary estimates). Upon reviewing the details of the simple payback calculation, it was clear that the installed costs for each site were higher than expected. This increase had multiple components summarized in Table 24.

Table 24. Components of Increased Cost.

	Truax 510	Selfridge 124/127	Selfridge 303	Expected
Installation time (hr/fixture)	1.20	0.64	1.33	0.40
Fixture density (ft ² /fixture)	51	35	52	80
Total fixture markup (%)	34%	59%	77%	18%

The expected installation time per fixture of 0.4 hours was estimated by an electrical contractor during the proposal stage of this demonstration project. Note that this electrical contractor was not the one who eventually installed the lighting. The actual installation times per fixture ranged from 0.64 to 1.33 hours, translating to much higher labor costs. The higher actual labor hours may be due to the small areas associated with our sites. For each site, there is a fixed amount of time associated with traveling to the site, unloading fixtures and getting setup, and understanding the installation process. Once these are complete, the installation of a given fixture goes relatively quickly. However, since our sites were small, the fixed time became a larger component of the overall labor cost.

We originally estimated a fixture density of 80 ft²/fixture by assuming a fixture space of 8 ft × 10 ft on center. The actual fixture density was much lower, between 35 and 52 ft²/fixture. This translated to more fixtures and a higher materials cost per site. This higher fixture count per site was in part due to the prevalence of private office and conference rooms, which tend to have higher fixture densities than open office. However, the selected site open offices also had lower fixture spacing and correspondingly higher fixture counts than our original assumptions.

During the proposal stage of this project, we originally assumed a markup of 18% based on input from an electrical contractor. This is significantly lower than the 34 to 77% markup from the demonstration sites. The reasoning behind the increased markup is unclear. However, one potential reason may be the research nature of this demonstration. Contractors and distributors may have increased their bids to offset their uncertainty in installing a new, high end system that they had no previous experience with. It should be noted that manufacturers may be open to discussing selling their fixtures directly to large entities such as the DoD. Under this approach, the significant markup would be bypassed. DoD facilities would likely need to use their own facility staff for the installation and commissioning.

7.2.2 Life-Cycle Cost Analysis

Using the NIST Building Life Cycle Cost Analysis program, version 5.3, and methodology [Fuller 1995], we calculated the NPV and SIR related to the demonstrated lighting system installation at each building.

We completed the analysis for four different timeframes: 5 year, 10 years, 20 years, and 33 years. We included 33 years as it represents the full lifetime of the demonstrated lighting system, assuming 100,000 hours of system life [Cree 2019] and 3,000 hours of use annually. While 100,000 hours is related to lumen depreciation, there are other factors that may shorten the system life such as driver failure. This estimate may therefore be considered an upper bound of system life, in addition to the shorter timeframes. We estimated 3,000 hours of use as it is similar to both the average hours of use for the three buildings in this study as well as an estimate for a typical office building's annual lighting use [U.S. DOE 2017]. We applied a general price inflation of 0.1%, a nominal discount rate of 3.1% and the utility escalation rates documented in the NIST BLCCA program.

For upfront cost, we assumed no cost for the baseline and used the hardware and installation costs in Table 21 for the demonstrated lighting system alternative, minus the value of a one-time rebate for the purchase of LED lights. For operation, maintenance, and repair costs, we used the values in Table 21. However, based on estimated lifetimes, we did not include maintenance savings from avoided fluorescent lamp or ballast replacements in the 5-year analysis. Table 25 presents the NPV and SIR for each site and timeframe.

Table 25. Life-cycle Cost Analysis Results

Site	5 Years		10 Years		20 Years		33 Years	
	NPV	SIR	NPV	SIR	NPV	SIR	NPV	SIR
Truax 510	-7,505	0.18	-5,652	0.38	-3,174	0.65	-805	0.91
Selfridge 124/127	-20,695	0.11	-17,110	0.26	-12,758	0.45	-8,585	0.63
Selfridge 303	-18,855	0.31	-10,598	0.61	1,351	1.05	12,709	1.47

Only Selfridge 303 has a positive NPR and SIR greater than 1.0 by the end of the rated lifetime of the demonstrated lighting system. This is driven primarily by the high capital costs associated with the three demonstration sites. The positive NPV at Selfridge 303, compared to the other two sites' negative NPV, can be partially explained by its larger annual energy savings.

Alternative Capital Cost Scenarios

The capital costs for this project were significantly higher than both our initial estimate for this project and costs for similar installation projects. For that reason, we completed a life-cycle cost analysis using hardware and installation costs from recent demonstration projects of advanced and networked lighting controls. The Baseline scenario is defined by area-weighted averaging the 3 sites for this project. The Better scenario is defined by capital costs from General Service Administration (GSA) Proving Ground project. [PNNL 2018]. The Best scenario capital costs come from the Department of Energy LiTES project [Osbourne 2020]. Table 26 summarizes the cost elements, per square foot, under these alternatives.

Table 26. Cost Elements for Alternative Capital Costs (per square foot)

Cost Element	Baseline	Better	Best
Total Installation Cost	\$8.63	\$5.46	\$3.41
Rebate	\$0.21	\$0.21	\$0.21
Maintenance – LEDs (after year 10)	\$0.004	\$0.002	\$0.002
Facility operational cost savings – Energy	\$0.42	\$0.42	\$0.42
Facility operational cost savings – fluorescent lamp and ballast replacements	\$0.052	\$0.052	\$0.052

The Better and Best total installation costs are 37% and 60% lower, respectively, the Baseline scenario. They therefore represent much better economic scenarios. We assumed the same level of rebate and facility operational cost savings as our DoD demonstration sites. The LED maintenance for the Better and Best scenarios was adjusted based on their respective upfront material cost. We estimated material cost at about two-thirds of total installation cost, which is based on secondary literature [Rubinstein 2015] and this project’s breakdown of labor and material cost. Table 27 presents the NPV and SIR for the alternative capital cost scenarios.

Table 27. Life-cycle Cost Analysis Results – Alternative Capital Cost

Site	Simple Payback (yr)	5 Years		10 Years		20 Years		33 Years	
		NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)	NPV (\$/ft ²)	SIR (-)
Baseline	20.2	-6.52	0.23	-4.49	0.47	-1.69	0.80	0.99	1.12
Better	12.6	-3.35	0.36	-1.32	0.75	1.49	1.28	4.17	1.79
Best	7.7	-1.30	0.59	0.73	1.23	3.55	2.11	6.23	2.95

The results show that the NPV and SIR improve considerably when using Better and Best capital cost scenarios. In the 33-year analysis, both the NPV and SIR are significantly higher under the alternatives compared to the DoD project. Furthermore, the lower project costs in the Better scenario result in positive savings within 20 years, while the Best scenario results in positive savings within 10 years. Additionally, the Better and Best alternatives have simple payback periods of 12.6 and 7.7 years, respectively. The Best scenario would therefore meet our economic success criteria of a payback of 11 years or less.

7.2.3 Sensitivity Analysis

This project quantified the energy impacts and associated economics of the demonstrated lighting system at three specific DoD facilities. To better understand the range of potential impacts at DoD installations nationwide, we performed a sensitivity analysis of the most impactful system properties. This sensitivity analysis included:

- Space type
 - High and low pre-retrofit LPD
 - High and low annual occupied hours

- Post-retrofit lighting system with and without controls
- High, average and low capital costs
- High, average and low electric consumption utility rates
- With and without electric demand charges
- High, average and low rebates

The primary drivers of energy savings are the pre-retrofit installed LPD and annual occupied hours. Both depend on the space type of retrofit space. We analyzed applicable space types for the demonstrated lighting system including private and open office, conference, corridor, storage, classroom, as well as dining, exercise, and library areas.

We defined the high and low pre-retrofit installed LPD using the space-by-space method from ANSI/ASHRAE/IES Standard 90.1-2004 and 90.1-2013, respectively. We defined the occupied hours for each space type using the occupancy schedules developed for the U.S. DOE commercial reference models. [U.S Department of Energy 2011]

Table 28 summarizes the assumed range of installed LPD and annual hours of occupancy, as well as the resulting annual electricity usage, for each space type.

Table 28. Summary of Space Types and Associated Properties Used in Sensitivity Analysis.

Space Type	Installed LPD (W/ft ²)		Annual Occupancy (hr)		Annual Electric Consumption (kWh/ft ²)	
	Low (2013)	High (2004)	Low	High	Low	High
Private office	1.11	1.5	1491	3654	1.7	5.5
Open office	0.98	1.3	1491	3654	1.5	4.8
Conference	1.23	1.5	634	1057	0.8	1.6
Corridor	0.66	0.7	1491	3654	1.0	2.6
Storage	0.63	1.1	2135	3558	1.3	3.9
Classroom	1.24	1.6	2573	3913	3.2	6.3
Dining Area	0.65	1.4	2573	5488	1.7	7.7
Exercise Area	0.75	1.1	2573	5216	1.9	5.7
Library Area	1.06	1.8	2573	3744	2.7	6.7

We assumed that occupancy controls are being installed in a significant percentage of applicable DoD spaces. However, the occupancy controls proportion of our savings estimates was relatively low (4%). We further assumed that if an existing lighting system already has photocontrol, it is likely a high performing system that would not make economic sense to retrofit with the demonstrated lighting system. Finally, task tuning is a relatively new control strategy and not implemented broadly in commercial buildings. We therefore did not perform a sensitivity on the savings from pre-retrofit lighting systems with occupancy, photosensor or task tuning controls. However, the retrofit spaces within our demonstration project had a range of post-retrofit controls:

- From open offices with consistent occupancy to conference rooms and private offices with highly variable occupancy
- From internal spaces with no daylight to perimeter spaces with significant daylight
- From spaces with the appropriate amount of light level to spaces that were significantly overlit

We therefore performed a sensitivity of post-retrofit lighting system both with and without controls. The electricity consumption and demand savings for the case with controls were taken as the full savings from our combined demonstration sites; 69% and 70%, respectively. For the case without controls, we subtracted the photocontrol, occupancy control and task tuning proportions from Table 14. The electricity consumption and demand savings for the case without controls were therefore calculated as 38% and 39%, respectively. The electricity consumption and demand savings were calculated by applying these percentages to the annual electricity consumption and LPD in Table 28, respectively. Table 29 summarizes the electricity consumption and demand savings for each space type both with and without controls.

Table 29. Electricity Consumption and Demand Savings for Each Space Type Both with and Without Controls.

Space Type	Electric Consumption Savings (kWh/ft ²)				Peak Demand Savings (W/ft ²)			
	With Controls		Without Controls		With Controls		Without Controls	
	Low	High	Low	High	Low	High	Low	High
Private office	1.1	3.8	0.9	3.0	0.8	1.0	0.6	0.8
Open office	1.0	3.3	0.8	2.6	0.7	0.9	0.5	0.7
Conference	0.5	1.1	0.4	0.9	0.9	1.0	0.7	0.8
Corridor	0.7	1.8	0.5	1.4	0.5	0.5	0.4	0.4
Storage	0.9	2.7	0.7	2.1	0.4	0.8	0.3	0.6
Classroom	2.2	4.3	1.7	3.4	0.9	1.1	0.7	0.9
Dining Area	1.2	5.3	0.9	4.2	0.5	1.0	0.4	0.8
Exercise Area	1.3	4.0	1.1	3.1	0.5	0.8	0.4	0.6
Library Area	1.9	4.6	1.5	3.7	0.7	1.3	0.6	1.0
<i>Minimum</i>	<i>0.5</i>	<i>1.1</i>	<i>0.4</i>	<i>0.9</i>	<i>0.4</i>	<i>0.5</i>	<i>0.3</i>	<i>0.4</i>
<i>Median</i>	<i>1.1</i>	<i>3.8</i>	<i>0.9</i>	<i>3.0</i>	<i>0.7</i>	<i>1.0</i>	<i>0.5</i>	<i>0.8</i>
<i>Maximum</i>	<i>2.2</i>	<i>5.3</i>	<i>1.7</i>	<i>4.2</i>	<i>0.9</i>	<i>1.3</i>	<i>0.7</i>	<i>1.0</i>

The highest electric consumption savings were realized in spaces with long hours of operation and high LPDs. These included classrooms, dining areas and libraries. The lowest consumption savings were conversely in spaces with low hours of operation and low LPDs. These included corridors and conference rooms. Demand savings were highest in spaces with high LPDs.

This included private office, conference, classroom and libraries. As expected, both consumption and demand savings were highest in spaces with controls as compared to those without.

In order to calculate simple payback from consumption and demand savings, we needed to define a capital cost and rebate, as well as electricity consumption and demand utility rates. We defined the high, average and low capital cases using the cost data from our project (\$8.63/ft²), the GSA (\$5.46/ft²) [PNNL 2018], and DOE LiTES (\$3.41/ft²) [Osbourne 2020], respectively. We defined high, average, and low electric consumption utility rates from U.S. EIA data. [U.S. EIA 2019] This data showed a maximum electricity consumption utility rate of \$0.292/kWh, a minimum of \$0.078/kWh and a national average of \$0.110/kWh. We defined high demand charges of \$20/kW as this threshold covers a significant proportion of the U.S. population. [McLaren 2017] The low demand charge case was defined as having no demand charge.

In order to define the various rebate cases, we undertook an analysis of the range of rebates offered through various advanced lighting control utility programs. Fortunately, the DOE LiTES projected summarized the range of incentives they found in a review of applicable programs. [Osbourne 2020] Unfortunately, the available incentives have different bases (kW saved, kWh saved, ft²). We therefore normalized each range of incentives to a per square foot bases using the appropriate normalizing unit from our project (e.g. \$0.185/W controlled $\times$ 0.600 W controlled = \$0.11/ft²). Table 30 summarizes the range of incentives available, our normalizing unit, and the resulting per square foot incentive.

Table 30. Range of Incentives, Normalizing Unit and Resulting Per Square Foot Incentive.

Incentive Range (\$/Base Unit)			Normalizing (Base Unit/ft ²)	Incentive Range (\$/ft ²)	
Low	High	Bases Unit	Value	Low	High
\$0.185	\$0.800	W controlled	0.600	\$0.11	\$0.48
\$150	\$185	kW saved	0.001	\$0.15	\$0.19
\$0.18	\$0.25	kWh saved	2.554	\$0.46	\$0.64
\$0.05	\$0.75	ft ²	n/a	\$0.05	\$0.75
\$15	\$45	fixture	0.022	\$0.33	\$1.00

We defined the high rebate case as the average of the high incentive range or \$0.61/ft². We defined the average rebate case as average of the low incentive range or \$0.22/ft². The low rebate case was defined as having no rebates.

Baseline

Our baseline case was an average capital cost, no rebates, average electric consumption utility rates and no demand charges. Table 31 summarizes the calculated simple payback for the baseline case.

Table 31. Simple Payback for Baseline Case.*(Average capital cost, no rebates, average electric consumption utility rates and no demand charges)*

Space Type	Simple Payback (years)			
	With Controls		Without Controls	
	Low	High	Low	High
Private office	43.4	13.1	54.8	16.6
Open office	49.2	15.1	62.1	19.1
Conference	92.2	45.3	116.4	57.2
Corridor	73.1	28.1	92.2	35.5
Storage	53.4	18.4	67.5	23.2
Classroom	22.5	11.5	28.4	14.5
Dining Area	43.0	9.4	54.3	11.8
Exercise Area	37.3	12.5	47.0	15.8
Library Area	26.4	10.7	33.3	13.5
Minimum	22.5	9.4	28.4	11.8
Median	43.4	13.1	54.8	16.6
Maximum	92.2	45.3	116.4	57.2

Note that the Low case is defined by low LPDs and shorter hours of occupancy, while the High case is defined by higher LPDs and longer hours of occupancy. For the baseline case, simple paybacks are lowest in spaces with high LPDs and longer hours of occupancy (see Table 28 for more details). When implementing a system with the full range of controls, the lowest simple paybacks were in dining areas, library areas and classrooms. Paybacks increased by 26% when controls were not implemented. Paybacks were highest in spaces with low LPDs such as corridors or shorter hours of occupancy such as conference.

It is interesting to compare these results to the Life-Cycle Cost Analysis from the demonstration sites. The demonstration sites were primarily private and open offices with a minimal amount of corridors and conference rooms. They had controls and relatively high existing LPDs. The most relevant simple paybacks from Table 31 are therefore those from the “With Controls” and “High” column. The simple paybacks of 13.1 and 15.1 years for private and open offices, respectively, are lower than the demonstration site average of 20.2 years. This makes sense considering the average capital cost was 37% lower for the sensitivity analysis.

Capital Cost

Table 32 summarizes the capital cost sensitivity results. Note that only the High (90.1-2004 with longer hours of occupancy) cases are provided for simplicity, since Table 31 indicates that the Low cases (90.1-2013 and shorter hours of occupancy) should be avoided due to their high simple paybacks.

Table 32. Simple Payback for Capital Cost Sensitivity.*(No rebates, average electric consumption utility rates and no demand charges)*

Space Type	Simple Payback (years)					
	High Capital Cost (\$8.63/ft ²)		Average Capital Cost (\$5.46/ft ²)		Low Capital Cost (\$3.41/ft ²)	
	With Controls	Without Controls	With Controls	Without Controls	With Controls	Without Controls
Private office	20.7	26.2	13.1	16.6	8.2	10.3
Open office	23.9	30.2	15.1	19.1	9.4	11.9
Conference	71.7	90.5	45.3	57.2	28.3	35.8
Corridor	44.4	56.1	28.1	35.5	17.5	22.2
Storage	29.0	36.7	18.4	23.2	11.5	14.5
Classroom	18.1	22.9	11.5	14.5	7.2	9.1
Dining Area	14.8	18.7	9.4	11.8	5.8	7.4
Exercise Area	19.8	25.0	12.5	15.8	7.8	9.9
Library Area	16.9	21.3	10.7	13.5	6.7	8.4
Minimum	14.8	18.7	9.4	11.8	5.8	7.4
Median	20.7	26.2	13.1	16.6	8.2	10.3
Maximum	71.7	90.5	45.3	57.2	28.3	35.8

As expected, the simple payback is strongly influenced by capital cost with decreases in capital cost resulting in proportional decreases in simple payback. The average simple payback with controls decreases from 28.8 to 18.2 to 11.4 for the high, average and low cases, respectively.

Electric Consumption Utility Rate

Note that only the High (90.1-2004 with longer hours of occupancy) cases are provided for simplicity, since Table 31 indicates that the Low cases (90.1-2013 and shorter hours of occupancy) should be avoided due to their high simple paybacks.

As expected, the simple payback is strongly influenced by electric consumption utility rate with decreases in electric consumption utility rate resulting in proportional increases in simple payback (for the case with no rebate and no demand charge). The average simple payback with controls increases from 6.9 to 18.2 to 25.6 for the high, average and low cases, respectively. The regions with the highest electric consumption utility rates were New England, Mid Atlantic, Pacific Contiguous, Alaska and Hawaii making these the regions with the most favorable simple paybacks.

Demand Charge

Table 33 summarizes the demand charge sensitivity results. Note that only the High (90.1-2004 with longer hours of occupancy) cases are provided for simplicity, since Table 31 indicates that the Low cases (90.1-2013 and shorter hours of occupancy) should be avoided due to their high simple paybacks.

Table 33. Simple Payback for Demand Charge Sensitivity.*(Average electric consumption utility rate, average capital cost and no rebates)*

Space Type	Simple Payback (years)			
	High Demand Charge (\$20/kW)		Low Demand Charge (\$0/kW)	
	With Controls	Without Controls	With Controls	Without Controls
Private office	8.2	10.3	13.1	16.6
Open office	9.4	11.9	15.1	19.1
Conference	14.7	18.6	45.3	57.2
Corridor	17.5	22.2	28.1	35.5
Storage	11.3	14.3	18.4	23.2
Classroom	7.3	9.3	11.5	14.5
Dining Area	6.7	8.4	9.4	11.8
Exercise Area	8.8	11.1	12.5	15.8
Library Area	6.7	8.5	10.7	13.5
Minimum	6.7	8.4	9.4	11.8
Median	8.8	11.1	13.1	16.6
Maximum	17.5	22.2	45.3	57.2

Peak demand charges have a significant impact on simple payback. For this sensitivity, they reduced the average simple payback for spaces with controls by 44%, from 18.2 to 10.1 years. Note that the demand charge component of the overall energy cost savings was between 29% and 68% depending on the space type. Further note that we assumed the average electricity consumption utility rate for this sensitivity. However, regions with high demand charges tend to have higher consumption rates, which would further reduce the simple paybacks.

Rebate

Table 34 summarizes the rebate sensitivity results. Note that only the High (90.1-2004 with longer hours of occupancy) cases are provided for simplicity, since Table 31 indicates that the Low cases (90.1-2013 and shorter hours of occupancy) should be avoided due to their high simple paybacks.

Table 34. Simple Payback for Rebate Sensitivity.*(Average electric consumption utility rate, average capital cost and no demand charges)*

Space Type	Simple Payback (years)					
	High Rebate (\$0.61/ft ²)		Average Rebate (\$0.22/ft ²)		Low Rebate (\$0.00/ft ²)	
	With Controls	Without Controls	With Controls	Without Controls	With Controls	Without Controls
Private office	11.6	14.7	12.6	15.9	13.1	16.6
Open office	13.4	17.0	14.5	18.3	15.1	19.1
Conference	40.3	50.8	43.5	54.9	45.3	57.2
Corridor	25.0	31.5	27.0	34.0	28.1	35.5
Storage	16.3	20.6	17.6	22.2	18.4	23.2
Classroom	10.2	12.9	11.0	13.9	11.5	14.5
Dining Area	8.3	10.5	9.0	11.3	9.4	11.8
Exercise Area	11.1	14.0	12.0	15.2	12.5	15.8
Library Area	9.5	12.0	10.2	12.9	10.7	13.5
Minimum	8.3	10.5	9.0	11.3	9.4	11.8
Median	11.6	14.7	12.6	15.9	13.1	16.6
Maximum	40.3	50.8	43.5	54.9	45.3	57.2

Rebates have a minor impact on simple payback. For the high rebate case, they reduced the average simple payback for spaces with controls by 11%, from 18.2 to 16.2 years. For the low rebate case, they reduced the average simple payback for spaces with controls by 4%, from 18.2 to 17.5 years.

Sensitivity Conclusion

The best application for LED lighting systems with integrated controls is in spaces with the following characteristics:

- High existing LPD and limited lighting controls
- Long hours of occupancy
- Variable occupancy and significant daylight availability
- High electric consumption and demand charges

While rebates are helpful, they are usually secondary to these factors. However, they offset an increasing proportion of upfront costs, as capital costs decrease. Table 35 summarizes the simple payback in the best-case scenario.

Table 35. Simple Payback for Best Case Scenario

(High electric consumption utility rate of \$0.29/kWh, high demand charges of \$20/kW, low capital cost of \$3.49/ft², and high rebates of \$0.61/ft²)

Space Type	Simple Payback (years)	
	With Controls	Without Controls
Private office	2.1	2.6
Open office	2.4	3.0
Conference	4.9	6.2
Corridor	4.4	5.6
Storage	2.9	3.6
Classroom	1.8	2.3
Dining Area	1.6	2.0
Exercise Area	2.1	2.6
Library Area	1.7	2.1
<i>Minimum</i>	<i>1.6</i>	<i>2.0</i>
<i>Median</i>	<i>2.1</i>	<i>2.6</i>
<i>Maximum</i>	<i>4.9</i>	<i>6.2</i>

8.0 IMPLEMENTATION ISSUES

8.1 LESSONS LEARNED

Throughout the project, we learned several valuable lessons that would be beneficial to future projects.

The general trend is decreasing installed cost for these systems. As this trend continues, the overall economics of these lighting systems will naturally improve. However, the following may help expedite this within DoD facilities. The installed cost at our demonstration sites was much higher than expected. This involved several factors; installation time, fixture density, and markups. Our higher-than-expected labor hours may be due to the small areas associated with our sites. Fixed costs do not scale with site size, making it more advantageous to pursue lighting retrofit of larger areas ($>25,000 \text{ ft}^2$). Our sites also had more fixtures per square foot than originally expected. It is our general recommendation is to perform one-for-one lighting replacements. However, in spaces with high existing fixture density (6 ft $\times$ 8 ft or closer), photometric modeling should be performed to see if fewer fixtures can adequately light the space. The reduced number of fixtures may offset the additional time spent rewiring. The fixture markup for our demonstration sites was also higher than expected. We recommend that DoD facility staff work closely with their contractor network to develop a trained workforce with experience on integrated lighting control systems. As contractor's become more familiar with these systems, they will perceive less risk in installing them. This will result in more accurate bids and less time spent on projects "getting to know" the systems.

It is important to get facility staff and office managers buy-in. They are valuable resources throughout the retrofit process from coordinating site visits to the retrofit itself, providing relevant information about the spaces and systems to be retrofit (building plans, equipment specifications, schedules...), and communicating information to the space occupants. They also provide valuable feedback about the control setpoints for each space. Their assistance throughout the project is instrumental to its success. Obtaining their buy-in may be facilitated by explaining the benefits of the lighting system (energy savings, utility cost savings, increased occupant satisfaction) and how that aligns with their mission.

Specifically, we found it useful to create a control matrix. This control matrix outlined our assumptions regarding how each space's lighting would be controlled. The facility staff and office manager reviewed our assumptions and provided feedback based on their understanding of the space's needs. This feedback helped optimize the controls in each space and minimize subsequent occupant complaints. Table 36 illustrates an example control matrix.

Table 36. Example Control Matrix.

Zone	Control Mode	Occupied / Unoccupied Level	Occupancy Sensitivity	Occupancy Timeout	Daylighting Minimum Setpoint	Task Tuning
Private Office A	Manual On, Auto Off (default)	100% / 0% (default)	Medium	5 mins	0%	75%

Zone	Control Mode	Occupied / Unoccupied Level	Occupancy Sensitivity	Occupancy Timeout	Daylighting Minimum Setpoint	Task Tuning
Private Office B	Manual On, Auto Off (default)	100% / 0% (default)	Medium	5 mins	0%	80%
Private Office C	Manual On, Auto Off (default)	100% / 0% (default)	Medium	5 mins	Disabled	100% (default)
Open Office A	Manual On, Auto Off (default)	100% / 0% (default)	High (default)	20 mins (default)	30%	50%
Open Office B	Manual On, Auto Off (default)	100% / 0% (default)	High (default)	20 mins (default)	5% (default)	50%
Corridor	Auto On, Auto Off	5%	Low	20 mins (default)	5% (default)	50%

It is also important to obtain buy-in from the occupants. This similarly involves educating them about the benefits of the system and the basics of its operation. If they understand why the lights are dimming or turning off automatically, they are less likely to complain. This information may be provided to occupants through a succinct brochure left on occupant desks after the retrofit. It may also be disseminated via email prior to the retrofit as well. We also found that gathering occupant feedback throughout the project was beneficial. The pre-retrofit occupant survey identified areas that needed improvement. This data also informed the extent to which occupants would be comfortable with aggressive versus conservative control setpoints (e.g., shorter time out periods and lower task tuning setpoints).

We further found that photometric models are useful in estimating the illuminance in the post-retrofit spaces. However, they are not always accurate. In retrospect, our photometric models could have been improved by more specifically representing interior furniture, particularly tall partitions and associated storage cabinets. Confirming light levels with spot measurements and then adjusting task tuning setpoints accordingly is strongly recommended.

Finally, we learned several lessons during commissioning. Drawing any shades or blinds during the lighting system's commissioning process is a good idea. We anecdotally believe that the demonstrated lighting system's autocalibration of daylighting sensors is adversely affected by direct sunlight. So, minimizing direct sunlight will improve the calibration and subsequent daylighting controls. In addition, the auto-commissioning process shortens the time spent programming the demonstrated system. Combined with a set of reasonable defaults, the programming of the system may be very straightforward. However, in order to optimize the system's controls, more time is needed to update control settings. For instance, it was fairly time intensive to set all the different task tuning setpoints for each space via the handheld remote. Future projects should evaluate the tradeoff between the time spent adjusting control settings and the additional savings gained. Using one task tuning setpoint across an entire network of fixtures may be a quick way to capture additional savings. In this scenario, a more modest task tuning reduction should be applied since you no longer have the space-by-space granularity.

8.2 UFCS GOVERNING THE DEMONSTRATION

The UFC is the primary application regulation for the demonstrated lighting system. Specifically, UFC 1-200-02 (updated October 2019) covers High Performance and Sustainable Building Requirements. The following outlines relevant sections:

- 1-2 PURPOSE AND SCOPE: References ANSI/ASHRAE/IES Standard 90.1 and ASHRAE Standard 189.1 requirements.
- 1-4 UFC APPLICABILITY: Defines the project types which fall under the UFC. This includes new construction and existing building renovations.
- 1-7 LIFE-CYCLE COST ANALYSIS: Defines the cost effectiveness analysis requirements for projects including reference to CFR Title 10 Part 436 Subpart A.
- 1-8 CYBERSECURITY: References UFC 4-010-06 requirements.
- 2-3.1 ENERGY EFFICIENCY: Defines the energy consumption reduction target for new construction of 30% beyond ASHRAE 90.1 baseline, or best achievable per Life-Cycle Cost Effectiveness test.
- 2-5.2 DAYLIGHTING AND LIGHTING CONTROLS: References automated daylighting controls requirements for new construction within UFC 3-530-01.
- 3-4.1 ENERGY EFFICIENCY: Defines the energy consumption reduction target for existing buildings options which range between 20% and 30%.
- 3-6.2 DAYLIGHTING AND LIGHTING CONTROLS: References automated daylighting controls and occupancy/vacancy control requirements for existing buildings within UFC 3-530-01.

UFC 3-530-01 (updated November 2019) covers Interior and Exterior Lighting Systems and Controls in more depth. This document provides a lot of relevant information, the key components of which are outlined subsequently:

- 1-2 PURPOSE AND SCOPE: Defines the scope of the document and references the Illuminating Engineering Society's Lighting Handbook Reference and Application document.
- 1-3 APPLICABILITY: Defines the applicability projects including design interior lighting systems for new construction and existing buildings.
- 1-4 GENERAL BUILDING REQUIREMENTS: References UFC 1-200-02.
- 2-1 PRIORITIES FOR LIGHTING SYSTEMS: Defines the priorities for applicable projects including energy savings, reducing maintenance costs, improving lighting quality, and lowering life-cycle cost.
- 2-2 LIGHTING CONTROLS: Summarizes required lighting controls thru reference to ASHRAE 90.1 and 189.1.

- 2-2.1 DAYLIGHTING CONTROL REQUIREMENTS: Defines additional requirement for automatic continuous daylight dimming in task-oriented areas and turning off lights in non-task areas.
- 2-2.3 CONTROL STRATEGIES: Requires summarizing control strategies in each space within contract documents. Additional provides exception for occupancy sensor control in areas surrounding electrical service equipment.
- 2-4.1 LIGHT SOURCE TECHNOLOGY: Includes requirement for correlated color temperatures (CCT) below 4100 K and uniform CCT throughout project. Additional requirement for color rendering index (CRI) greater than or equal to 80.
- 2-4.1.1 SOLID STATE LIGHTING: Includes requirements for LED luminaires to be dimmable, and that NEMA SSLA 7A, IES LM-79, LM-80 and TM-21 testing reports should be provided. Also requires a 10-year warranty on LED luminaires.
- 2-4.2.1: SOLID STATE: Includes requirements of a total current harmonic distortion of less than or equal to 20% and a power factor of greater than or equal to 0.9.
- 2-8: LIGHTING SYSTEM ALTERATIONS: Recommends that lighting levels generally may be reduced as compared to those provided by existing lighting systems.
- 3-2 LIGHTING CALCULATIONS: Requires photometric modeling for verification of compliance with guidelines pertaining to horizontal illuminance, minimum, maximum and average illuminance, average-to-minimum and minimum-to-maximum ratios and lighting power density.
- 3-3 GENERAL BUILDING SPACES: Summarizes lighting control strategies, horizontal illuminance, vertical illuminance and illuminance uniformity by space type.

Note that when properly designed, the demonstrated lighting system will meet these requirements. Table 37 summarizes the demonstrated lighting system's characteristics that meet UFC requirements.

Table 37. Lighting System Characteristics Meeting UFC Requirements.

Correlated Color Temperature ≤ 4100 K
Color Rendering Index ≥ 80
Dimmable
10-year warranty of luminaires
Total Harmonic Distortion $\leq 20\%$
Power Factor ≥ 0.9
Occupant/Vacancy Control with updatable timeout periods
Automatic Daylighting Control
Task Tuning for aligning illuminance with space-specific recommendation
Light distribution for providing uniformity meeting space-specific minimum
Low fixture power for meeting space-specific LPD maximum

We therefore have no recommendations for updating the UFC to allow for future retrofits of the demonstrated lighting system.

8.3 PERMITS

No special permits were required within the scope of this project.

8.4 END USER CONCERNS

Occupant feedback is critical to project success. This feedback may result in reduced energy savings, primarily through increased task tuning setpoints. However, the overall impact on energy savings is relatively small. And energy savings are much more likely to persist if occupants are satisfied with their lighting.

The main end user concerns within this demonstration project were low light levels. These concerns were limited to a small portion, approximately 5%, of the overall users affected. These 3 respondents occupied private offices in each of the sites. We addressed these concerns by increasing the task tuning setpoint. We also raised the daylighting minimum from 5% to 35% in several areas and disabled daylighting altogether in 2 private offices.

There were minimal concerns reported by the installers and facility maintenance staff. Their feedback is summarized in the *Ease of Installation, Commissioning and Operating*

Subsection of the *PERFORMANCE ASSESSMENT* section.

8.5 PROCUREMENT ISSUES

The demonstrated lighting system is currently commercially available. It is relatively new with limited market penetration. It is therefore new to most electrical contractors and facility staff. The manufacturer provides support through design, installation and commissioning, which is helpful to successful project implementation.

It should be noted that many manufacturers may be open to discussing selling their fixtures directly to large entities such as the DoD. Under this approach, the significant markup from contractors and distributors would be bypassed, improving the project's economics. In this scenario, DoD facilities would likely need to use their own facility staff for the installation and commissioning.

Passing the cybersecurity review was slow for this demonstration project. This was due to education and time constraints as opposed to technological reasons. Only one person on base was trained to make the eMASS entries. Their availability was limited, causing long delays between progress. It would be beneficial for future projects to have more than one person trained and authorized to enter information. During the review, the eMASS entry was accidentally initiated within the incorrect AO boundary. We retroactively realized the mistake but did not have access to update to the correct boundary. This resulted in further delays as we determined who could make the adjustment. Future projects will benefit from the experience gained during correcting this mistake. Another issue was the discrepancy between the eMASS templates we filled out and the actual eMASS entry. Between our filling out the templates and entering the information, the system was updated. Future projects will benefit from a less dynamic process.

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APPENDIX A POINTS OF CONTACT

Points of Contact for the project are listed in Table 38 and Table 39.

Table 38. Installation Points of Contact.

Role	Truax Field	Selfridge ANGB
Installation commander	Col Erik Peterson WI Air National Guard	Gen Mike Stone MI Air National Guard
Primary contact for project	SMSgt Ryan P. Johnson Operations Management Supt 608.245.4320 ryan.johnson.40@us.af.mil	Steve Krajnik, Chief of Engineering 586.239.2013 james.s.krajnik.civ@mail.mil
Day-to-day contact for project	SMSgt Ryan P. Johnson Operations Management Supt 608.245.4320 ryan.johnson.40@us.af.mil	Darren Burton Construction Control 586.239.4994 darren.m.burton.civ@mail.mil

Table 39. Other Points of Contact.

Role	Contact
Project lead at Cree	Kris Evans Technical Sales Manager, Intelligent Lighting 414.841.1741 kevans@cree.com
Wisconsin monitoring installation subcontractor	Forward Electric Madison, WI Mark Loeffelholz 608.221.1945 phone mark@forwardelectric.com
Michigan monitoring installation subcontractor	Vet-Con Dave Gregg 810.252.7538 dgregg@vet-con.us
Photography	Adam Karl photography Adam Tyksinski 608.345.1751 adam45456@hotmail.com

APPENDIX B OCCUPANT SURVEY

Slipstream is completing a research study of the lighting system in your building. If you have a moment, we'd appreciate your feedback. Note that this survey is completely voluntary. *When you complete the form, please return it to your facility manager. Thank you!*

Base name: _____

Building name/number: _____

Which of the following best describes your workspace?

- ☐ Private Office
- ☐ Open Office
- ☐ Other: _____

Is your workspace within 15 feet of a window?

- ☐ Yes
- ☐ No

Do you have any of the following controls over the lighting in your workspace?

(check all that apply)

- ☐ Manual switch
- ☐ Manual dimmer
- ☐ Window blinds or shades
- ☐ Desk (task) lamp
- ☐ None of the above
- ☐ Other: _____

Please rank the following:

Your level of satisfaction with the amount of light in your workspace:

1 (very satisfied) 2 3 (neutral) 4 5 (very dissatisfied)

Your level of satisfaction with your ability to control your overhead lighting:

1 (very satisfied) 2 3 (neutral) 4 5 (very dissatisfied)

Your level of satisfaction with the visual comfort of the lighting (glare, reflections, contrast)

1 (very satisfied) 2 3 (neutral) 4 5 (very dissatisfied)

Your lighting quality's ability to enhance or interfere with your ability to do your work:

1 (enhance) 2 3 (neutral) 4 5 (interfere)

Please describe any other issues related to the lighting in your workspace that are important to you.

APPENDIX C INSTALLER AND FACILITY STAFF SURVEY

Please consider your responses with respect to a traditional fluorescent system with no controls and a similar high performing system with controls where applicable.

Installation

1. Was the installation process of the demonstrated lighting system more or less difficult to understand compared to:
 - a. Traditional System
 - b. Similar High Performing SystemAdditional Detail:
2. Was the installation of the demonstrated lighting system more or less difficult than:
 - a. Traditional System
 - b. Similar High Performing SystemAdditional Detail:
3. Did it take more time, less time or about the same amount of time to install the demonstrated lighting fixtures compared to:
 - a. Traditional System
 - b. Similar High Performing SystemAbout how much more or less time did it take?
Additional Detail:
4. If applicable, what specific problems did you encounter while installing the demonstrated lighting fixtures? What was easier about the demonstrated lighting fixture installation?
5. Did it take more time, less time or about the same amount of time to install the demonstrated dimming switches compared to:
 - a. Traditional System
 - b. Similar High Performing SystemAbout how much more or less time did it take?
Additional Detail:
6. What specific problems did you encounter while installing the dimming switches? What was easier about the dimming switch installation?

Commissioning

1. Was the commissioning process of the demonstrated lighting system more or less difficult to understand compared to:
 - a. Traditional System

- b. Similar High Performing System

Additional Detail:

- 2. Was commissioning the demonstrated lighting system more or less difficult compared to:

- a. Traditional System
- b. Similar High Performing System

Additional Detail:

- 3. Did it take more time, less time or about the same amount of time to commission the demonstrated lighting system compared to:

- a. Traditional System
- b. Similar High Performing System

Additional Detail:

- 7. What specific problems did you encounter while commissioning the demonstrated lighting system? What was easier about the commissioning?

Operation (if applicable)

- 1. Is the operation of the demonstrated lighting system more or less difficult to understand compared to:

- a. Traditional System
- b. Similar High Performing System

Additional Detail:

- 2. Is the operation of the demonstrated lighting system more or less difficult compared to:

- a. Traditional System
- b. Similar High Performing System

Additional Detail:

- 3. Does it take more time, less time or about the same amount of time to maintain the demonstrated lighting system compared to:

- a. Traditional System
- b. Similar High Performing System

Additional Detail:

- 8. What specific problems have you encountered while operating the demonstrated lighting system? What has been easier about the operation?

Overall

- 1. How would you rate your level of satisfaction with the demonstrated lighting system?

1 (very satisfied) 2 3 (neutral) 4 5 (very dissatisfied)

Additional Detail:

2. Would you select the demonstrated lighting system for a similar lighting project?

1 (definitely) 2 3 (maybe) 4 5 (definitely not)

Additional Detail:

3. What other feedback do you have regarding the demonstrated lighting system?

APPENDIX D EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

Equipment calibration

Prior to field installation, each equipment assembly of Onset CTV-A CTs and Onset Hobo UX120-006M 4 channel data loggers was compared to a calculated current drawn from a standard 125 W incandescent lamp. Any discrepancies were investigated and resolved.

The eGauge power meters were all new and came factory calibrated from the manufacturer.

The existing Extech EA30 light meter was calibrated traceable to National Institute of Standard and Technologies.

The existing LI-COR LI-210R photometric sensors were sent to the manufacturer for calibration. Both existing and new photosensors were calibrated traceable to National Institute of Standard and Technologies. Each equipment assembly was compared to the illuminance measurements of the Extech light meter prior to field installation under a constant light source. Any discrepancies were investigated and resolved.

Scott Schuetter and Dan Cautley ensured proper calibration of all data collection equipment.

Quality Assurance Sampling

We looked at eGauge data on a weekly basis to ensure that this monitoring equipment and associated cellular connection was operating properly. We downloaded Hobo data at least once during each monitoring period and at the end of each monitoring period. The battery charge and data storage limits were checked during these downloads.

We looked for missing data or data that was zero when we would expect non-zero values.

We looked for data exceeding the lighting system's maximum power as well as data below zero power. In addition, the lighting system should not be able to operate at powers between its photocontrol and occupancy control minimum settings, nor between its maximum power and tuned power settings. We looked for data between these ranges as well.

We removed any data that was well out of the range of normal operation, including monitored powers above the rated power of the lighting fixtures. After an in-depth data review, it was clear that abnormal data was associated with voltages below 80 V or above 150 V. The nominal voltage of every monitored lighting circuit was 120 V, with normal operation within ± 2 V. This abnormal data appeared to be associated with an eGauge firmware issue, as the occurrence of this data issue was resolved after a firmware update. The extent of the removed data was small, representing less than 0.05% of the entire dataset.

We additionally removed eGauge and Hobo data from days when Slipstream personnel were at a given site. The underlying assumption was that system operation were affected by our presence, and therefore did not represent normal operation.

Prior to monitoring, it was important to understand the characteristic timescale of the monitored systems. This timescale is a guide in selecting the frequency at which data is collected. We therefore performed a preliminary analysis to quantify the maximum sampling timescale that would capture dynamic system effects. The main dynamic system effects of a lighting system were occupancy or manual control and photosensor control. To understand the timescale of these controls, we visually inspected monitored lighting power from previous research studies. Figure 40 illustrates monitored power from two spaces, each with manual or automated photocontrol. We found that the timescale associated with occupancy/manual control was greater than that associated with photosensor control. We therefore focused on photosensor control in determining our data capture frequency.

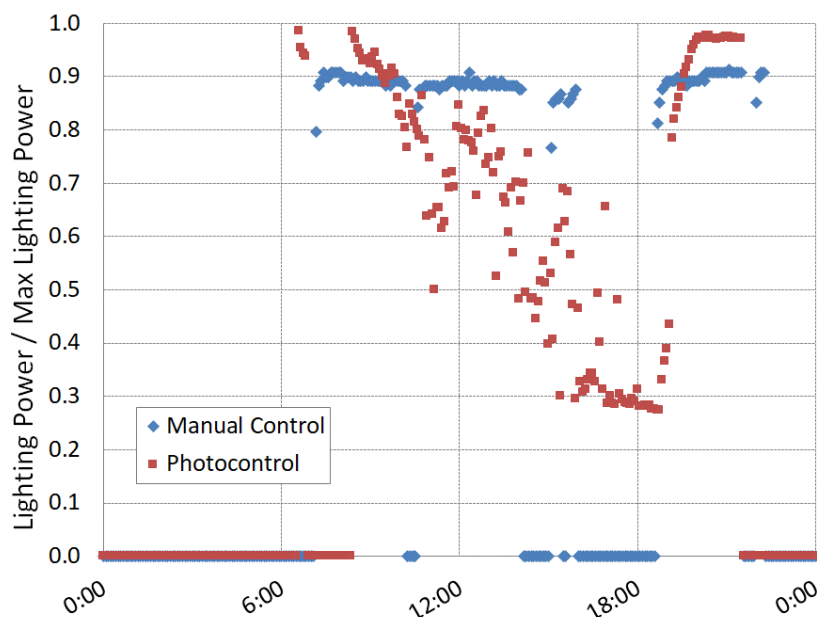


Figure 40. Monitored Lighting Power for a Manually Controlled and Photocontrolled Space During a Typical Day.

Photosensor controls typically have programmed delays and ramp periods to ensure the lights do not adjust too rapidly, minimizing occupant complaints. These settings are longer than that of the timescale of daylight illuminance variation. To understand the timescale of lighting systems with photocontrols, we measured total illuminance at the working plane in a strongly daylit space (Figure 41) at 10 second intervals. Note that this was Slipstream’s own space, and not one of the retrofit spaces from this demonstration.



Figure 41. Highly Daylit Space with Photocontrolled Lighting System.

Figure 42 illustrates monitored total illuminance at the working plane over an entire day. Note the high variability of illuminance during daylight periods and the constant illuminance during the evening.

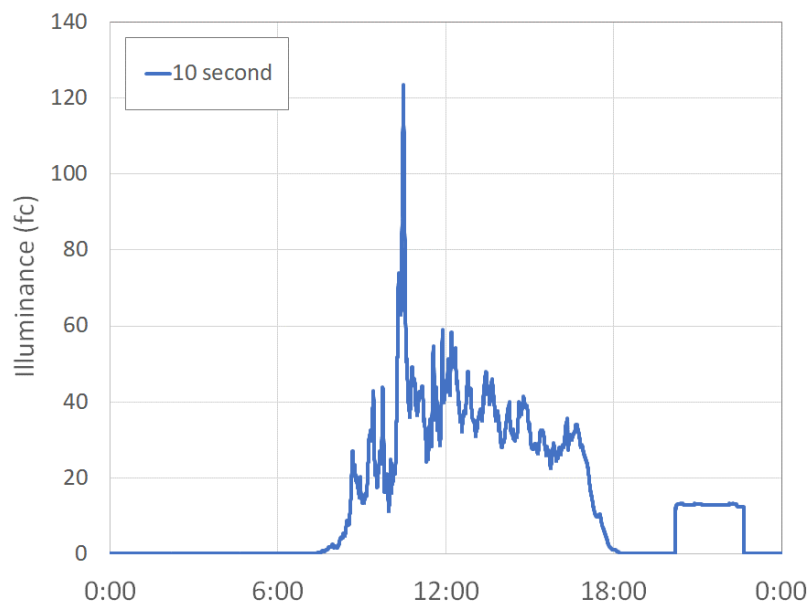


Figure 42. Monitored Total (Daylight and Electric) Illuminance at the Working Plane in a Photosensor Controlled, Highly Daylit Space.

We then plotted only the data points from this data set at varying time intervals (Figure 43).

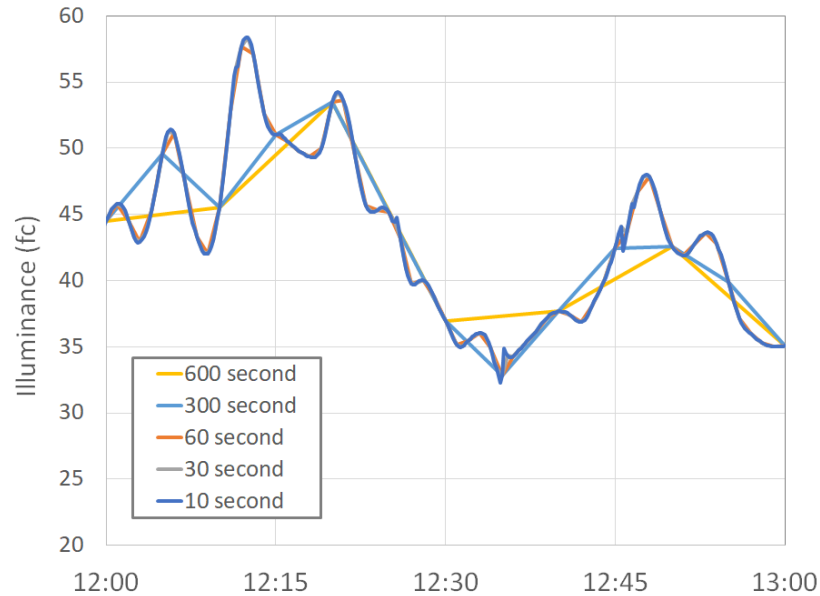


Figure 43. Monitored Total Illuminance at Varying Time Intervals Across One Hour with High Daylight Variability.

Note that 300 and 600 seconds were both too long of a timescale to accurately track the 10 second data series. However, 60 second intervals represent the 10 second data well. We therefore chose monitoring time intervals less than 60 seconds. Due to high data storage capacity, we were able to sample at 1 second intervals for eGauge data and 10 second intervals for current and illuminance data. For analysis purposes, we selected 10 second intervals, and did not lose accuracy related to time resolution.

APPENDIX E SAVINGS PROPORTIONS

We analyzed electric lighting power at 14 switch groups, each of which we assumed to be controlled as a single occupancy group. The time period studied was February 15, 2019 to June 21, 2019.

Using the interval switch group lighting power data, we calculated the different control savings for each time interval of measured electrical power. Figure 44 illustrates the varying control savings for an idealized day. Note that this figure is for illustration purposes and the proportional savings should not be taken as the final result.

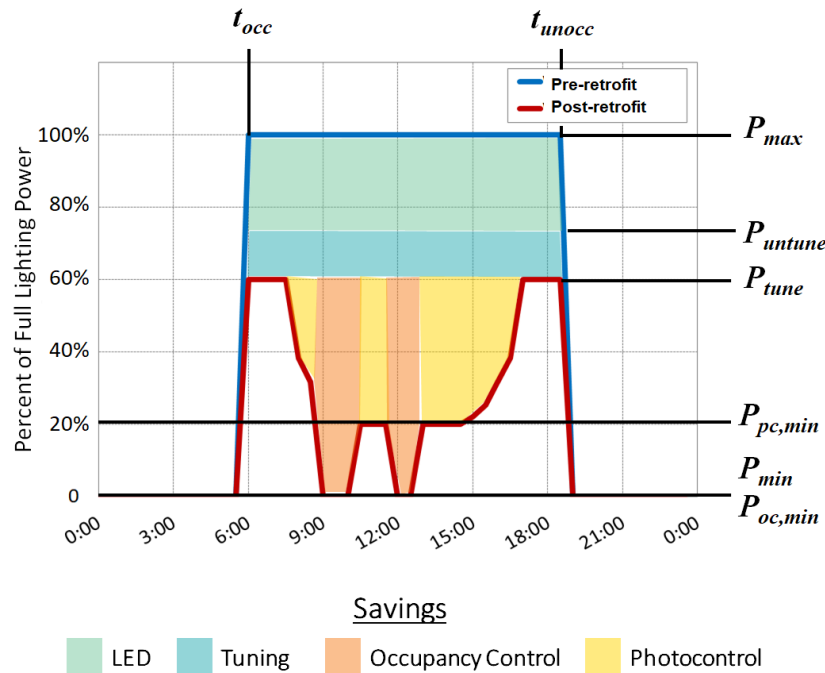


Figure 44. Control Savings for An Idealized Day.

In this idealized case, the pre-retrofit lighting system is off overnight. When the first occupant arrives at 0600, the lights come on to their pre-retrofit maximum power, P_{max} . The lights remain at full power until the last occupant leaves for the evening at 1900, at which point they are shut off. LED savings (orange) and Tuning savings (blue) occur during all periods and are defined by the untuned, P_{untune} , and tuned power, P_{tune} . Occupancy control savings (red) occur during occupied periods when the monitored electric power approaches the minimum occupancy control power, $P_{oc,min}$. Photocontrol savings (yellow) occur as monitored power fluctuates between tuned maximum power and the minimum photocontrol power, $P_{pc,min}$. It is important to note that the relative savings of each control strategy is interactive, depending on the hierarchical order. Our order places LED savings first, then tuning, followed by occupancy controls, and finally photosensor controls. This order makes logical sense for our project; base staff have put a high priority on optimizing light levels through task tuning, secondarily the lights should never be on when no one is present, leaving photocontrol as the final strategy.

Savings only occur during occupied periods, so the first step in calculating the savings from each control is identifying periods of unoccupancy. For each day, we identified the first and last 10-second time interval where power was above the photocontrol sensor minimum. This allowed us to define the start and end of occupancy based on each day's usage pattern rather than typical working hours. Days where power never went above the threshold were identified as unoccupied.

To further refine this analysis, we identified consecutive time intervals within occupied hours where power was below the photocontrol sensor minimum. We reasoned that individuals would turn off the lights manually if they were planning to be gone for a period equivalent to a working day, 10 hours, and thus, categorized any intervals with power below the threshold for ten hours or longer as unoccupied.

Once the periods of non-occupancy were identified, we applied the following:

$$\begin{aligned}\Delta P_{i,LED} &= -P_{min} \\ \Delta P_{i,tune} &= 0 \\ \Delta P_{i,oc} &= 0 \\ \Delta P_{i,pc} &= 0\end{aligned}$$

Where:

$\Delta P_{i,LED}$ is the electric power savings from LED at time interval i in W,

$\Delta P_{i,tune}$ is the electric power savings from tuning at time interval i in W,

$\Delta P_{i,oc}$ is the electric power savings from occupancy control at time interval i in W, and

$\Delta P_{i,pc}$ is the electric power savings from photocontrol at time interval i in W.

The minimum power, P_{min} , of the demonstrated lighting system is non-zero as the LED fixtures draw some small amount of power all the time. Thus, as seen in the above equations, we applied an energy penalty, $-P_{min}$, during unoccupied hours to LED savings.

During occupied periods, the control savings differ based on which control strategies are relevant. This relevance is defined by the switch group's lighting power (P_i). We applied the following conditions to categorize energy savings at each time interval:

If $P_i = (P_{tune} \pm 10\%)$

$$\begin{aligned}\Delta P_{i,LED} &= P_{max} - P_{untune} \\ \Delta P_{i,tune} &= P_{untune} - P_i \\ \Delta P_{i,oc} &= 0 \\ \Delta P_{i,pc} &= 0\end{aligned}$$

If $P_i \leq (P_{min} + 10\%)$

$$\begin{aligned}\Delta P_{i,LED} &= P_{max} - P_{untune} \\ \Delta P_{i,tune} &= P_{untune} - P_{tune} \\ \Delta P_{i,oc} &= P_{tune} - P_i \\ \Delta P_{i,pc} &= 0\end{aligned}$$

If $(P_{min} - 10\%) < P_i \leq (P_{tune} + 10\%)$

$$\begin{aligned}\Delta P_{i,LED} &= P_{max} - P_{untune} \\ \Delta P_{i,tune} &= P_{untune} - P_{tune} \\ \Delta P_{i,oc} &= 0 \\ \Delta P_{i,pc} &= P_{tune} - P_i\end{aligned}$$

This approach assumed that $P_{pc,min}$ is greater than $P_{oc,min}$. The demonstrated lighting system default for $P_{pc,min}$ is 5% of full power and $P_{oc,min}$ is 0% of full power. Additional savings could be captured by reducing the photocontrol minimum to 0%. However, this often leads to occupant complaints and disabled systems. We therefore left the settings in their default state, and only updated them to address occupant feedback. A switch group's actual settings were used within this analysis. If the settings were updated such that $P_{pc,min}$ equaled zero, an alternate approach to differentiating between occupancy and photocontrol savings would be required. Finally, note that if the system is untuned ($P_{tune} = P_{untune}$), the equations are still valid, with tuning savings collapsing to zero.

Once we calculated the control savings at each monitored time interval, the next step was to calculate daily control savings. We considered four typical days. We first summed the savings over each day and then to calculate the average daily savings by day type, we used the following:

$$\begin{aligned}\Delta P_{LED} &= \frac{\sum_{i=1}^{n_{ts}} \Delta P_{i,LED}}{n} \\ \Delta P_{tune} &= \frac{\sum_{i=1}^{n_{ts}} \Delta P_{i,tune}}{n} \\ \Delta P_{oc} &= \frac{\sum_{i=1}^{n_{ts}} \Delta P_{i,oc}}{n} \\ \Delta P_{pc} &= \frac{\sum_{i=1}^{n_{ts}} \Delta P_{i,pc}}{n}\end{aligned}$$

Where:

- $\Delta P_{j,LED}$ is the daily electric power savings from LED in W,
- $\Delta P_{j,tune}$ is the daily electric power savings from tuning in W,
- $\Delta P_{j,oc}$ is the daily electric power savings from occupancy control in W,
- $\Delta P_{j,pc}$ is the daily electric power savings from photocontrol in W, and
- n_{ts} is the number of days for each day type in the dataset.

The next step was to calculate for a typical year the percent of savings from each of the four controls. By switch group, we identified the number of days in a year that fall into each day type and multiplied this by the average daily savings by day type. We then calculated percent savings from each control by dividing each control's yearly savings by total savings.

The last step was to calculate a typical year's proportional savings from each control. As each of the switch groups contribute differently to total power within the building, we calculated a weighted average of percent savings by control, using:

$$\%P_{control} = \sum_{i=1} \%power_i * \%P_{control,i}$$

Where:

$\%P_{control}$ is the percentage of electric power savings from each respective control over a year,

$\%P_{control,switchgroup}$ is the percentage of electric power savings from a respective control for switchgroup i , and

$\%power_{switchgroup}$ is switchgroup i 's percent of total building power.

APPENDIX F DATA SAMPLING SUMMARY

The following tables represent averaged values for the corresponding hour and day type. The data ranges for each period are provided in Table 36.

ELECTRICAL POWER FOR EACH LIGHTING SWITCH GROUP (W)

Electrical power (W) for Selfridge 124/127, switch group 101-b.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	161.0	77.4	35.8	235.0	6.8	6.5	6.6	6.3
1 AM	161.3	77.4	35.8	235.5	15.0	18.9	8.8	7.7
2 AM	161.5	77.4	35.9	236.0	16.5	18.0	9.6	8.5
3 AM	161.8	77.7	35.9	236.7	14.0	20.4	8.0	15.6
4 AM	162.1	77.7	36.1	237.8	13.5	22.0	7.2	6.6
5 AM	238.1	79.6	36.2	238.9	33.7	18.9	6.6	21.0
6 AM	467.8	203.4	36.3	357.2	87.8	80.6	9.0	72.3
7 AM	465.7	329.0	36.4	491.6	81.2	77.5	12.3	69.8
8 AM	463.6	326.8	36.4	490.8	66.5	63.8	10.3	57.3
9 AM	463.6	325.8	36.2	488.5	52.3	48.9	10.0	43.1
10 AM	462.3	325.3	36.1	486.0	42.6	38.1	8.7	35.3
11 AM	460.0	324.7	36.0	476.3	38.3	36.3	7.0	33.7
12 PM	450.4	323.9	35.8	470.8	36.5	36.0	8.7	31.6
1 PM	438.5	322.4	21.6	467.0	35.7	32.4	8.7	32.1
2 PM	438.8	320.0	0.0	466.2	35.7	33.5	7.3	32.0
3 PM	408.2	319.3	0.0	462.4	37.4	34.2	6.5	32.4
4 PM	252.6	319.7	0.0	462.7	30.3	34.4	8.6	39.2
5 PM	105.5	313.6	0.0	460.0	27.5	20.3	6.9	38.9
6 PM	102.9	242.5	0.0	460.0	14.2	12.3	7.1	21.6
7 PM	102.3	233.9	0.0	461.6	7.9	7.8	7.5	12.6
8 PM	102.1	233.8	0.0	463.0	8.1	6.5	6.5	12.3
9 PM	102.2	234.0	0.0	463.4	6.6	6.5	6.5	6.2
10 PM	102.4	234.2	0.0	464.5	6.5	6.5	6.6	10.5
11 PM	102.7	235.2	0.0	466.0	7.5	6.5	8.7	6.2

Electrical power (W) for Selfridge 124/127, switch group 103-a&b pre-retrofit became 103-a post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	2.1	2.1	2.0	2.2
1 AM	0.0	0.0	0.0	0.0	2.1	2.1	2.1	2.0
2 AM	0.0	0.0	0.0	0.0	2.1	2.1	2.1	2.3
3 AM	0.0	0.0	0.0	0.0	2.1	2.1	2.0	2.1
4 AM	0.0	0.0	0.0	0.0	2.2	2.1	2.0	2.2
5 AM	0.0	0.0	0.0	0.0	4.3	2.2	2.1	2.2
6 AM	226.8	206.6	0.0	163.4	54.0	64.5	2.1	45.8
7 AM	425.4	417.2	0.0	434.3	103.7	107.4	2.1	90.0
8 AM	424.5	419.6	0.0	631.1	106.9	106.1	2.0	107.1
9 AM	425.1	419.8	0.0	629.3	105.3	104.6	2.1	102.6
10 AM	425.0	419.3	0.0	629.4	102.9	102.0	2.1	99.5
11 AM	425.5	419.6	0.0	621.4	98.6	97.4	2.1	79.7
12 PM	424.8	419.7	0.0	621.1	96.2	92.0	2.0	75.0
1 PM	424.6	419.1	0.0	620.0	95.2	95.6	2.1	93.6
2 PM	416.2	417.0	0.0	619.4	92.7	92.0	2.1	89.7
3 PM	290.6	225.1	0.0	452.7	66.4	19.1	2.1	69.5
4 PM	172.1	171.2	0.0	40.5	27.6	9.3	2.0	46.5
5 PM	2.6	13.2	0.0	0.0	6.5	9.5	2.1	35.4
6 PM	0.0	0.0	0.0	0.0	2.5	3.2	2.1	14.8
7 PM	0.0	0.0	0.0	0.0	2.2	2.2	2.1	13.7
8 PM	0.0	0.0	0.0	0.0	2.1	2.1	2.0	9.1
9 PM	0.0	0.0	0.0	0.0	2.1	2.1	2.1	13.9
10 PM	0.0	0.0	0.0	0.0	2.1	2.1	2.1	4.9
11 PM	0.0	0.0	0.0	0.0	2.1	2.1	2.1	2.0

Electrical power (W) for Selfridge 124/127, switch group 104-g.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	8.9	3.2	7.3	21.8	0.6	0.5	0.5	0.6
1 AM	9.0	3.2	7.3	22.0	2.0	2.7	0.9	0.8
2 AM	9.0	3.2	7.2	21.9	2.4	2.6	1.1	0.9
3 AM	9.0	3.2	7.2	22.0	1.9	2.9	0.8	2.4
4 AM	9.2	3.2	7.2	22.1	1.8	3.4	0.6	0.7
5 AM	11.0	3.4	7.3	23.3	5.2	2.7	0.5	3.0
6 AM	21.2	8.7	7.2	24.8	16.2	14.6	0.9	13.3
7 AM	22.1	11.2	7.3	26.0	16.5	15.7	1.6	15.6
8 AM	22.8	12.4	7.3	28.1	16.6	16.4	1.5	16.6
9 AM	23.1	12.3	7.3	26.7	16.3	16.4	1.7	16.4
10 AM	23.1	12.0	7.3	27.4	16.0	15.9	1.4	16.2
11 AM	22.6	12.1	7.3	27.0	15.5	15.6	0.7	15.8
12 PM	22.5	12.1	7.3	24.7	15.2	15.3	0.8	15.7
1 PM	22.7	12.3	6.8	24.5	14.6	14.3	1.5	15.2
2 PM	23.2	12.1	5.8	24.4	14.2	13.8	0.7	15.1
3 PM	21.7	12.0	4.9	23.6	14.8	13.9	0.5	13.0
4 PM	16.8	11.7	4.4	21.1	11.4	11.5	1.2	15.0
5 PM	8.6	11.4	4.3	19.1	7.9	4.5	0.7	12.9
6 PM	8.4	11.3	4.3	18.8	2.4	1.9	0.8	5.2
7 PM	8.0	10.8	4.3	18.7	0.8	0.8	0.7	2.3
8 PM	7.9	10.6	4.3	18.7	0.8	0.5	0.5	1.7
9 PM	7.9	10.6	4.3	18.6	0.6	0.5	0.5	0.6
10 PM	7.9	10.6	4.3	18.6	0.5	0.5	0.5	1.3
11 PM	7.9	10.6	4.3	18.7	0.7	0.5	0.9	0.5

Electrical power (W) for Selfridge 124/127, switch group 106-a&b pre-retrofit became 106-c post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
1 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
2 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
3 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
4 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
5 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
6 AM	4.4	1.4	0.0	9.0	3.5	3.1	0.7	1.0
7 AM	28.0	17.3	0.0	11.3	10.0	5.3	0.7	1.1
8 AM	29.3	40.0	0.0	32.5	11.6	7.5	0.7	1.1
9 AM	28.2	41.9	0.0	2.3	11.1	7.2	0.7	1.6
10 AM	24.8	34.3	0.0	3.1	10.8	5.7	0.7	3.1
11 AM	21.3	40.0	0.0	25.5	9.8	4.2	0.7	1.5
12 PM	24.2	31.2	0.0	24.9	8.8	3.1	0.7	1.9
1 PM	28.4	23.2	0.0	4.8	9.1	6.0	0.7	1.4
2 PM	30.5	28.7	0.0	11.0	9.6	6.4	0.7	1.1
3 PM	33.0	21.0	0.0	1.5	6.2	1.5	0.7	1.0
4 PM	32.1	11.0	0.0	0.0	1.8	0.7	0.7	0.9
5 PM	2.1	0.0	0.0	0.0	0.7	0.7	0.7	0.8
6 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
7 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
8 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
9 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
10 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
11 PM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7

Electrical power (W) for Selfridge 124/127, switch group 108-a&b pre-retrofit became 108-d post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	7.5	0.0	0.0	0.0	0.7	0.7	0.7	0.8
1 AM	7.5	0.0	0.0	0.0	0.7	0.7	0.7	0.8
2 AM	7.6	0.0	0.0	0.0	0.7	0.7	0.7	0.8
3 AM	7.6	0.0	0.0	0.0	0.7	0.7	0.7	0.8
4 AM	11.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8
5 AM	52.2	0.0	0.0	0.0	2.3	0.8	0.7	1.3
6 AM	179.4	0.4	0.0	0.0	12.1	1.0	0.7	5.1
7 AM	179.4	0.6	0.0	0.4	12.8	1.1	0.7	5.4
8 AM	178.7	0.6	0.0	0.5	12.8	1.1	0.7	6.9
9 AM	179.6	0.6	0.0	0.5	12.8	1.1	0.7	7.4
10 AM	179.8	0.7	0.0	0.5	12.9	1.1	0.7	9.7
11 AM	180.0	0.6	0.0	0.5	13.0	1.1	0.7	9.7
12 PM	177.1	0.6	0.0	0.5	12.7	1.1	0.7	9.6
1 PM	173.3	0.6	0.0	0.5	12.3	1.1	0.7	10.0
2 PM	169.2	0.6	0.0	0.5	12.6	1.1	0.7	11.7
3 PM	156.4	0.5	0.0	0.4	12.4	0.8	0.7	6.5
4 PM	79.6	0.4	0.0	0.0	6.6	0.8	0.7	5.0
5 PM	8.4	0.0	0.0	0.0	1.4	0.8	0.7	2.2
6 PM	7.5	0.0	0.0	0.0	0.7	0.7	0.7	0.8
7 PM	7.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8
8 PM	7.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8
9 PM	7.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8
10 PM	7.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8
11 PM	7.3	0.0	0.0	0.0	0.7	0.7	0.7	0.8

Electrical power (W) for Selfridge 124/127, switch group 109-a&b pre-retrofit became 109-e post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
1 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
2 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
3 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
4 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
5 AM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	1.5
6 AM	0.4	0.0	0.0	0.0	1.5	0.8	0.6	3.3
7 AM	0.4	0.4	0.0	0.0	7.1	1.9	0.6	3.4
8 AM	0.4	0.4	0.0	0.0	8.6	3.3	0.6	2.6
9 AM	0.4	0.4	0.0	0.0	7.9	5.8	0.6	3.0
10 AM	0.4	8.3	0.0	0.0	5.7	7.7	0.6	3.5
11 AM	0.4	0.4	0.0	0.0	5.0	5.1	0.6	1.1
12 PM	0.4	0.4	0.0	0.0	3.9	4.4	0.6	1.1
1 PM	0.4	0.4	0.0	0.0	3.8	5.9	0.6	5.0
2 PM	0.4	0.4	0.0	0.0	4.7	5.9	0.6	3.5
3 PM	0.4	0.0	0.0	0.0	6.2	5.6	0.6	2.0
4 PM	0.0	0.0	0.0	0.0	4.9	2.5	0.6	4.5
5 PM	0.0	0.0	0.0	0.0	1.9	0.6	0.6	3.1
6 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.7
7 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.7
8 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
9 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
10 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6
11 PM	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6

During the pre-retrofit period, the occupant of this private office rarely turned on their lights, preferring to work in the dark. During the post-retrofit period, the occupant used the lights, but at a dimmed level.

Electrical power (W) for Selfridge 124/127, switch group B127.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	1.0	1.1	1.0	1.0	1.7	1.7	1.7	1.7
1 AM	1.0	1.1	1.0	1.0	1.7	1.7	1.7	1.7
2 AM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.7
3 AM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.8
4 AM	1.0	1.0	1.0	0.9	1.7	1.7	1.7	1.7
5 AM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	10.4
6 AM	3.2	1.1	1.0	1.0	5.7	2.7	1.7	50.6
7 AM	18.6	1.2	1.0	75.0	19.9	2.9	1.7	12.9
8 AM	153.3	1.2	1.0	378.0	35.8	14.6	1.7	5.2
9 AM	307.4	107.5	1.0	503.4	44.7	36.3	1.7	4.2
10 AM	469.1	84.0	1.0	468.0	47.6	48.7	1.7	10.0
11 AM	247.5	28.9	1.0	114.1	44.4	33.4	2.3	9.4
12 PM	160.0	1.4	1.0	67.0	31.3	16.4	1.8	4.0
1 PM	298.4	10.7	1.0	1.0	55.1	15.6	1.7	17.9
2 PM	288.5	17.3	1.0	1.1	43.8	16.1	1.7	8.3
3 PM	191.3	1.1	1.0	106.7	25.7	12.9	1.7	15.7
4 PM	37.5	49.5	1.0	76.6	10.7	17.4	1.7	2.4
5 PM	3.5	1.0	1.0	41.1	4.6	4.9	1.7	1.8
6 PM	1.0	1.0	1.0	1.0	2.1	1.7	1.7	1.7
7 PM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.8
8 PM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.7
9 PM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.7
10 PM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.7
11 PM	1.0	1.0	1.0	1.0	1.7	1.7	1.7	1.8

Electrical power (W) for Selfridge 303, switch group 140-n.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.7
1 AM	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.7
2 AM	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.7
3 AM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.7
4 AM	0.4	0.4	0.3	0.3	0.8	0.8	0.7	0.8
5 AM	0.3	0.4	0.3	0.4	0.8	0.8	0.7	0.8
6 AM	87.0	0.4	0.3	0.3	14.6	1.9	1.2	1.7
7 AM	151.2	0.4	0.3	102.4	25.4	3.8	3.8	17.6
8 AM	103.0	0.4	0.3	84.4	23.7	3.8	4.6	21.7
9 AM	130.3	0.3	0.3	155.6	19.5	3.8	4.0	17.8
10 AM	128.7	0.3	0.3	168.0	23.7	2.4	4.0	20.0
11 AM	127.3	0.3	0.3	168.2	19.6	0.9	2.4	20.0
12 PM	120.0	0.3	0.3	167.7	16.7	0.9	1.2	15.4
1 PM	85.5	0.3	0.3	167.9	17.1	0.9	0.7	18.0
2 PM	74.0	0.3	0.3	167.9	14.7	0.9	0.7	10.7
3 PM	102.1	0.3	0.3	167.2	15.9	0.9	0.7	7.0
4 PM	42.8	0.4	0.3	4.7	10.4	0.9	0.7	1.0
5 PM	0.4	0.3	0.3	0.3	1.1	0.8	0.7	0.8
6 PM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.8
7 PM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.8
8 PM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.8
9 PM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.8
10 PM	0.3	0.3	0.3	0.3	0.8	0.8	0.7	0.8
11 PM	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.8

Electrical power (W) for Selfridge 303, switch group 141-m.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.5
1 AM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.5
2 AM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.5
3 AM	0.5	0.4	0.5	0.5	1.5	1.5	1.5	1.5
4 AM	0.5	0.5	0.4	0.5	1.5	1.5	1.5	1.5
5 AM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.5
6 AM	12.9	13.6	0.5	0.5	1.9	1.8	1.6	2.2
7 AM	87.7	85.9	0.5	91.6	2.4	2.3	1.6	3.2
8 AM	123.9	141.6	0.5	86.9	2.0	2.1	1.6	2.3
9 AM	103.2	114.9	7.6	86.3	1.9	2.0	1.6	2.0
10 AM	95.1	108.2	20.0	86.1	1.8	1.9	1.5	1.8
11 AM	75.0	75.3	27.0	133.8	1.8	1.9	1.5	1.9
12 PM	64.6	68.9	23.4	86.2	1.7	1.8	1.5	1.7
1 PM	59.1	86.1	13.7	51.9	1.7	1.8	1.5	1.7
2 PM	43.4	41.4	0.9	0.5	1.6	1.7	1.5	1.6
3 PM	26.8	13.2	0.4	0.5	1.6	1.6	1.5	1.6
4 PM	9.7	0.5	0.4	0.5	1.6	1.6	1.5	1.5
5 PM	0.5	0.4	0.5	0.5	1.6	1.5	1.5	1.5
6 PM	0.4	0.4	0.5	0.5	1.5	1.5	1.5	1.5
7 PM	0.4	0.4	0.5	0.5	1.5	1.5	1.5	1.5
8 PM	0.4	0.4	0.5	0.5	1.5	1.5	1.5	1.5
9 PM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.5
10 PM	0.4	0.4	0.5	0.5	1.5	1.5	1.5	1.6
11 PM	0.4	0.4	0.4	0.5	1.5	1.5	1.5	1.6

During the pre-retrofit period, the occupant of this private office worked staggered periods compared to the overall office. This resulted in higher average usage during the LWD days as opposed to the NWD. During the post-retrofit period, the occupant did not use the lights. The low power is due to the constant low power draw of the fixtures when off.

Electrical power (W) for Selfridge 303, switch group 142-1.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
1 AM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
2 AM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
3 AM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
4 AM	0.5	0.5	0.4	0.4	0.8	0.8	0.7	0.7
5 AM	0.4	0.4	0.4	0.5	2.0	0.8	0.7	0.8
6 AM	53.6	24.1	8.3	6.4	21.1	5.7	1.5	11.5
7 AM	89.7	75.4	25.1	27.8	26.3	10.9	2.1	20.8
8 AM	88.0	70.7	30.3	15.1	21.7	10.0	1.5	18.3
9 AM	79.7	73.1	31.6	55.3	19.2	8.6	2.0	12.2
10 AM	81.2	77.9	25.9	52.1	14.6	6.8	1.4	5.3
11 AM	69.4	69.6	19.3	6.9	7.9	1.2	0.8	2.9
12 PM	53.2	55.2	19.2	0.5	3.8	1.5	1.1	1.5
1 PM	71.9	51.0	21.1	51.5	6.3	1.7	1.4	0.9
2 PM	59.5	78.0	6.9	12.4	5.6	1.1	2.0	0.8
3 PM	58.8	62.2	2.4	0.4	7.2	1.4	1.7	0.8
4 PM	65.6	39.8	8.1	3.9	6.3	4.2	0.7	0.8
5 PM	30.5	31.0	0.5	0.4	6.0	1.2	0.7	0.7
6 PM	7.0	8.1	0.4	0.4	1.9	0.9	0.7	0.7
7 PM	0.4	0.4	0.4	0.4	0.7	0.8	0.7	0.7
8 PM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
9 PM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
10 PM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7
11 PM	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7

Electrical power (W) for Selfridge 303, switch group 144-k.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.3	0.3	85.1	0.5	0.5	0.5	0.5
1 AM	0.4	0.4	0.4	85.2	0.5	0.5	0.5	0.5
2 AM	0.4	0.4	0.4	85.2	0.5	0.5	0.5	0.5
3 AM	0.4	0.4	0.4	85.3	0.5	0.6	0.5	0.5
4 AM	0.4	0.4	0.3	84.4	0.6	0.6	0.5	0.6
5 AM	0.4	0.4	0.3	83.7	0.8	0.6	0.5	0.6
6 AM	0.6	0.4	0.3	132.0	4.9	1.4	0.6	8.8
7 AM	78.4	61.7	32.0	161.3	18.7	16.6	2.3	25.0
8 AM	120.4	141.3	60.8	168.9	21.6	28.5	2.4	20.5
9 AM	106.6	126.7	64.9	161.2	19.6	26.1	2.4	23.2
10 AM	102.9	99.5	55.3	168.5	22.6	27.5	2.4	23.7
11 AM	58.9	94.1	33.8	138.5	16.5	12.1	1.3	11.9
12 PM	83.4	107.9	26.2	104.2	20.7	13.9	0.7	16.4
1 PM	103.8	135.4	26.3	94.5	19.9	26.7	0.5	15.2
2 PM	108.7	87.8	26.2	83.6	17.3	26.6	0.5	11.5
3 PM	100.0	46.2	19.4	134.9	10.0	6.9	0.5	8.6
4 PM	60.8	11.5	12.9	102.9	4.7	1.3	0.5	2.9
5 PM	29.9	0.3	0.4	84.9	4.1	1.3	0.5	0.6
6 PM	11.3	0.3	0.4	85.1	1.3	0.6	0.5	0.6
7 PM	0.4	0.4	0.4	85.0	0.6	0.6	0.5	0.5
8 PM	0.4	0.4	0.4	85.1	0.6	0.6	0.5	0.5
9 PM	0.4	0.4	0.4	85.2	0.6	0.6	0.5	0.5
10 PM	0.4	0.4	0.4	85.2	0.5	0.5	0.5	0.5
11 PM	0.4	0.4	0.4	85.1	0.5	0.5	0.5	0.5

Electrical power (W) for Selfridge 303, switch group 145-j.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
1 AM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
2 AM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
3 AM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.8
4 AM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
5 AM	0.4	0.4	0.4	0.4	0.8	0.8	0.8	0.9
6 AM	24.8	28.3	1.7	38.9	2.2	1.9	0.9	2.0
7 AM	129.9	136.4	9.5	176.4	4.2	4.5	1.1	6.1
8 AM	75.1	86.9	13.9	176.1	4.7	5.4	2.0	8.9
9 AM	59.0	87.6	13.9	175.8	3.6	4.5	1.5	6.8
10 AM	27.8	87.4	13.9	129.5	2.5	3.8	0.9	3.1
11 AM	7.3	47.3	13.9	40.7	1.9	2.5	0.9	1.8
12 PM	6.1	29.5	13.9	0.3	1.7	1.9	0.9	1.6
1 PM	8.9	29.5	13.9	63.1	1.6	1.5	0.8	1.2
2 PM	6.7	24.1	9.0	56.4	1.5	1.5	0.8	1.2
3 PM	5.6	29.5	1.3	0.3	1.3	1.2	0.8	1.1
4 PM	0.4	2.1	12.1	0.3	1.4	1.3	0.8	1.1
5 PM	0.3	0.4	0.4	0.3	1.1	1.0	0.8	0.9
6 PM	0.4	0.4	0.4	0.3	0.9	0.8	0.8	0.9
7 PM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
8 PM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.8
9 PM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.8
10 PM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.9
11 PM	0.4	0.4	0.4	0.3	0.8	0.8	0.8	0.8

Electrical power (W) for Selfridge 303, switch group 146-i.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.4	0.4	0.3	0.5	0.5	0.5	0.6
1 AM	0.4	0.4	0.4	0.3	0.5	0.5	0.5	0.6
2 AM	0.4	0.4	0.4	0.3	0.5	0.5	0.5	0.6
3 AM	0.4	0.4	0.4	0.3	0.5	0.6	0.5	0.6
4 AM	0.4	0.4	0.4	0.3	0.6	0.6	0.5	0.6
5 AM	0.4	0.4	0.4	0.4	0.6	0.6	0.5	0.6
6 AM	44.3	0.4	0.4	0.4	1.2	1.3	0.6	0.8
7 AM	105.2	29.9	13.1	0.3	9.0	6.0	1.5	5.7
8 AM	100.0	41.0	14.1	0.4	13.2	8.9	1.1	3.1
9 AM	87.0	59.1	14.0	0.4	9.8	8.2	0.9	3.4
10 AM	84.7	59.0	14.0	0.4	8.6	6.7	0.7	3.7
11 AM	64.4	35.9	6.9	0.4	5.5	4.9	0.7	3.6
12 PM	80.6	23.1	0.4	0.4	5.3	4.8	0.7	2.7
1 PM	90.0	29.8	0.4	0.4	5.5	4.5	0.5	1.7
2 PM	93.3	29.8	0.4	0.4	5.9	3.3	0.5	1.8
3 PM	103.9	18.5	2.9	0.4	6.9	3.6	0.5	2.3
4 PM	99.8	0.4	0.4	0.4	5.3	3.2	0.5	0.7
5 PM	29.4	0.4	0.4	0.4	1.4	0.8	0.5	0.6
6 PM	1.2	0.4	0.4	0.3	0.6	0.6	0.5	0.6
7 PM	0.4	0.4	0.4	0.3	0.6	0.6	0.5	0.6
8 PM	2.7	0.4	0.4	0.3	0.6	0.6	0.5	0.5
9 PM	0.4	0.4	0.4	0.3	0.6	0.6	0.5	0.5
10 PM	0.4	0.4	0.4	0.3	0.6	0.5	0.5	0.6
11 PM	0.4	0.4	0.4	0.3	0.5	0.5	0.5	0.6

Electrical power (W) for Selfridge 303, switch group 149-h.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.4	0.4	0.4	0.4	1.2	1.1	1.2	1.2
1 AM	0.4	0.4	0.4	0.4	1.2	1.1	1.2	1.2
2 AM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
3 AM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
4 AM	0.4	0.5	0.4	0.4	1.2	1.2	1.2	1.2
5 AM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.3
6 AM	6.8	0.5	0.4	17.7	2.7	3.5	1.2	1.4
7 AM	20.6	0.4	1.3	125.6	6.4	4.8	1.5	2.5
8 AM	36.9	13.7	8.3	175.6	9.6	3.3	1.5	9.2
9 AM	43.0	95.1	11.8	175.5	7.7	1.8	1.4	5.8
10 AM	47.4	79.9	0.4	103.8	6.5	4.4	1.4	2.9
11 AM	14.1	34.4	12.2	88.1	5.1	2.3	1.2	2.3
12 PM	12.0	25.6	14.0	25.0	5.2	3.7	1.2	2.3
1 PM	32.5	7.6	2.2	13.6	7.7	4.5	1.2	3.1
2 PM	29.0	0.4	0.4	7.6	7.6	3.6	1.2	3.0
3 PM	32.9	0.4	11.3	82.6	5.9	3.8	1.2	1.4
4 PM	17.1	7.1	1.7	2.1	3.8	1.3	1.2	1.3
5 PM	0.6	0.4	0.4	0.4	1.4	1.3	1.2	1.2
6 PM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
7 PM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
8 PM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
9 PM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
10 PM	0.4	0.4	0.4	0.4	1.2	1.2	1.2	1.2
11 PM	0.4	0.4	0.4	0.4	1.2	1.1	1.2	1.2

Electrical power (W) for Selfridge 303, entire open office.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	318.0	2.7	2.6	1709.9	10.7	7.5	10.4	8.5
1 AM	312.5	2.7	2.6	1719.4	11.0	8.9	9.9	9.9
2 AM	311.4	2.7	2.6	1716.2	11.8	16.3	8.9	8.9
3 AM	296.5	2.7	2.6	1702.0	10.3	10.0	8.1	8.8
4 AM	295.2	2.6	2.6	1716.9	14.0	11.1	8.2	8.4
5 AM	363.3	2.6	2.6	1691.3	23.8	7.7	8.6	12.1
6 AM	3030.0	2408.5	1168.6	2076.0	311.0	229.6	54.8	238.8
7 AM	3577.3	3554.6	1776.5	2968.8	430.2	409.2	74.4	411.7
8 AM	3573.8	3573.0	1793.4	2966.6	422.2	419.9	78.1	418.4
9 AM	3573.4	3569.1	1780.6	2966.4	399.3	416.2	70.0	415.4
10 AM	3573.0	3574.9	1781.9	2962.9	396.0	405.7	54.6	406.8
11 AM	3573.3	3573.8	1386.9	2965.0	391.8	401.3	57.5	390.0
12 PM	3573.3	3574.9	1144.1	2958.6	384.7	395.3	39.8	365.8
1 PM	3578.7	3574.8	1134.9	2963.7	377.7	391.7	22.3	379.2
2 PM	3572.1	3575.2	1151.4	2963.1	364.2	383.1	13.9	360.0
3 PM	3568.0	3541.8	1116.5	2964.4	359.5	383.3	20.1	300.9
4 PM	3472.3	3085.1	672.6	1691.1	336.0	361.4	10.2	188.0
5 PM	2771.7	1823.7	31.4	0.7	234.4	162.7	10.5	40.1
6 PM	1736.6	1069.2	2.6	0.7	65.5	17.9	12.0	24.9
7 PM	751.9	1016.8	2.6	0.7	27.7	10.8	14.4	11.8
8 PM	354.7	979.6	2.6	0.7	18.8	14.9	8.8	7.4
9 PM	323.5	958.9	2.6	0.7	17.5	10.0	8.1	8.3
10 PM	297.3	973.3	2.6	0.7	20.5	9.0	7.7	11.0
11 PM	306.4	977.7	2.6	0.7	12.0	7.7	8.0	12.1

Combining all switch groups for the given period for the entire open office.

Electrical power (W) for Truax 510, switch group 102.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
1 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
2 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
3 AM	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.7
4 AM	0.7	0.0	0.0	0.0	0.7	0.8	0.7	0.8
5 AM	75.5	19.2	0.0	67.5	4.3	1.3	0.9	4.6
6 AM	130.7	46.5	0.0	180.7	6.6	1.8	1.0	6.2
7 AM	117.7	52.5	0.0	177.4	6.4	2.0	0.7	6.8
8 AM	118.3	71.7	0.0	162.4	6.0	1.7	0.7	6.6
9 AM	122.4	56.9	0.0	162.1	6.0	2.0	1.1	5.9
10 AM	123.2	48.4	0.0	132.4	6.3	2.0	1.1	5.7
11 AM	121.6	53.8	0.0	113.1	6.4	1.9	1.1	4.5
12 PM	121.3	62.6	0.0	135.0	6.1	1.8	1.1	6.1
1 PM	112.9	68.1	0.0	147.8	6.3	1.8	1.1	7.1
2 PM	108.9	58.8	0.0	98.7	5.8	1.8	1.1	6.7
3 PM	110.7	49.2	0.0	64.4	5.9	1.8	0.9	6.0
4 PM	78.9	25.1	0.0	32.6	5.4	1.7	0.7	4.5
5 PM	12.5	0.0	0.0	0.0	3.0	0.7	0.7	1.1
6 PM	8.4	0.0	0.0	0.0	1.9	0.7	0.7	0.7
7 PM	4.0	0.0	0.0	0.0	1.2	0.7	0.7	0.7
8 PM	0.0	0.0	0.0	0.0	1.2	0.7	0.7	0.7
9 PM	0.0	0.0	0.0	0.0	1.1	0.7	0.7	0.7
10 PM	0.0	0.0	0.0	0.0	0.9	0.7	0.7	0.7
11 PM	0.0	0.0	0.0	0.0	0.8	0.7	0.7	0.7

Combining all switch groups for the given period for the private office 102.

Electrical power (W) for Truax 510, switch group 107-S.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	Switch Group Adjusted				0.4	0.4	0.4	0.4
1 AM					0.4	0.4	0.4	0.4
2 AM					0.4	0.4	0.4	0.4
3 AM					0.4	0.4	0.4	0.4
4 AM					0.4	0.4	0.4	0.4
5 AM					1.6	0.6	0.4	1.6
6 AM					7.0	4.0	0.4	8.9
7 AM					6.4	4.4	0.5	11.2
8 AM					5.7	2.0	0.7	11.9
9 AM					5.0	0.6	0.6	8.8
10 AM					4.4	1.3	0.6	7.0
11 AM					3.8	1.2	0.6	6.3
12 PM					3.7	0.6	0.5	5.0
1 PM					3.1	0.5	0.4	5.2
2 PM					3.4	0.5	0.4	5.5
3 PM					3.4	0.5	0.6	2.8
4 PM					2.3	0.4	0.4	1.1
5 PM					1.0	0.4	0.4	0.4
6 PM					0.6	0.4	0.4	0.4
7 PM					0.6	0.4	0.4	0.4
8 PM					0.6	0.4	0.4	0.4
9 PM					0.6	0.4	0.4	0.4
10 PM					0.5	0.4	0.4	0.4
11 PM					0.6	0.4	0.4	0.4

New switch group post-retrofit

Electrical power (W) for Truax 510, switch group 107-U pre-retrofit became 107-T post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	14.1	0.0	0.0	0.4	0.4	0.4	0.4
1 AM	0.0	14.5	0.0	0.0	0.4	0.4	0.4	0.4
2 AM	0.0	14.3	0.0	0.0	0.4	0.4	0.4	0.4
3 AM	0.0	4.0	0.0	0.0	0.4	0.4	0.4	0.4
4 AM	0.0	3.7	0.0	0.0	0.4	0.4	0.4	0.4
5 AM	11.9	14.8	0.0	18.2	2.5	1.0	0.4	1.8
6 AM	77.6	27.5	0.0	99.4	10.4	2.3	0.4	4.9
7 AM	87.8	41.2	0.0	105.4	10.3	2.4	0.4	3.8
8 AM	90.4	49.4	0.0	105.1	9.0	2.2	0.4	4.3
9 AM	93.4	33.4	0.0	105.0	7.9	2.5	0.4	3.2
10 AM	91.9	32.4	6.4	105.2	7.2	2.6	0.4	3.2
11 AM	94.2	34.2	7.1	105.1	6.7	2.3	0.4	5.2
12 PM	96.7	23.9	7.0	104.5	5.5	0.5	0.4	6.6
1 PM	97.5	17.7	0.0	104.1	4.5	0.5	0.4	5.8
2 PM	96.9	18.1	0.0	91.4	4.9	0.5	0.4	4.9
3 PM	95.5	14.8	0.0	76.2	4.7	0.5	0.4	1.1
4 PM	61.5	13.7	0.0	9.1	3.8	0.4	0.4	0.5
5 PM	23.9	0.8	0.0	0.0	1.1	0.4	0.4	0.4
6 PM	22.2	0.0	0.0	0.0	0.6	0.4	0.4	0.4
7 PM	21.9	0.0	0.0	0.0	0.6	0.4	0.4	0.4
8 PM	22.9	0.0	0.0	0.0	0.6	0.4	0.4	0.4
9 PM	19.3	0.0	0.0	0.0	0.6	0.4	0.4	0.4
10 PM	5.1	0.0	0.0	0.0	0.5	0.4	0.4	0.4
11 PM	3.7	0.0	0.0	0.0	0.6	0.4	0.4	0.4

Electrical power (W) for Truax 510, switch group 107-V pre-retrofit became 107-U post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	19.0	0.0	0.0	0.8	0.8	0.8	0.8
1 AM	0.0	19.6	0.0	0.0	0.8	0.8	0.8	0.8
2 AM	0.0	19.3	0.0	0.0	0.8	0.8	0.8	0.8
3 AM	0.0	5.5	0.0	0.0	0.8	0.8	0.8	0.8
4 AM	0.0	4.7	0.0	0.0	0.8	0.8	0.8	0.8
5 AM	38.3	23.1	0.0	40.8	7.0	1.8	0.8	2.8
6 AM	240.6	74.3	0.0	265.5	47.1	10.4	2.8	33.3
7 AM	242.8	94.8	0.0	287.4	45.6	10.8	1.0	39.1
8 AM	241.8	113.1	0.0	286.8	41.3	9.2	3.0	38.3
9 AM	243.4	90.0	0.0	286.6	38.7	8.6	2.7	39.4
10 AM	241.7	86.2	0.0	287.0	36.1	8.0	2.7	36.7
11 AM	242.1	92.1	0.0	287.2	33.5	7.5	2.6	33.4
12 PM	242.1	96.3	0.0	286.6	32.7	6.0	3.1	29.0
1 PM	241.1	81.0	0.0	285.9	34.7	6.5	3.1	29.0
2 PM	239.5	95.4	0.0	192.3	35.9	7.4	1.2	22.3
3 PM	237.5	79.7	0.0	147.4	37.1	8.5	0.8	22.0
4 PM	162.1	59.0	0.0	14.0	23.6	5.1	0.8	8.4
5 PM	73.8	19.7	0.0	0.0	4.1	0.8	0.8	0.8
6 PM	49.7	3.0	0.0	0.0	1.6	0.8	0.8	0.8
7 PM	30.3	0.0	0.0	0.0	1.4	0.8	0.8	0.8
8 PM	28.0	0.0	0.0	0.0	1.1	0.8	0.8	0.8
9 PM	22.2	0.0	0.0	0.0	1.4	0.8	0.8	0.8
10 PM	5.0	0.0	0.0	0.0	0.9	0.8	0.8	0.8
11 PM	4.9	0.0	0.0	0.0	0.8	0.8	0.8	0.8

Electrical power (W) for Truax 510, switch group 107-W pre-retrofit became 107-V post-retrofit.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.9	1.5	0.8	0.8
1 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
2 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
3 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
4 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
5 AM	0.0	0.0	0.0	15.3	5.1	2.3	0.8	6.3
6 AM	6.5	8.1	0.0	47.8	15.4	8.2	0.8	20.7
7 AM	5.9	8.7	0.0	62.4	15.6	5.7	0.8	11.7
8 AM	4.0	10.0	0.0	62.1	16.4	5.3	0.8	12.6
9 AM	3.9	9.5	0.0	62.2	16.8	4.9	0.8	12.2
10 AM	5.0	9.0	0.0	62.8	15.7	4.7	0.8	12.9
11 AM	5.7	9.8	0.0	62.5	15.1	4.5	0.8	16.6
12 PM	5.7	10.0	0.0	61.9	13.3	4.1	0.8	17.2
1 PM	5.7	10.0	0.0	62.3	12.9	4.3	0.8	16.8
2 PM	5.6	10.0	0.0	55.3	12.9	4.2	0.8	11.2
3 PM	5.7	8.6	0.0	45.3	15.1	4.5	0.8	10.7
4 PM	5.2	7.9	0.0	9.7	14.7	4.9	0.8	2.6
5 PM	5.7	8.1	0.0	0.0	11.9	1.3	0.8	0.8
6 PM	5.2	5.9	0.0	0.0	11.1	0.8	0.8	0.8
7 PM	0.5	0.0	0.0	0.0	10.5	0.8	0.8	0.8
8 PM	0.0	0.0	0.0	0.0	9.7	0.8	0.8	0.8
9 PM	0.8	0.0	0.0	0.0	9.7	0.8	0.8	0.8
10 PM	0.7	0.0	0.0	0.0	7.8	0.8	0.8	0.8
11 PM	0.0	0.0	0.0	0.0	4.7	0.8	0.8	0.8

Electrical power (W) for Truax 510, switch group 107-W.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	Switch Group Adjusted				3.6	2.3	1.2	1.2
1 AM					1.2	1.1	1.2	1.2
2 AM					1.2	1.1	1.2	1.2
3 AM					1.2	1.1	1.2	1.2
4 AM					1.2	1.1	1.2	1.2
5 AM					11.8	2.4	1.5	6.8
6 AM					54.0	14.6	3.2	63.2
7 AM					54.9	14.9	2.5	57.6
8 AM					53.8	14.3	2.9	69.5
9 AM					52.5	13.6	2.8	69.3
10 AM					49.5	13.7	2.8	65.0
11 AM					46.5	12.4	2.8	56.8
12 PM					43.1	9.5	2.9	52.0
1 PM					45.8	10.3	2.9	49.9
2 PM					50.5	11.7	2.6	38.0
3 PM					55.2	13.5	1.2	38.9
4 PM					50.3	9.4	1.2	17.8
5 PM					38.9	1.2	1.2	1.2
6 PM					36.1	1.2	1.2	1.2
7 PM					34.8	1.2	1.2	1.2
8 PM					31.2	1.1	1.2	1.2
9 PM					26.5	1.1	1.2	1.2
10 PM					15.5	1.1	1.2	1.2
11 PM					11.2	1.1	1.2	1.2

New switch group added post-retrofit

Electrical power (W) for Truax 510, switch group 107-X.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	25.4	0.0	72.1	1.7	0.8	0.8	0.8
1 AM	0.0	25.5	0.0	72.1	0.8	0.8	0.8	0.8
2 AM	0.0	25.4	0.0	14.5	0.8	0.8	0.8	0.8
3 AM	0.0	9.7	0.0	0.0	0.8	0.8	0.8	0.8
4 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
5 AM	92.7	22.5	0.0	99.8	15.8	2.5	1.2	11.4
6 AM	381.2	120.6	0.0	410.6	59.7	16.9	2.7	66.1
7 AM	427.0	298.7	0.0	427.9	62.8	32.1	2.4	57.1
8 AM	427.1	311.0	0.0	427.0	59.0	25.7	3.2	66.5
9 AM	427.2	327.9	0.0	426.7	55.7	26.8	2.9	62.7
10 AM	426.8	326.0	0.0	426.7	51.9	23.9	2.9	55.4
11 AM	421.0	295.3	0.0	427.0	49.0	21.2	2.8	51.0
12 PM	420.0	277.5	0.0	426.3	45.6	14.9	3.3	44.3
1 PM	420.3	253.4	0.0	425.5	49.0	16.4	3.3	45.8
2 PM	420.7	230.9	0.0	268.9	51.5	16.4	3.0	36.9
3 PM	423.2	137.0	0.0	143.0	54.5	13.6	1.0	25.7
4 PM	389.2	62.7	0.0	27.7	48.3	8.4	0.9	17.9
5 PM	336.2	25.3	0.0	0.0	19.1	0.9	0.8	0.8
6 PM	326.3	19.1	0.0	0.0	9.2	0.8	0.8	0.8
7 PM	319.4	0.0	0.0	0.0	7.4	0.8	0.8	0.8
8 PM	303.5	5.4	0.0	0.0	7.3	0.8	0.8	0.8
9 PM	239.7	25.5	0.0	0.0	7.0	0.8	0.8	0.8
10 PM	12.0	25.4	0.0	0.0	6.5	0.8	0.8	0.8
11 PM	6.2	25.5	0.0	0.0	5.0	0.8	0.8	0.8

Electrical power (W) for Truax 510, switch group 107-Y.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4
1 AM	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4
2 AM	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4
3 AM	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4
4 AM	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4
5 AM	0.0	0.0	0.0	8.4	0.6	0.4	0.4	1.2
6 AM	3.5	5.8	0.0	59.1	1.6	0.5	0.4	4.0
7 AM	4.8	6.1	0.0	68.5	1.4	0.5	0.4	4.3
8 AM	6.0	6.1	0.0	68.3	1.3	0.5	0.4	3.7
9 AM	6.0	6.1	0.0	68.2	1.2	0.5	0.4	4.2
10 AM	6.0	6.0	0.0	68.2	1.1	0.5	0.4	4.8
11 AM	6.3	5.9	0.0	68.1	1.1	0.5	0.4	4.4
12 PM	7.5	5.9	0.0	67.9	1.4	0.4	0.4	4.2
1 PM	7.4	6.0	0.0	67.8	1.4	0.5	0.4	4.1
2 PM	7.4	6.0	0.0	52.4	1.1	0.5	0.4	3.9
3 PM	6.8	6.0	0.0	34.0	1.2	0.5	0.4	4.1
4 PM	4.2	5.1	0.0	10.0	1.1	0.5	0.4	2.1
5 PM	1.5	0.0	0.0	0.0	0.8	0.5	0.4	0.4
6 PM	1.5	0.0	0.0	0.0	0.5	0.4	0.4	0.4
7 PM	2.4	0.0	0.0	0.0	0.5	0.4	0.4	0.4
8 PM	4.3	0.0	0.0	0.0	0.4	0.4	0.4	0.4
9 PM	10.4	0.0	0.0	0.0	0.9	0.4	0.4	0.4
10 PM	0.4	0.0	0.0	0.0	0.9	0.4	0.4	0.4
11 PM	0.0	0.0	0.0	0.0	0.5	0.4	0.4	0.4

Electrical power (W) for Truax 510, switch group 110-Z.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
1 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
2 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
3 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
4 AM	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8
5 AM	0.5	0.0	0.0	15.6	2.4	0.9	1.1	3.7
6 AM	51.2	15.2	0.0	115.1	36.2	9.5	2.6	49.0
7 AM	56.1	23.6	0.0	136.7	34.2	9.2	2.0	53.2
8 AM	56.2	24.1	0.0	136.4	30.0	4.4	3.0	48.5
9 AM	56.2	24.1	0.0	136.3	26.7	4.7	2.6	49.3
10 AM	56.1	26.6	0.0	121.3	24.0	6.7	2.6	44.6
11 AM	59.7	31.9	0.0	133.4	22.5	4.1	2.6	40.6
12 PM	63.3	31.9	0.0	117.1	22.7	3.2	3.0	25.8
1 PM	65.4	31.9	0.0	135.9	21.8	3.9	3.0	20.0
2 PM	65.3	31.9	0.0	81.7	21.5	3.3	2.8	11.6
3 PM	58.5	26.1	0.0	45.2	23.6	4.1	0.8	12.0
4 PM	27.7	15.5	0.0	11.8	17.7	3.9	0.8	5.0
5 PM	14.5	0.0	0.0	0.0	4.9	0.9	0.8	0.8
6 PM	13.6	0.0	0.0	0.0	5.8	0.8	0.8	0.8
7 PM	15.7	0.0	0.0	0.0	6.1	0.8	0.8	0.8
8 PM	21.3	0.0	0.0	0.0	5.0	0.8	0.8	0.8
9 PM	21.1	0.0	0.0	0.0	6.4	0.8	0.8	0.8
10 PM	1.0	0.0	0.0	0.0	5.6	0.8	0.8	0.8
11 PM	0.0	0.0	0.0	0.0	3.6	0.8	0.8	0.8

ELECTRICAL POWER FOR EACH LIGHTING CIRCUIT (W)

Electrical power (W) for Selfridge 124/127, circuit 26. Includes switch groups 103, 106, 109, and 110. See lighting plans for more detail.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	4.3	0.7	0.7	0.5	16.2	16.1	16.1	16.2
1 AM	3.6	0.7	0.7	0.5	16.2	16.3	16.3	15.8
2 AM	3.6	0.7	0.7	0.5	16.2	16.1	16.4	16.5
3 AM	3.6	0.7	0.7	0.5	16.3	16.3	16.1	15.8
4 AM	5.1	0.6	0.7	0.5	16.2	16.0	16.1	16.2
5 AM	41.2	0.6	0.7	0.0	21.5	16.2	16.3	19.7
6 AM	390.4	222.7	0.7	247.5	97.1	85.3	16.4	77.2
7 AM	631.6	440.5	0.7	497.4	172.0	134.9	16.1	123.3
8 AM	642.6	467.1	0.7	581.6	181.6	141.0	16.0	138.3
9 AM	649.3	468.8	0.7	559.1	176.6	142.3	16.3	133.9
10 AM	646.1	466.6	0.7	544.5	169.1	138.5	16.4	132.5
11 AM	638.0	461.6	0.7	471.5	162.0	126.7	16.1	110.7
12 PM	625.0	453.2	0.7	530.4	155.5	118.5	16.0	114.8
1 PM	625.2	449.5	0.7	544.4	154.2	130.4	16.3	138.5
2 PM	618.2	450.0	0.7	526.0	154.7	127.3	16.4	133.9
3 PM	439.2	240.9	0.7	301.9	121.4	42.5	16.1	100.0
4 PM	212.7	88.5	0.7	1.3	60.7	26.4	16.0	72.6
5 PM	7.5	5.5	0.7	0.5	23.6	23.6	16.3	55.9
6 PM	3.7	0.6	0.7	0.5	16.6	17.1	16.4	29.2
7 PM	3.6	0.6	0.7	0.5	16.3	16.2	16.1	27.7
8 PM	3.6	0.7	0.7	0.5	16.2	16.1	16.0	23.4
9 PM	3.6	0.7	0.7	0.5	16.2	16.3	16.4	27.9
10 PM	3.6	0.7	0.7	0.5	16.2	16.1	16.4	19.2
11 PM	5.3	0.7	0.7	0.6	16.3	16.3	16.2	15.8

Electrical power (W) for Selfridge 124/127, circuit 28. Includes switch groups Corridor S, 107, and 100. See lighting plans for more detail.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	165.9	135.9	125.4	262.7	61.5	61.3	61.2	61.3
1 AM	165.7	135.7	125.3	263.2	71.9	76.9	64.2	62.8
2 AM	165.8	135.5	125.4	263.5	74.1	76.1	65.8	63.2
3 AM	165.8	135.4	125.3	263.2	70.8	78.9	63.3	73.6
4 AM	166.3	136.0	125.4	264.3	69.9	80.5	62.1	61.7
5 AM	233.7	136.8	125.5	274.2	97.1	76.8	61.5	80.5
6 AM	448.9	231.9	125.8	451.8	166.0	155.4	65.2	145.5
7 AM	456.7	330.7	125.6	524.7	160.0	152.0	68.8	143.5
8 AM	453.9	330.0	125.7	521.8	139.5	134.2	66.0	125.3
9 AM	453.0	327.3	125.6	516.8	119.8	114.6	65.7	106.1
10 AM	450.0	325.0	125.6	515.6	105.1	98.2	64.6	91.9
11 AM	450.9	325.7	125.3	512.8	99.0	94.9	62.1	90.7
12 PM	449.5	328.0	124.6	511.6	95.4	93.5	63.8	87.2
1 PM	449.3	327.8	118.6	508.6	94.1	89.4	63.7	88.4
2 PM	451.7	324.8	110.0	506.7	95.0	91.5	63.0	88.3
3 PM	416.7	324.0	110.0	506.5	97.9	92.0	61.3	90.5
4 PM	281.9	324.0	110.0	505.4	88.7	92.9	63.7	98.8
5 PM	149.2	322.8	110.0	502.9	86.7	78.1	61.7	100.8
6 PM	117.6	295.2	110.0	504.7	71.1	68.8	62.7	79.5
7 PM	117.2	291.7	110.4	505.7	63.2	63.1	62.7	69.7
8 PM	117.1	290.9	110.6	507.4	63.3	61.1	61.3	68.8
9 PM	117.2	290.7	110.8	507.9	61.4	61.1	61.4	61.1
10 PM	117.3	290.8	110.8	508.7	61.6	61.5	62.1	65.6
11 PM	117.2	290.9	110.6	509.1	62.7	61.4	64.2	61.5

High power draw during unoccupied hours due to vestibule lighting.

Electrical power (W) for Selfridge 124/127, circuit 30. Includes switch groups Corridor N. See lighting plans for more detail.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	148.9	155.7	145.6	190.7	36.0	35.4	35.0	38.6
1 AM	148.3	154.6	145.4	190.6	44.3	47.9	37.8	39.4
2 AM	148.2	155.0	145.4	190.6	45.8	47.3	38.7	39.5
3 AM	148.3	154.6	145.6	190.0	43.1	49.3	36.9	46.3
4 AM	148.5	154.5	145.7	190.8	42.9	50.9	35.6	38.5
5 AM	157.5	155.3	145.7	190.9	62.1	47.4	35.5	51.9
6 AM	198.0	168.4	145.5	204.5	117.8	110.9	38.0	106.2
7 AM	213.2	177.2	145.4	216.2	118.7	118.2	41.6	114.9
8 AM	222.5	189.2	145.5	225.8	118.0	119.0	40.0	119.1
9 AM	223.6	193.8	145.2	209.1	116.7	118.1	42.2	120.0
10 AM	222.5	188.5	145.4	214.7	116.8	117.3	39.7	122.8
11 AM	220.7	184.3	144.8	219.3	114.8	117.1	36.1	118.8
12 PM	222.2	182.5	143.9	200.8	112.8	116.4	36.7	119.4
1 PM	220.7	183.3	143.3	204.9	111.9	112.3	41.1	118.6
2 PM	220.6	187.1	142.0	203.7	110.7	113.2	36.5	117.8
3 PM	209.1	178.6	140.9	208.3	110.8	111.4	35.1	103.2
4 PM	180.0	173.8	140.0	190.4	90.5	95.9	38.9	113.3
5 PM	148.3	168.0	140.3	183.8	75.1	55.1	36.3	99.5
6 PM	147.0	168.7	140.3	186.5	45.8	42.5	36.7	61.3
7 PM	147.3	168.6	140.0	187.3	37.6	36.9	36.3	43.3
8 PM	147.1	168.6	140.3	187.1	37.8	35.4	35.0	42.9
9 PM	147.2	168.4	140.0	187.6	36.3	35.5	35.5	36.2
10 PM	147.2	168.5	140.0	187.3	36.2	35.7	35.6	39.6
11 PM	147.1	168.5	140.0	187.7	37.1	35.7	37.3	34.9

Electrical power (W) for Selfridge 124/127, circuit 6. Includes switch groups B127, Break room (unretrofit) and private office (unretrofit). See lighting plans for more detail.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	59.5	58.2	57.7	47.1	35.3	32.5	32.4	32.5
1 AM	59.6	58.3	57.8	47.0	35.2	32.4	32.3	31.9
2 AM	59.6	57.5	57.8	47.1	35.4	32.5	32.5	32.1
3 AM	59.5	56.2	57.8	47.0	35.5	32.4	32.6	33.0
4 AM	59.2	56.1	57.8	47.0	35.2	32.2	32.4	32.5
5 AM	61.6	56.8	57.7	44.3	36.2	32.6	32.3	43.5
6 AM	49.7	59.3	57.8	18.9	58.6	45.0	32.5	100.5
7 AM	90.0	67.9	58.0	58.6	75.0	48.9	32.8	56.2
8 AM	208.1	79.7	58.0	294.2	109.6	65.4	32.7	44.3
9 AM	351.9	140.8	58.2	345.2	132.1	117.4	32.6	42.8
10 AM	496.9	184.3	58.0	233.1	126.0	137.6	32.9	75.4
11 AM	310.4	133.0	57.5	164.8	123.1	120.0	34.2	70.7
12 PM	237.8	175.5	56.9	236.0	103.0	71.4	33.3	62.5
1 PM	403.6	190.4	56.9	32.7	146.9	59.7	33.3	82.6
2 PM	380.9	111.3	58.0	38.4	122.7	63.1	32.8	68.5
3 PM	252.8	74.2	57.9	74.1	93.3	54.4	32.8	62.8
4 PM	92.1	86.5	57.9	54.9	59.8	57.1	32.6	40.4
5 PM	68.4	56.9	58.3	66.2	43.1	37.4	32.4	33.1
6 PM	59.8	56.2	58.0	47.3	36.6	32.8	32.6	32.1
7 PM	59.6	56.4	57.9	47.4	35.7	32.6	32.6	33.2
8 PM	59.5	56.4	57.8	47.3	35.3	32.2	32.4	32.7
9 PM	59.5	56.4	57.7	47.3	35.2	32.2	32.2	31.9
10 PM	59.6	56.4	57.8	47.2	35.5	32.4	32.4	31.9
11 PM	59.4	56.3	57.8	47.1	35.5	32.4	32.6	33.0

Electrical power (W) for Selfridge 303, circuit 1. Includes switch groups, 149, 15, Corridor NS, 150 and approximately one-third of open office. See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	282.4	246.8	247.6	247.1	109.6	108.0	110.9	107.3
1 AM	282.4	247.0	247.7	247.0	110.4	107.9	110.0	108.2
2 AM	282.3	247.0	247.6	247.0	111.7	118.2	108.5	108.3
3 AM	282.2	246.8	247.6	246.9	110.5	109.4	107.8	108.2
4 AM	281.7	246.5	247.6	246.8	113.5	110.5	108.3	107.9
5 AM	335.2	266.5	247.5	246.1	123.2	108.3	108.8	111.7
6 AM	1374.1	926.1	315.9	762.3	397.5	304.6	152.4	322.6
7 AM	1624.4	1546.0	364.1	1611.4	510.7	452.3	167.7	479.6
8 AM	1627.4	1551.5	368.1	1621.5	502.9	456.3	166.5	500.7
9 AM	1610.9	1583.2	371.1	1633.3	479.0	450.0	160.6	485.3
10 AM	1604.5	1577.3	364.4	1599.6	471.2	445.1	149.3	465.1
11 AM	1570.8	1553.8	336.0	1608.3	448.6	438.4	150.4	437.0
12 PM	1542.0	1555.2	333.7	1497.1	433.8	430.7	135.0	411.8
1 PM	1560.3	1543.8	329.0	1573.7	432.5	427.0	121.9	419.3
2 PM	1562.2	1534.2	328.2	1534.9	416.5	418.4	114.2	401.7
3 PM	1547.2	1517.0	332.9	1581.2	413.7	419.8	119.1	351.3
4 PM	1481.2	1299.7	288.5	383.5	389.2	394.7	110.5	243.9
5 PM	954.9	689.5	247.4	247.8	281.8	215.1	111.0	132.1
6 PM	556.4	540.9	247.1	247.8	151.9	114.0	113.0	118.7
7 PM	298.5	412.8	247.0	247.8	123.4	110.0	114.6	112.5
8 PM	247.4	402.1	247.1	247.8	116.5	114.3	108.9	107.3
9 PM	247.3	402.2	247.1	247.9	115.5	108.2	108.4	108.1
10 PM	247.5	402.3	247.1	247.7	118.3	108.2	107.9	108.2
11 PM	247.5	402.2	247.0	247.6	111.6	108.1	107.6	113.3

Electrical power (W) for Selfridge 303, circuit 3. Includes switch groups approximately one-third of open office. See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	48.5	0.3	0.3	426.8	0.3	0.3	0.3	0.4
1 AM	48.5	0.3	0.3	425.5	0.3	0.3	0.3	0.4
2 AM	48.4	0.3	0.3	425.9	0.3	0.3	0.3	0.4
3 AM	48.3	0.0	0.3	425.9	0.3	0.3	0.3	0.4
4 AM	48.1	0.0	0.3	424.9	0.3	0.3	0.3	0.4
5 AM	89.3	33.1	0.3	422.1	0.3	0.3	0.3	0.4
6 AM	1423.4	1091.1	152.1	964.9	0.3	0.3	0.3	0.3
7 AM	1691.4	1690.3	307.7	1700.7	0.3	0.3	0.3	0.3
8 AM	1688.1	1691.6	382.2	1699.6	0.0	0.0	0.3	0.3
9 AM	1665.6	1687.2	371.4	1698.9	0.0	0.0	0.3	0.0
10 AM	1687.9	1689.4	322.6	1696.0	0.0	0.0	0.3	0.0
11 AM	1690.0	1689.1	211.1	1697.9	0.0	0.0	0.3	0.3
12 PM	1689.7	1689.5	97.1	1698.5	0.0	0.0	0.3	0.4
1 PM	1688.9	1690.6	97.0	1697.8	0.0	0.0	0.3	0.4
2 PM	1687.8	1689.5	97.1	1698.2	0.0	0.0	0.3	0.3
3 PM	1661.1	1685.2	96.8	1696.4	0.0	0.0	0.3	0.3
4 PM	1574.8	1470.6	48.7	537.1	0.0	0.0	0.3	0.3
5 PM	812.0	419.9	1.3	0.0	0.0	0.0	0.3	0.4
6 PM	320.0	271.8	0.3	0.0	0.3	0.3	0.3	0.4
7 PM	113.5	214.0	0.3	0.0	0.3	0.3	0.3	0.4
8 PM	63.1	214.2	0.3	0.0	0.3	0.3	0.3	0.4
9 PM	31.4	214.0	0.3	0.0	0.3	0.3	0.3	0.4
10 PM	24.2	214.1	0.3	0.0	0.3	0.3	0.3	0.4
11 PM	24.2	214.1	0.3	0.0	0.3	0.3	0.3	0.4

Electrical power (W) for Selfridge 303, circuit 5. Includes switch groups approximately one-third of open office. See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	164.9	165.4	165.2	208.5	34.5	27.3	36.4	41.8
1 AM	164.9	165.5	165.2	208.5	32.8	31.0	33.8	41.9
2 AM	164.9	165.4	165.2	208.5	34.6	32.9	32.2	41.1
3 AM	164.8	164.8	165.2	208.6	33.2	31.6	31.0	38.3
4 AM	164.0	165.2	165.3	208.2	35.2	33.5	32.2	44.4
5 AM	177.9	179.5	165.2	207.6	61.6	28.1	36.4	42.4
6 AM	806.8	614.4	198.1	586.7	434.7	336.0	111.8	394.6
7 AM	1085.0	947.0	261.9	1056.1	536.3	515.3	156.7	538.6
8 AM	1067.4	998.1	303.0	1060.0	544.1	546.3	167.4	529.2
9 AM	1023.7	999.8	301.7	1030.3	514.5	537.9	144.1	528.7
10 AM	996.1	987.6	285.2	999.7	517.9	531.7	138.6	519.1
11 AM	928.7	922.7	245.1	925.1	502.3	500.0	122.8	494.3
12 PM	947.4	918.9	216.5	885.6	506.4	500.7	95.5	484.8
1 PM	972.7	941.2	216.6	853.2	505.5	515.0	57.3	490.0
2 PM	972.9	909.2	214.2	748.2	496.1	510.9	45.4	458.6
3 PM	962.8	871.5	210.4	745.6	483.5	476.1	47.4	420.7
4 PM	882.3	723.9	192.6	310.7	449.9	449.9	39.5	248.6
5 PM	439.6	212.7	165.6	208.7	339.7	239.9	37.4	87.1
6 PM	245.6	184.1	166.4	208.9	130.8	56.7	35.9	50.5
7 PM	186.1	164.7	165.5	208.9	64.1	38.2	34.2	37.8
8 PM	172.7	164.8	165.5	208.9	51.7	37.6	33.1	29.9
9 PM	164.8	164.8	165.5	208.9	47.9	40.0	33.0	30.5
10 PM	164.8	164.8	165.5	208.9	50.4	32.8	31.1	38.9
11 PM	164.8	164.9	165.5	208.9	34.0	34.9	31.9	37.5

Electrical power (W) for Selfridge 303, circuit 7. Includes switch groups Corridor and Break Room. Both unretrofit. See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	51.1	14.2	32.9	49.3	89.3	93.7	91.8	92.8
1 AM	51.2	14.5	33.2	49.3	89.4	93.9	91.9	92.9
2 AM	51.2	14.3	33.2	49.4	89.3	93.7	92.0	92.9
3 AM	51.5	14.4	33.2	49.3	89.2	93.4	92.0	92.9
4 AM	52.0	14.7	33.1	49.2	88.8	93.1	92.0	92.8
5 AM	43.6	22.5	33.2	49.7	93.6	93.4	92.0	92.8
6 AM	205.6	123.9	20.3	40.0	168.4	122.6	100.0	140.6
7 AM	383.4	307.1	52.5	331.6	190.3	135.3	105.0	178.1
8 AM	408.2	356.5	61.3	284.7	181.2	133.6	105.5	175.7
9 AM	350.4	296.9	74.8	373.0	172.0	130.6	105.4	160.0
10 AM	345.4	273.3	71.8	357.0	172.6	125.3	104.3	155.8
11 AM	293.6	251.9	58.8	295.6	156.1	113.8	99.4	151.4
12 PM	261.0	236.7	55.9	280.8	144.2	113.0	96.8	139.0
1 PM	280.0	261.7	57.9	280.6	148.3	110.6	96.3	140.6
2 PM	277.4	259.2	46.9	320.8	140.7	107.4	97.1	120.4
3 PM	261.7	236.4	40.4	293.3	143.2	106.9	96.5	114.3
4 PM	214.2	132.4	21.7	124.9	127.2	104.2	94.8	86.8
5 PM	95.7	88.1	15.0	124.7	99.0	87.2	94.8	89.6
6 PM	49.1	92.9	15.0	125.9	90.6	88.0	94.8	90.4
7 PM	48.7	91.6	15.0	125.9	88.9	87.9	94.8	90.3
8 PM	43.1	91.5	15.0	70.0	89.0	88.0	94.8	90.4
9 PM	38.8	91.5	15.0	1.6	89.0	88.1	94.8	94.4
10 PM	42.2	91.5	15.0	0.0	89.1	88.2	94.9	95.9
11 PM	42.4	91.5	15.0	0.0	89.1	88.3	94.9	95.8

Electrical power (W) for Truax 510, circuit 8. Includes switch groups 102, and approximately one-half of open office, 107. See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	0.0	30.4	0.0	0.6	20.8	17.4	14.1	14.1
1 AM	0.0	30.5	0.0	0.0	14.1	14.0	14.1	14.1
2 AM	0.0	30.4	0.0	0.0	14.0	14.0	14.1	14.1
3 AM	0.0	8.1	0.0	0.0	14.0	13.9	14.1	14.1
4 AM	0.6	7.4	0.0	0.0	14.1	14.1	14.1	14.3
5 AM	106.0	51.5	0.0	132.9	87.2	25.0	15.4	73.7
6 AM	453.5	145.4	0.0	610.3	267.0	84.2	21.4	258.8
7 AM	450.4	173.2	0.0	646.0	270.0	113.9	18.0	242.3
8 AM	448.3	182.5	0.0	631.5	260.0	96.4	22.4	272.9
9 AM	456.2	145.3	0.0	630.5	250.0	97.4	21.9	259.1
10 AM	462.1	142.3	6.2	600.0	237.6	90.5	21.9	241.0
11 AM	461.9	142.5	6.7	580.7	229.5	81.3	21.9	228.1
12 PM	464.3	138.8	6.7	601.6	218.4	66.2	23.2	214.5
1 PM	458.0	128.7	0.0	612.3	217.1	64.9	22.9	217.0
2 PM	454.8	132.4	0.0	445.0	228.1	66.0	19.9	179.7
3 PM	451.2	131.9	0.0	310.3	240.8	62.5	15.8	154.7
4 PM	284.2	98.7	0.0	52.8	219.5	44.8	14.7	84.1
5 PM	76.5	26.7	0.0	0.0	142.3	14.3	14.0	14.4
6 PM	51.9	8.3	0.0	0.0	116.4	13.8	14.0	13.8
7 PM	32.3	0.0	0.0	0.0	108.0	13.9	14.1	13.9
8 PM	28.1	0.0	0.0	0.0	101.2	14.0	14.2	14.0
9 PM	25.7	0.0	0.0	0.0	91.4	14.0	14.2	14.1
10 PM	9.2	0.0	0.0	0.0	62.4	14.0	14.3	14.1
11 PM	7.4	0.0	0.0	0.0	48.6	14.0	14.2	14.0

8 fixtures were moved from circuit 10 onto circuit 8 as part of retrofit. This reduces the savings on circuit 8, while increasing the savings on circuit 10.

Electrical power (W) for Truax 510, circuit 10. Includes switch groups 110, and approximately one-half of open office, 107. Also includes 113 and 114 (unretrofit). See lighting plans for more details.

Hour	Pre-Retrofit				Post-Retrofit			
	NWD	LWD	WEH	TRN	NWD	LWD	WEH	TRN
12 AM	2.6	27.0	3.7	73.8	5.5	5.5	5.3	5.4
1 AM	2.6	27.0	3.8	73.7	5.5	5.5	5.4	5.3
2 AM	2.6	26.9	1.8	15.1	5.5	5.5	5.4	5.4
3 AM	2.6	10.8	2.3	1.5	5.5	5.5	5.4	5.4
4 AM	2.6	1.6	1.5	1.5	5.5	5.5	5.4	5.4
5 AM	105.7	26.8	1.5	144.5	9.2	5.9	5.8	10.7
6 AM	442.0	154.0	0.0	602.2	54.8	17.2	7.5	73.6
7 AM	493.8	339.2	0.9	670.3	52.1	16.7	7.0	80.3
8 AM	497.0	345.7	0.0	654.8	47.2	10.9	8.1	73.5
9 AM	496.7	362.6	0.0	614.2	43.5	11.2	7.7	77.3
10 AM	488.5	360.3	0.0	627.8	40.3	14.3	7.7	72.2
11 AM	499.3	332.1	0.0	629.6	36.8	11.0	7.7	66.3
12 PM	500.4	327.2	0.0	646.8	38.2	9.3	8.1	48.2
1 PM	502.7	300.4	0.0	680.9	37.8	10.8	8.0	42.9
2 PM	493.5	276.9	0.0	442.3	37.5	10.3	7.9	30.7
3 PM	496.6	178.1	0.0	245.2	39.8	11.5	5.7	30.4
4 PM	433.5	67.7	0.0	58.9	30.3	12.3	5.8	15.4
5 PM	369.1	25.1	0.0	14.9	11.6	6.7	5.7	5.6
6 PM	346.5	20.0	0.0	13.9	11.5	5.5	5.7	5.3
7 PM	340.0	0.0	0.9	13.9	11.7	5.7	5.3	5.3
8 PM	332.2	7.1	1.5	13.9	10.3	5.4	5.3	5.3
9 PM	272.0	27.0	1.5	13.9	12.5	5.4	5.3	5.3
10 PM	14.6	26.9	1.5	5.0	11.7	5.4	5.3	5.3
11 PM	8.5	27.0	1.5	1.4	8.6	5.4	5.3	5.4

8 fixtures were moved from circuit 10 onto circuit 8 as part of retrofit. This reduces the savings on circuit 8, while increasing the savings on circuit 10.

MEASURED ILLUMINANCE AT MULTIPLE LOCATIONS IN EACH SPACE (FC)

Note that the post-retrofit values are after task tuning has been implemented, but do not account for adjustments made due to occupant feedback after commissioning. The values represent only the electric component of the illuminance.

Selfridge 303: Pre-Retrofit

Location	149	145	140	Office SW	146	Office Central	Corridor NS	Office SW	142
p-1	31	31	36	47	34	11	54	47	37
p-2	34	37	20	15	32	23	34	15	37
p-3									
p-4									
q-1	37	42	64	45	49	47	57	45	50
q-2	38	47	40	38	39	24	62	38	47
q-3							72		
q-4							56		
q-5							31		
q-6							35		
q-7							35		
q-8							40		
r-1	62	54	56	54	53	87		54	55
r-2	55	45	41	62	52	68		62	53
r-3				42		62		42	
r-4				55		45		55	
r-5									
r-6									
r-7									
r-8									
t-1	48	43	39	51	40	88		51	44
t-2	43	42	32	43	42	47		43	38
t-3	51	25	27	22	46	33		22	29
t-4	47	29	20	17	46	38		17	28
<i>Ave</i>	37	37	34	31	38	36	48	31	39

Selfridge 303: Pre-Retrofit

Location	Office NW	Office Central	141	Corridor EW	Office S	144	Office E	151
p-1	44	11	36	26	16	33	32	25
p-2	46	23	30	15	53	31	18	42
p-3								
p-4								
q-1	50	47	52	33	42	43	55	31
q-2	57	24	47	26	25	39	51	52
q-3				24				
q-4				16				
q-5				39				
q-6				25				
q-7				24				
q-8				25				
r-1	96	87	57		84	60	57	63
r-2	102	68	51		84	63	74	57
r-3	82	62			60		54	
r-4	99	45			60		72	
r-5								
r-6								
r-7								
r-8								
t-1	92	88	41		60	40	27	43
t-2	72	47	37		41	35	17	42
t-3		33	38		23	46	57	45
t-4		38	35		17	39	61	43
<i>Ave</i>	64	36	38	25	35	36	40	38

Selfridge 124/127: Pre-Retrofit

Location	109	103	Corridor S	108	Corridor N	106	B127
p-1	40	26	9	23	9	44	36
p-2	38	30	13	25	5	45	47
p-3					12		
p-4					14		
q-1	49	25	14	32	9	11	69
q-2	48	28	12	31	14	17	60
q-3	47	36	17	36	14	49	62
q-4	44	32	19	30	14	39	64
q-5					14		
q-6					14		
q-7					9		
q-8					5		
r-1	56	58	20	40		56	81
r-2	61	47	18	43		52	85
r-3	61	40	16	42		54	84
r-4	71	50	19	45		62	84
r-5		40					
r-6		48					
r-7		57					
r-8		47					
t-1	40	32	13	33		51	48
t-2	46	46	16			45	53
t-3	44	37	16			48	54
t-4	54	43	17			43	50
<i>Ave</i>	49	41	16	33	12	44	67

Truax 510: Pre-Retrofit

Location	110	107	102
p-1	9	19	49
p-2	26	18	15
p-3			
p-4			
q-1	43	34	100
q-2	76	45	24
q-3			
q-4			
q-5			
q-6			
q-7			
q-8			
r-1	33	52	90
r-2	30	44	97
r-3	36	44	70
r-4	63	51	85
r-5			
r-6			
r-7			
r-8			
t-1	25	29	65
t-2	10	26	41
t-3	15	26	91
t-4	18	26	67
<i>Ave</i>	32	25	51

Selfridge 303: Post-Retrofit

Location	149	145	140	Office SW	146	Office Central	Corridor NS	Office SW	142
p-1	16	10	25	25	26	9	28	25	23
p-2	20	29	25	13	22	29	27	13	21
p-3									
p-4									
q-1	22	14	35	18	36	18	24	18	36
q-2	25	34	32	25	32	23	25	25	34
q-3							23		
q-4							26		
q-5							34		
q-6							30		
q-7							33		
q-8							32		
r-1	41	46	38	32	52	36		32	38
r-2	44	38	32	42	49	35		42	41
r-3				31		36		31	
r-4				34		33		34	
r-5									
r-6									
r-7									
r-8									
t-1	32	35	24	24	35	21		24	26
t-2	28	25	23	34	33	21		34	25
t-3	30	31	27	12	34	30		12	23
t-4	32	26	19	11	32	26		11	21
<i>Ave</i>	22	23	27	19	29	20	28	19	26

Selfridge 303: Post-Retrofit

Location	Office NW	Office Central	141	Corridor EW	Office S	144	Office E	151
p-1	33	9	19	19	8	23	26	26
p-2	47	29	18	11	29	25	12	28
p-3								
p-4								
q-1	29	18	30	26	11	32	22	15
q-2	49	23	29	18	26	28	18	34
q-3				19				
q-4				19				
q-5				24				
q-6				17				
q-7				18				
q-8				20				
r-1	68	36	21		29	46	27	43
r-2	58	35	37		29	42	39	44
r-3	70	36			42		19	
r-4	65	33			42		42	
r-5								
r-6								
r-7								
r-8								
t-1	54	21	14		30	22	16	28
t-2	51	21	21		26	29	18	28
t-3	38	30	21		9	29	28	31
t-4	40	26	21		11	26	32	28
<i>Ave</i>	43	20	21	19	18	26	21	27

Selfridge 124/127: Post-Retrofit

Location	109	103	Corridor S	108	Corridor N	106	B127
p-1	21	18	17	20	6	23	28
p-2	25	25	14	34	10	24	45
p-3					8		
p-4					20		
q-1	26	23	11	31	18	26	52
q-2	21	25	13	31	13	25	42
q-3	28	27	21	24	17	27	44
q-4	23	25	21	21	15	27	42
q-5					15		
q-6					21		
q-7					17		
q-8					14		
r-1	28	32	22	32		32	59
r-2	34	35	22	36		28	63
r-3	36	27	19	33		27	59
r-4	36	33	22	36		30	52
r-5		34					
r-6		34					
r-7		40					
r-8		38					
t-1	26	22	12	29		24	38
t-2	24	26	17	36		21	38
t-3	26	34	18	23		24	45
t-4	31	34	17	11		24	39
<i>Ave</i>	27	30	23	28	15	26	48

Truax 510: Post-Retrofit

Location	110	107	102
p-1	17	9	19
p-2	15	10	8
p-3			
p-4			
q-1	23	14	31
q-2	31	16	15
q-3			
q-4			
q-5			
q-6			
q-7			
q-8			
r-1	32	30	40
r-2	32	24	36
r-3	23	24	30
r-4	30	28	40
r-5			
r-6			
r-7			
r-8			
t-1	19	15	32
t-2	24	25	30
t-3	6	21	41
t-4	15	18	37
<i>Ave</i>	19	15	22