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Energy Savings from Networked Lighting Control (NLC) Systems with and without LLLC

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About the Northwest Energy Efficiency Alliance

The Northwest Energy Efficiency Alliance (NEEA) is an alliance of more than 140 utilities and energy efficiency organizations working on behalf of more than 13 million energy consumers. NEEA is dedicated to accelerating both electric and gas energy efficiency, leveraging its regional partnerships to advance the adoption of energy-efficient products, services and practices. Since 1997, NEEA and its partners have saved enough energy to power more than 700,000 homes each year.

About the DesignLights Consortium

The DesignLights Consortium® (DLC) is a non-profit organization whose mission is to achieve energy optimization by enabling controllability with a focus on quality, people, and the environment. The DLC promotes high-quality, energy-efficient lighting products in collaboration with utilities and energy efficiency program members, manufacturers, lighting designers, and federal, state, and local entities. Through these partnerships, the DLC establishes product quality specifications, facilitates thought leadership, and provides information, education, tools, and technical expertise.

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Data Contributors

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Definitions

Building Information

Building type: A building classification. Commonly designated and referenced to characterize energy consumption based on the building's primary purpose.

Personally identifiable information (PII): Any data that could potentially identify a specific individual or organization.

Space type: A classification of a subspace within a building. Commonly designated and referenced to characterize energy consumption for a specific use within a building (e.g. open office, hall, breakroom).

Power/Energy Measurement

Apparent power measurement: Power measurement method determined by multiplying root mean square (RMS) voltage measurement and RMS current measurement.

Control factor: The fractional energy savings achieved by NLCs to the light source they are controlling. This excludes any energy savings resulting from changes to light sources.

Correlated power: The power consumption calculated from the supplied control signal based on a known dimming signal versus power curve.

Dimming level: Amount of delivered light relative to maximum output, typically reported as a value of the dimming signal from 0-100%.

Energy monitoring: The capability of a system, luminaire, or device to report its own energy consumption or the energy consumption of any controlled device via direct measurement or other methodology (i.e. true, apparent, or correlated power).

Power-dimming curve: A curve representing the relationship between a dimming signal and corresponding power output as a function of control signal from 0-100%.

Rated power: Maximum rated luminaire or zonal wattage without controls enabled.

Reporting interval: The interval in which power and/or energy measurements are reported as a single value (e.g. every 5 minutes, every 15 minutes, hourly, or daily).

Sampling interval: The interval between which discrete power measurements occur. NLC sampling intervals are typically less than five seconds.

State change: Change in luminous output caused by a triggering of control strategy (e.g. occupancy, scheduling, daylighting, etc.). An event-based interval reporting method utilizes state changes, rather than defined time intervals, to report power or energy data.

True power measurement: Power measurement method where instantaneous voltage measurement is multiplied by instantaneous current measurement, then accumulated and integrated over a specific time period of at least one complete cycle.

Networking and Lighting Control Strategies

Daylight harvesting: The capability to automatically affect the operation of lighting or other equipment based on the amount of daylight and/or ambient light present in a space, area, or exterior environment.

High-end trim (aka "task tuning"): The capability to set the maximum light output to a less-than maximum state of an individual or group of luminaires at the time of installation or commissioning.

Luminaire level lighting control (LLLC): The capability to have a networked occupancy sensor and ambient light sensor installed for each luminaire or kit, and directly integrated or embedded into the form factor during the luminaire or kit manufacturing process.

Networked lighting control (NLC) systems: NLC systems are lighting systems with a combination of sensors, network interfaces, and controllers that effect lighting changes in luminaires, retrofit kits, or lamps.

Networking of luminaires and devices: The capability of individual luminaires and control devices to exchange digital data with other luminaires and control devices on the system.

Occupancy sensing: The capability to automatically affect the operation of lighting equipment based on the detection of the presence or absence of people in a space or exterior environment.

Personal control: The capability for individuals to adjust the illuminated environment of a light fixture or group of light fixtures in a specific task area to their personal preferences, via networked means.

Scheduling: The capability to automatically affect the operation of lighting equipment based on time of day, week, month, or year.

Executive Summary

While connected lighting currently comprises less than 1% of all luminaires in the United States[1], the Department of Energy (DOE) estimates that it can provide up to one quad of energy savings by 2035[2]. By 2035, just under a third of installed luminaires in commercial buildings are expected to have network connectivity (DOE 2019).

Luminaire level lighting control (LLLC) is available in a subset of networked lighting control (NLC) systems. LLLC includes sensors and control logics at each individual luminaire, whereas sensors in NLC systems without LLLC control groups of fixtures (zones).

This project is an expansion upon the 2017 NLC data collection and analysis project, referred to hereafter as the 2017 NLC Savings Study, which culminated in the 2017 DesignLights Consortium report, *Energy Savings from Networked Lighting Control (NLC) Systems* (DLC 2017). This study builds upon the 2017 NLC Savings Study by utilizing all of the 2017 data and expanding the project sample size, increasing the representation of NLC systems with LLLC, providing a separate analysis for savings achieved by systems with LLLC, and increasing building-type diversity.

This research project collected, aggregated, and analyzed building-, zone- and fixture-level energy monitoring interval data from NLC systems, including those with and without LLLC, in 194 buildings across a variety of building types in North America, with an average of 13 weeks of monitoring data per building. Overall, the study found average energy savings from all NLC systems to be 49%, although values are highly site-specific (see Figure 1 and Table 1 below).

[1] In their Forecast Report, the DOE defines connected lighting as "an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate and exchange data with other devices." (DOE, 2019)

[2] A quad is a unit of energy typically used (including by the DOE) when discussing global or national energy supply and demand. It is defined as 1 quadrillion (10^{15}) BTU, or 1.055×10^{18} joules.

Figure 1. Distribution of NLC savings across all buildings analyzed (n=194).

Table 1. Summary of estimated control factors by building types.

Building Type	Total Buildings	Unique Manufacturers	Control Factor* (% Savings)			
			Average	25th–75th Percentile**	High-End Trim Contribution	Other Control Strategies***
Assembly	6	2	0.28	0.11 - 0.45	0.07	0.23
Education	14	5	0.41	0.19 - 0.58	0.19	0.32
Healthcare	2	1	0.52	0.48 - 0.56	0.33	0.24
Manufacturing	73	4	0.40	0.20 - 0.55	0.16	0.29
Office	57	8	0.64	0.53 - 0.81	0.46	0.36
Restaurant	3	2	0.59	0.47 - 0.68	0.27	0.30
Retail	29	1	0.44	0.39 - 0.48	0.22	0.27
Warehouse	10	2	0.68	0.53 - 0.79	0.38	0.48
Overall	194	12	0.49	0.35 - 0.69	0.27	0.32

* A control factor is a number between 0 and 1, representing the fraction of the energy saved through controls. 0 represents no savings, and 1 means all energy is saved. Control factor is equivalent to percent savings (% savings) when presented in percentage. For example, a control factor of 0.49 is equivalent to 49 percent savings (49% savings).

** The range for the middle 50% is displayed instead of the full range between the minimum and the maximum to provide a more representative range of savings one can generalize and expect.

*** In this report, the control factors for control strategies other than high-end trim, unless otherwise noted, are in comparison to an inferred baseline with savings from high-end trim removed. Therefore, the control factors for high-end trim and other control strategies will not add up to the overall control factor. See Page 33 for a more detailed discussion.

This project reflects an important step towards advanced measurement and verification (M&V), or "M&V 2.0" – moving from generalized engineering calculations to leveraging building-specific, standardized energy data collected by building systems (in this case NLC lighting control systems) to predict, measure, and verify energy savings. This report provides key findings to inform energy savings estimates used by the building design and construction, lighting controls, and utility and energy efficiency program industries; as well as recommendations for improving methods for collecting and analyzing NLC monitoring data.

Key Findings and Recommendations

Finding #1: The portfolio-level average energy savings across all buildings in this study was 49%.

Similar to the trends observed in the 2017 NLC Savings Study, there does not seem to be a clear correlation between energy savings and building type. Site-specific variation is a much larger driver of energy savings than general factors such as building type. The variation in savings results among buildings within the same building type is likely due to the following factors:

- Site-specific NLC system commissioning and the combination of control strategies that are actually implemented.
- High variation in settings for the strategies that are used.
- Variation in site characteristics, occupancy patterns, and user behavior.

A better understanding of the causal factors that influence energy savings is an important consideration for future study. This will require a significantly larger dataset and collection of additional site information, which is feasible if energy efficiency programs for NLCs begin collecting this data in a standardized fashion.

Recommendation #1: Based on this dataset, utility and energy efficiency programs are able to use 49% as the best estimate of average portfolio-level energy savings for NLC incentive programs.

The portfolio-level average energy savings across all 194 buildings in this study was 49%. This estimate is similar to the 2017 NLC Savings Study. Because the buildings included in this study were not identified through a random sample, it is not possible to make statistical inferences about a broader building stock. For the same reason, it is also not possible to definitively determine if the 2% gain in the savings estimate is due to increased familiarity with the technology and improved programming and commissioning. However, 49% represents the average savings from NLC systems across twelve manufacturers, eight building types, and 194 buildings, and is therefore the best available estimate of average NLC performance. A reasonable interpretation of the results is that “across a portfolio of buildings, NLC is likely to save roughly half of the lighting energy”.

Finding #2: The NLC systems with LLLC showed overall higher savings, although additional study is needed to confirm this finding.

Within this study's dataset, NLC systems with LLLC showed overall higher savings than systems without LLLC (see Table 2 below). While this finding suggests that more granular control may lead to higher savings, it should not be inferred at this time that LLLC is universally superior in all applications, building types, and design criteria. A larger study including more diverse NLC systems with LLLC and controlling for potentially confounding variables is still needed to confirm this finding at the portfolio level. Future study should also address the potential "checkerboard[3]" effect and the potential issues related to user perception and satisfaction.

Table 2. Summary of estimated control factors by LLLC and control strategies.

LLLC Presence	Total Buildings	Control Factor (% Savings)			
		Average	25th–75th Percentile	High-End Trim Contributions	Other Control Strategies*
NLCs w/ LLLC	98	0.63	0.50 - 0.79	0.37	0.41
NLCs w/o LLLC	96	0.35	0.17 - 0.48	0.17	0.22
All NLCs	194	0.49	0.35 - 0.69	0.27	0.32

Note: The numbers in this table are meant to provide a high-level overview of average savings trends. Additional study is needed to control for potentially confounding variables, and thus, at this time, the data does not imply that LLLC is universally superior and applicable to all building types.

*In this report, the control factors for control strategies other than high-end trim, unless otherwise noted, are in comparison to an inferred baseline with savings from high-end trim removed. Therefore, the control factors for high-end trim and other control strategies will not add up to the overall control factor. See Page 33 for a more detailed discussion.

Recommendation #2: Based on this finding, it may be worthwhile to explore energy efficiency programs around LLLC for greater average energy savings.

Further study is still needed to create more robust savings estimates for NLCs with LLLC at the portfolio level and for each building type. However, it may be worthwhile to pilot programs targeting the building types where LLLC seems to exhibit significantly higher savings, such as offices, manufacturing facilities, and other similar building types (see Table 7). Other aspects around LLLC can also be investigated through the pilot programs, including suitable applications (e.g. luminaire layouts, space configurations, etc.) and occupant perception, as noted in Finding #2.

[3] The "checkerboard" effect refers to the scenario where a connected space is unevenly lit, and the ceiling is showing dark spots as some luminaires are turned off or dimmed significantly. This occurs when each fixture turns off or dims itself in the absence of an occupant in its field of view, while other locations within the same space are still occupied and the luminaires above the occupied areas are at a much higher light output level.

Additional Findings and Recommendations

The control factor results described above in the Executive Summary, and in more detail in the Results and Discussion, are the primary outcome and of this report. This section provides additional findings to inform the continued growth of the NLC industry and utility and energy efficiency programs, as well as recommendations for improving how NLC monitoring data is collected and analyzed. For more in-depth discussions, see the Project Findings and Recommendations section of the report.

Finding #3: Ownership of, management of, and access to NLC energy data varies from NLC manufacturer to manufacturer.

During the data collection process, it became evident that NLC manufacturers had varying abilities to provide viable data to the study, stemming from varying levels of knowledge on the whereabouts and details of their NLC installations and ability to provide energy data due to different sales models. Some manufacturers centrally manage energy data in the cloud and had contractual agreements with customers to access the data. Other manufacturers enable energy monitoring by default or as an option and store energy data locally within the system. Most of these manufacturers rely on sales representative agencies, distributors, and contractors for sales, installation, and commissioning; and therefore, have little or no direct access to or knowledge about the installations.

This translated to a high level of effort in outreach and collecting NLC energy data for this study. More importantly, from the energy efficiency program perspective, it may not always be practical to expect the involvement and support of manufacturers in submitting NLC energy data as part of an energy efficiency program. Recommendation #2 in the next section specifically advocates for energy efficiency programs for NLCs to be the primary drivers for collecting NLC energy data as part of their energy efficiency programs.

Recommendation #3: Energy efficiency programs for NLCs should drive the sharing and use of anonymized NLC energy data for all participating projects.

While the 49% portfolio savings for NLCs may be used as deemed savings in the near term, the most accurate savings claims will always be the savings measured at each installation. With energy reporting becoming ubiquitous in NLCs, evaluating savings at each installation should be the ultimate direction energy efficiency programs move towards. As pointed out in Finding #3, administrators of energy efficiency programs for NLCs are the only market actor that have direct engagement with NLC program participants in all cases. Energy efficiency programs for NLCs should strongly consider including clauses in their customer participation agreements that authorize the sharing of anonymized data with the program administrators.

In addition to collecting NLC energy data submitted by the program participants, this recommendation also advocates for the energy efficiency program administrator’s active use of the collected data. A standardized data submission format and process (detailed in Recommendation #5) should be specified by the energy efficiency program and included as part of the customer participation agreement. This recommendation is consistent with and reinforces the recommendation in the DLC report, *Interoperability for Networked Lighting Controls* (DLC 2020), that the program administrator should be the primary driver and promoter for the use case of energy data reporting for incentive savings verification.

Finding #4: The process for exporting static attributes of the energy data, such as the post-NLC rated power, is more error-prone than for time-series data and can skew the estimated savings.

For energy data directly reported by NLCs, the time series data is a direct export from the NLCs. The static attributes, on the other hand, were typically provided in a separate document during the data collection period, which is much more susceptible to human data entry and transcription error. Some NLCs may be able to export static attributes, but they are still only as accurate as the information manually entered into the NLC by the commissioning providers at the time of system startup, programming, or commissioning.

Recommendation #4: As part of the NLC energy data, essential static attributes of an NLC installation should be required and verified carefully to ensure accuracy and quality of the analyses.

Whether or not NLC energy data is collected as part of a utility or energy efficiency program or for future savings characterizations like this study, the static attributes, such as the post-NLC rated power, gross building area of the NLC installation, etc., need to be carefully verified by the data collector for accuracy. This is critical in ensuring the accuracy and quality of estimated savings as discussed in Finding #4. From the energy efficiency program perspective, the best time to accurately collect these essential static attributes is at the completion of the NLC installation.

Finding #5: Most manufacturers do not have an existing mechanism to easily export the data required for energy efficiency program evaluation.

The size of a dataset grows rapidly as the spatial and temporal granularities and the overall duration of measurement increase[4]. The highly granular and long duration datasets used in this study presented challenges, both in terms of the data providers transferring the data, and in the time required for the project team to process, normalize, and load the datasets into the NLC database.

[4] Spatial granularity refers to the spatial level at which the data is provided (i.e., building-level, zone-level, and fixture-level). Temporal granularity refers to the reporting interval (i.e., hourly, 15-minute intervals, event-based, etc.). These terms are explained in more detail in the Data Normalization and Aggregation section.

The challenges encountered in this study suggest that it would not be a scalable model for utility and energy efficiency programs to require the most granular energy data for NLCs. The program data requirements will need to strike a balance between accuracy and scalability, as suggested in Recommendation #5 in the next section.

Recommendation #5: Energy efficiency programs for NLCs should standardize the NLC energy data reporting format and requirements to facilitate program participation and streamline the process. Based on these reporting guidelines, manufacturers should consider developing administrator-specific reporting functionality to support the energy efficiency program data intake process.

As Finding #5 points out, the large size of some NLC data files will make data intake, processing, and analysis very challenging and unscalable for efficiency programs. It is critical for energy efficiency programs for NLCs to specify and standardize the spatial and temporal granularity and duration requirements based on the metrics and methodology that will be used to assess or verify the NLC energy performance.

A standardized data reporting format and requirements will also provide manufacturers clear guidance and motivation to develop NLC energy reporting functionalities that support efficiency program needs.

The DLC is supporting progress on Recommendations #4 and #5 through the NEMA ANSI C137 committee. This progress will enable the DLC and program administrators to encourage the installation of products with standardized data reports, as per Recommendation #3.

Finding #6: In this study, buildings with NLC systems had significantly longer operating hours than typical prescribed estimates of building operating hours.

The average occupied hours for buildings in this study's dataset are substantially longer than the average lighting system operating hours assumed by many efficiency programs throughout the US in their Technical Reference Manuals (TRMs). This is consistent with previous findings from the 2017 NLC Savings Study. Figure 20 in the Findings and Recommendations section compares operating hours found in this study and operating hours for fixtures across several TRMs, including California, Illinois, Mid-Atlantic, New York and the Northwest regions. The large discrepancy between observed hours and operating hours found in TRMs may result in lower overall savings for projects using deemed operating hours. This study, and any future updates to this study, could serve as additional data points for TRMs to calibrate deemed operating hours.

Introduction

Why is this Report Important?

While connected lighting currently comprises less than 1% of all luminaires in the United States, the US Department of Energy (DOE) estimates that it can provide up to one quad of energy savings by 2035 and that, by 2035, just under a third of installed luminaires in commercial buildings will have network connectivity (DOE 2019).

Although NLC systems are expected to be a major driver of future energy savings, historically, the impact of lighting controls has been difficult to measure at scale. As the market penetration of connected devices with energy monitoring capabilities continues to grow, building owners and energy efficiency programs are transitioning away from using static engineering calculations and moving toward measuring and verifying performance via granular data from installed systems. This radical shift toward "M&V 2.0" has the potential to improve understanding of building energy use.

The 2017 DLC report, *Energy Savings from Networked Lighting Control (NLC) Systems*, hereafter referred to as the "2017 NLC Savings Report", represented an important first step for M&V 2.0 by collecting and analyzing zone-level interval data for NLC systems in 114 buildings, and providing a framework for this type of empirical savings analysis (DLC 2017).

This report is the second iteration of the 2017 NLC Savings Report. As in the 2017 iteration, this study provides a savings analysis of installed NLC systems. It builds upon the 2017 NLC Savings Study by utilizing all of the 2017 data and expanding the project sample size with new data, increasing the representation of LLLC sites and providing a separate analysis for LLLC savings, and increasing building-type diversity – with a particular focus on the following priority building types: office, warehouse, healthcare, and education. As the NLC market continues to evolve, it is important to collect and analyze data from more recent installations to provide energy efficiency program managers and building owners with savings estimates that reflect the current NLC market.

Why is Better Quantification Necessary?

In order for incentive programs to better support the adoption of NLC systems, two key elements are required: (1) access to information and (2) reliable third-party quantification and verification of energy savings. However, reliable savings estimates at scale are lacking.

Several studies have quantified energy savings from lighting controls. Compared to the methodology used in this study, these studies typically follow a more stringent monitoring and verification (M&V) procedure by utilizing separate equipment for pre- and post-installation data monitoring and are therefore more accurate; however they have typically been limited to a small number of sites and third-party case studies (DLC 2015; Wei et al. 2015; Mutmansky & Berkland 2013, and NextEnergy 2020). Small sample sizes and limited sampling duration combined with high variability in control savings by building type has made it difficult to confidently predict savings achievable by NLC systems. At the time of the 2017 NLC Savings Study, the best available large-scale dataset on controls energy savings came from a 2011 meta-analysis from Lawrence Berkeley National Lab (LBNL) (Williams et al. 2011).[5] The 2017 NLC Savings Study represented a substantial improvement in large-scale, empirical quantification of NLC energy savings potential. The control factors estimated for each building type were incorporated into the technical reference manuals (TRMs) for energy efficiency measures related to networked lighting controls (Shelter Analytics 2019).

Project Objectives

This project serves as a follow-up to the 2017 NLC Savings Study and provides an update on the interior NLC energy savings potential. The objective is to leverage anonymized performance data from NLC systems in order to continue to provide efficiency program administrators, regulators, manufacturers, and potential customers with better estimates of interior NLC energy savings across existing and future installations. To support this broader objective, this report has three core goals (see Figure 2):

1. **Improve existing NLC energy savings estimates.** Improve industry understanding of NLC energy savings and reduce performance risk to efficiency programs, regulators, and customers through a detailed analysis of available project interval data.
2. **Provide energy savings estimates for NLC systems with luminaire level lighting control (LLLC).** Characterize the energy savings potential for NLC systems with LLLC, which has gained traction in the past years and is touted for ease of deployment.
3. **Augment the existing database of NLC performance data.** The 2017 NLC Savings Study established a database of NLC performance data, with the potential to grow in size and sophistication. This project enhances the database by adding more recent NLC performance data and ensures up-to-date information to further support NLC adoption and industry advancement.

[5] This study reviewed 240 savings estimates from 88 papers and case studies from 1982 to 2011, categorizing each study by control strategy to estimate the savings from individual control strategies and their potential when implemented together (Williams et al 2011). In order to integrate such a wide range of studies into one analysis, the authors did not filter or standardize baselines, so that savings may be measured over different time periods (e.g., weekday core hours vs. a 24/7 baseline).

Figure 2. Overview of NLC data project goals.

Intended Uses for this Study

NLC energy monitoring data and this report have three primary intended uses:

1. **Quantify savings claims of interior NLC systems to potential customers:** While many manufacturers, manufacturer representatives, and contractors typically use their own literature and calculators to estimate energy savings, reliable third-party estimates improve customer confidence that NLC systems can achieve the savings claims touted by a manufacturer or salesperson. Although energy savings are highly site-specific, improved quantification and a larger dataset can provide both a range of expected savings and an average of what a portfolio of buildings might be expected to achieve.
2. **Improve the utility and energy efficiency program evaluation process:** Historically, incentive programs have based controls savings claims on engineering calculations and deemed savings assumptions: occupancy sensors save X% in building type/space type Y. To validate these calculations, evaluators at times conduct time-intensive and costly metering studies of a small subset of installed systems for a short period, then extrapolate those results to an entire portfolio. NLC systems enable more thorough and granular data collection at every site and provide the potential to capture that data more economically, which can significantly increase both program administrator and evaluator confidence in NLC system energy savings claims.
3. **Support utility and energy efficiency program planners:** Program planners can leverage energy monitoring data to better estimate savings claims, align incentives with performance, and predict program cost-effectiveness, all the while increasing

the likelihood of a successful program. In addition, program planners can use the findings and recommendations to inform their NLC program policy and strategy.

Technology and Market Overview

Technology Overview

While NLC system architecture varies by manufacturer, they are generally composed of the following components:

- **Sensors:** Measure occupancy, light levels, and a wide (and growing) range of environmental data such as temperature and humidity at the fixture or zone level.
- **Network connectivity:** The capability of individual luminaires and control devices to exchange digital data with other luminaires and controls devices on the system.
- **Processing:** The incorporation of inputs from the sensors with programmed information (such as scheduling, occupancy timeouts, etc.) to identify and execute a control to optimize lighting. This processing and decision-making can be done at either the local level, on a site-based server, or in the cloud.
- **Web or app-based user interface:** Enables the configuration of specific controls settings, review of energy monitoring reports, and remote controllability of fixtures, based on the information received from the sensors and lighting.

The DLC manages a Networked Lighting Controls (NLC) Program, which provides specific technical requirements and maintains a Qualified Product List (QPL) for systems that meet those requirements. Most energy efficiency programs for NLCs reference the DLC QPL for eligible products. To meet DLC's requirements for NLC systems, each interior system must have occupancy sensing, daylight harvesting, high-end trim, zoning, individual addressability, continuous dimming, cybersecurity, and energy monitoring, as outlined in Table 3.[6]

[6] The requirements are based on the NLC Technical Requirement V5 released in June 23, 2020. For a complete list of DLC's requirements for NLCs and the most up-to-date information, see: https://www.designlights.org/lighting-controls/qualify-a-system/technical-requirements/

Table 3. NLC definition of control capabilities (as defined by the DLC).

CONTROL CAPABILITY	DLC DEFINITION
Daylight harvesting	The capability to automatically affect the operation of lighting or other equipment based on the amount of daylight and/or ambient light present in a space, area, or exterior environment.
Occupancy sensing	The capability to automatically affect the operation of lighting equipment based on the detection of the presence or absence of people in a space or exterior environment.
High-end trim	The capability to set the maximum light output to a less-than maximum state of an individual or group of luminaires at the time of installation or commissioning.
Scheduling (reported, not required)	The capability to automatically affect the operation of lighting equipment based on time of day, week, month, or year.
Personal control (reported, not required)	The capability for individual users to adjust the illuminated environment of a light fixture or group of light fixtures in a specific task area to their personal preferences, via networked means.
Luminaire level lighting control (reported, not required)	The capability to have a networked occupancy sensor and ambient light sensor installed for each luminaire or kit, and directly integrated or embedded into the form factor during the luminaire or kit manufacturing process.

At the time of the 2017 DLC Study, energy monitoring was a reported capability on the DLC's NLC QPL, but has since been classified as a required capability in the NLC5 Technical Requirements, except for room-based systems. While the vast majority of currently listed systems on the NLC QPL have energy monitoring capabilities[7], the sophistication of their reporting functionality and methods for calculating energy use (and savings) vary widely by manufacturer. This inconsistency is in part due to end-users with varying degrees of sophistication or interest in energy data being the primary consumer of this information. Energy reporting to energy efficiency programs for NLCs for savings verification has been identified as one of the most important top-priority use cases in a recent DLC study, *Interoperability for Networked Lighting Controls* (DLC 2020). Several utilities and program administrators have started to either require energy monitoring and reporting eligibility criteria or provide additional incentives under their energy efficiency programs. However, because utilities and efficiency programs have yet to become a major consumer of NLC reporting data, there has been no driver to standardize the industry's data reporting and measurement practices explicitly for their use.

Major Drivers of NLC Energy Savings

There are two major drivers of NLC energy savings within a building, both of which are often relatively independent of building or space type (Williams et al. 2011 and Asif ul Haq et al. 2014):

- **Site characteristics and occupancy patterns:** While there is generally some degree of similarity within building types, actual site characteristics are one of the greatest drivers of NLC energy savings, as they interact with settings for the enabled features. NLC systems produce the greatest savings at sites with long operating hours, large swings in occupancy throughout the day, and that are less than 100% occupied, resulting in lower overall traffic. Daylighting has an important but often secondary influence on energy savings.
- **Control strategies enablement and control settings:** Energy savings are highly dependent on which control strategies are enabled and the specific settings to which each control strategy is set. For example, enabling and implementing high-end trim has a tremendous impact on energy savings. Similarly, five-minute occupancy timeouts deliver significantly greater savings than fifteen-minute timeouts. However, proper programming and commissioning is critical to achieving energy savings. If configured improperly, NLC systems can have minimal impact and even increase energy use in some cases.

[7] Energy monitoring became a required NLC capability in NLC V4. The QPL is scheduled to start to list V5 qualified products starting in August 2020. V3 qualified products where the energy monitoring capability is a reported and optional capability will remain on the QPL until October 2020. Therefore, at the time of this report (September 2020), not all NLCs on the QPL have the energy monitoring capability.

Market Adoption Overview

Lighting controls have been installed for decades, but primarily as individual components, such as occupancy sensors or dimmers installed within specific parts of a building. However, total stock penetration of lighting controls remains low, and over two thirds of US buildings have no lighting controls in place (see Table 4).

Table 4. 2017 US installed stock penetration of lighting controls in the commercial sector (DOE 2019).

TYPE OF CONTROLS	INSTALLED STOCK PENETRATION (%)
None	66%
Dimmer	3%
Daylighting	<1%
Occupancy Sensor	6%
Timer	4%
Energy Management Systems	15%
Multiple Strategies	4%
Connected	<1%

Adoption of lighting controls is expected to increase, primarily driven by the sophisticated sensing and processing capabilities of connected NLC systems, which provide more insight into how buildings are used and operated. This insight creates three distinct overarching value propositions:

- Deeper energy savings from the optimization of multiple control strategies and improved quantification of energy use.
- Increased insight into facility operation that can result in reduced maintenance costs.
- As NLC products mature, an emerging suite of Internet of Things (IoT) use cases that can help optimize building operations, improve employee productivity, and increase revenue and business efficiency.

While emerging IoT use cases will provide significant benefits beyond lighting and become increasingly important over time in business decision-making, energy savings, code compliance, and monitoring capabilities are the current major drivers of NLC system adoption today. Because of energy savings' critical role in business decisions and project economics, increasing customer and program administrators' confidence in savings claims is critical to increasing NLC adoption in the near term.

Even as IoT use cases gain prominence in the market, energy monitoring capabilities will be crucial so that energy efficiency programs for NLCs can support—and customers can choose—products that will provide both energy savings and IoT benefits.

Methods

Large-scale collection and analysis of NLC energy monitoring data is a relatively new method for estimating energy savings for utility and energy efficiency programs and end-use customers. Moreover, it reflects the transition from a previously static and relatively simple approach to calculating energy savings to a significantly more complex, robust, and granular approach using building-specific usage data. The 2017 DLC report was the first study of such size and scale using building-specific monitoring data to calculate NLC energy savings. To further industry standardization and support future refinement, the entire process of data collection, aggregation and normalization, and analysis is presented below.

Outreach and Data Collection

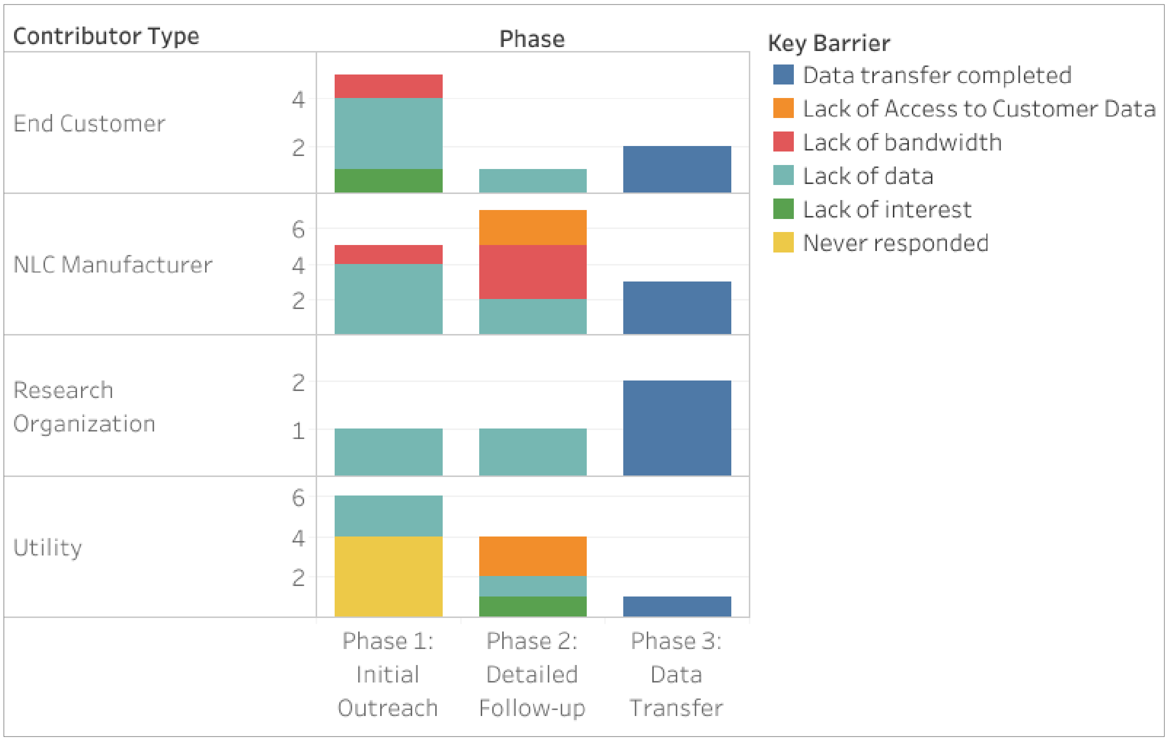
Outreach and data collection closely followed the approach taken in the 2017 NLC Savings Study. The process was conducted in three high-level sequential phases: (1) initial outreach, (2) detailed discussions of data access and format, and (3) data collection.

Figure 3 provides an overview of the 38 organizations which were contacted, the outreach stage during which engagement with each of these organizations ended, and the key barrier to participation. Overall, lack of data was the primary barrier preventing organizations from participating in the data transfer phase. The following are the high-level categories of barriers to participation:

- **Lack of access to customer data**: Refers both to the physical difficulty of downloading data from the installed systems, as well as the difficulty of gaining authorization to do so. In the case of manufacturers, this is due to the manufacturer business model, meaning that in order to access data, one would need to track down the customers that had NLC energy monitoring enabled and work with each individual customer to authorize and transfer data, rather than the manufacturer having the ability to provide data for a group of sites across multiple customers. In the case of energy efficiency program administrators, this barrier most often stemmed from the need for dedicated customer outreach to explain project objectives, gain consent, and coordinate data transfer.
- **Lack of time/prioritization:** Refers to a general lack of time, resources, or bandwidth to prioritize engagement on this project. In some cases, organizations were not able to prioritize this effort because of other specific high-priority initiatives and situations, including impacts of COVID-19 on operations.
- **Lack of data:** This could be due to the fact that installations were too new, were not commissioned to include reporting capabilities, or organizations were otherwise not able to provide data in a format which could be used in this study (i.e., time series data).
- **Lack of interest:** Organizations responded initially, but eventually stopped engaging.

- **Never Responded:** No response to initial or follow-up emails.

Figure 3. Outreach phases, participating organizations, and barriers to providing data.



Phase 1: Initial Outreach

Starting in October 2019, outreach was conducted to nearly forty organizations – energy efficiency program administrators, NLC manufacturers, end customers, and research organizations with existing or previous NLC projects – in order to solicit anonymized project performance data. The initial outreach phase refers to the first several engagement efforts aimed at determining whether the organization had any potential to share data. The organizations which appear in Phase 1 of Figure 3 either never responded or made it clear fairly quickly that they would not be able to participate in the project. Approximately 55% of organizations contacted (21 of 38) progressed to the next phase of outreach.

Phase 2: Detailed Follow-up

This detailed follow-up phase represents the bulk of outreach activities. This phase generally started after an organization was determined to have some potential to share data, and spanned the process of finding and getting in contact with the right person at the organization through the confirmation that they had the right type of data (interval time series data) and that they were willing and able to share it. After confirming the availability of project data, detailed follow-up conversations were scheduled with each organization to discuss the details of data authorization, access, and format.

Questions posed included:

- Where is the data stored, and what is the level of effort required for retrieval?
- What is the spatial and temporal granularity of the data?
- What is the estimated number of datasets that will be contributed?
- In what format can the data be exported from the NLC system and transferred?
- How will the static project attribute data (such as location and building type) be included as part of the transferred datasets?[8]

Based on these conversations, each potential participant was sent a detailed data specification, as developed for the 2017 NLC Savings Study, with slight modifications (see Figure 4).

Figure 4. Sample of data specification fields by category.

Building-Level Characteristics	Zone/Fixture-Level Characteristics	Lighting Energy Use Interval Data
• Building ID • Building type • Location • NLC product installed • LLLC	• Building ID • Zone name • Fixture ID • Interior/exterior • Space type description • Post-retrofit maximum power without controls	• Building zone, or fixture ID (depending on the spatial scale of the data) • Timestamp • Average power in each interval

The surveyed organizations had widely varying data formats and different degrees of difficulty in exporting data at the granularity required for the purposes of this study or that of program evaluators.[9] To reduce reporting burden on participating energy efficiency programs and manufacturers, a sample dataset was obtained to determine if it met the project criteria. The sample dataset was typically made up of one to four buildings worth of data. Once the data format was agreed upon and any outstanding issues were resolved, each contributing organization confirmed the number of buildings to be shared and exported the data from their system.[10]

[8] For example, several manufacturers had challenges in exporting linked databases which housed separate attributes, such as interval data and building characteristics. In some cases, interval data was provided but the building type was unknown, limiting the applicability of that building's interval data in the study.

[9] For further discussion on the lack of mechanisms to export highly detailed energy data, see the "Project Findings and Recommendations" section.

[10] While many organizations initially expressed interest in providing project data, a large number of them were unable to proceed due to data authorization issues or the challenge of exporting relevant data. A more detailed discussion of authorization issues is included in the "Project Findings and Recommendations" section.

Phase 3: Transfer of Anonymized Project Data

Ultimately, eight organizations provided anonymized interval data for the project. Due to the size of the files being shared, this process required close coordination to ensure a viable, secure, and complete file transfer – with several organizations uploading files in phases. Once received, all datasets were evaluated to ensure that critical information required to appropriately categorize the building and calculate energy savings was present. Ultimately, datasets from five providers were of sufficient quality to use in the study.

Data Collection Overview

During the 2020 NLC Savings Study, monitoring data was collected for 103 buildings, from the previously mentioned eight organizations. Of those buildings, 72 were of relevant building type and had sufficient data quality to be included in the present analysis. The 2020 viable dataset also includes eight buildings which had been collected during the 2017 NLC Savings Study but were not used in the report. These were recovered for use in the 2020 NLC Savings Report, enabled by a new methodology developed in 2020 to utilize building-level monitoring data, resulting in a total of 80 new sites included in the 2020 dataset.

This report presents results from the analysis of the combined datasets gathered during the 2017 and 2020 NLC Savings Studies. In total, this dataset incudes 194 sites. Figure 5 provides an overview of those 194 buildings, grouped by building type.

Figure 5. Number of buildings collected by building type and NLC manufacturer.

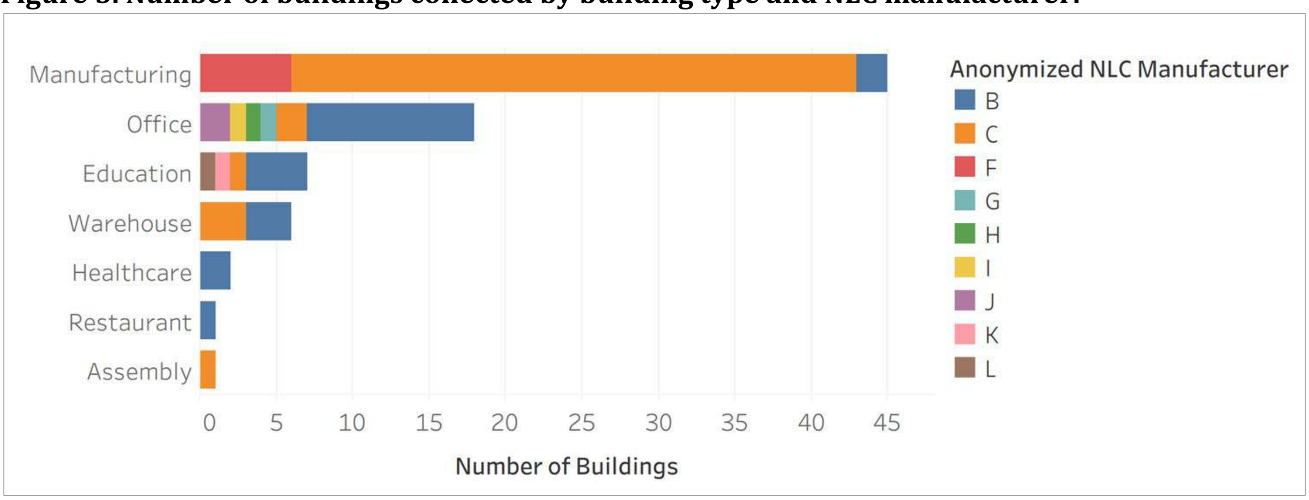
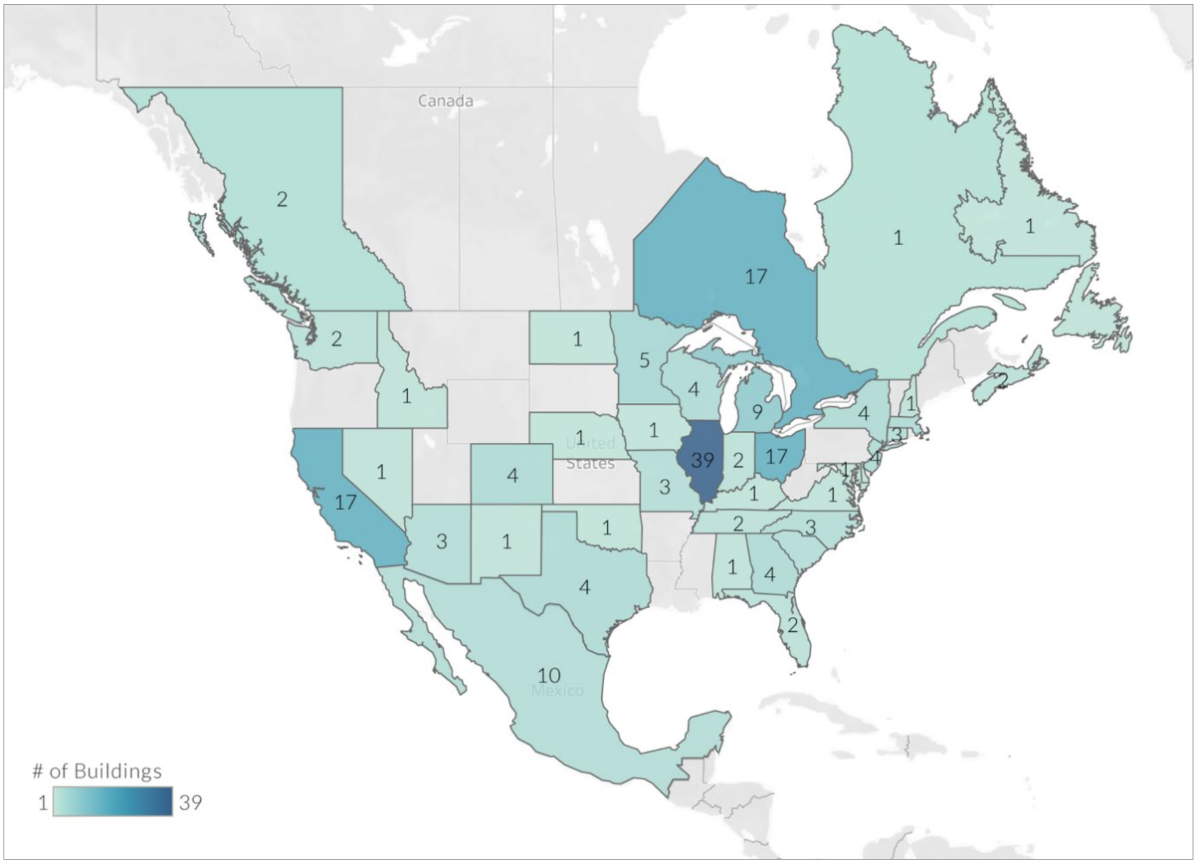


Figure 6. Geographic distribution of buildings by state.

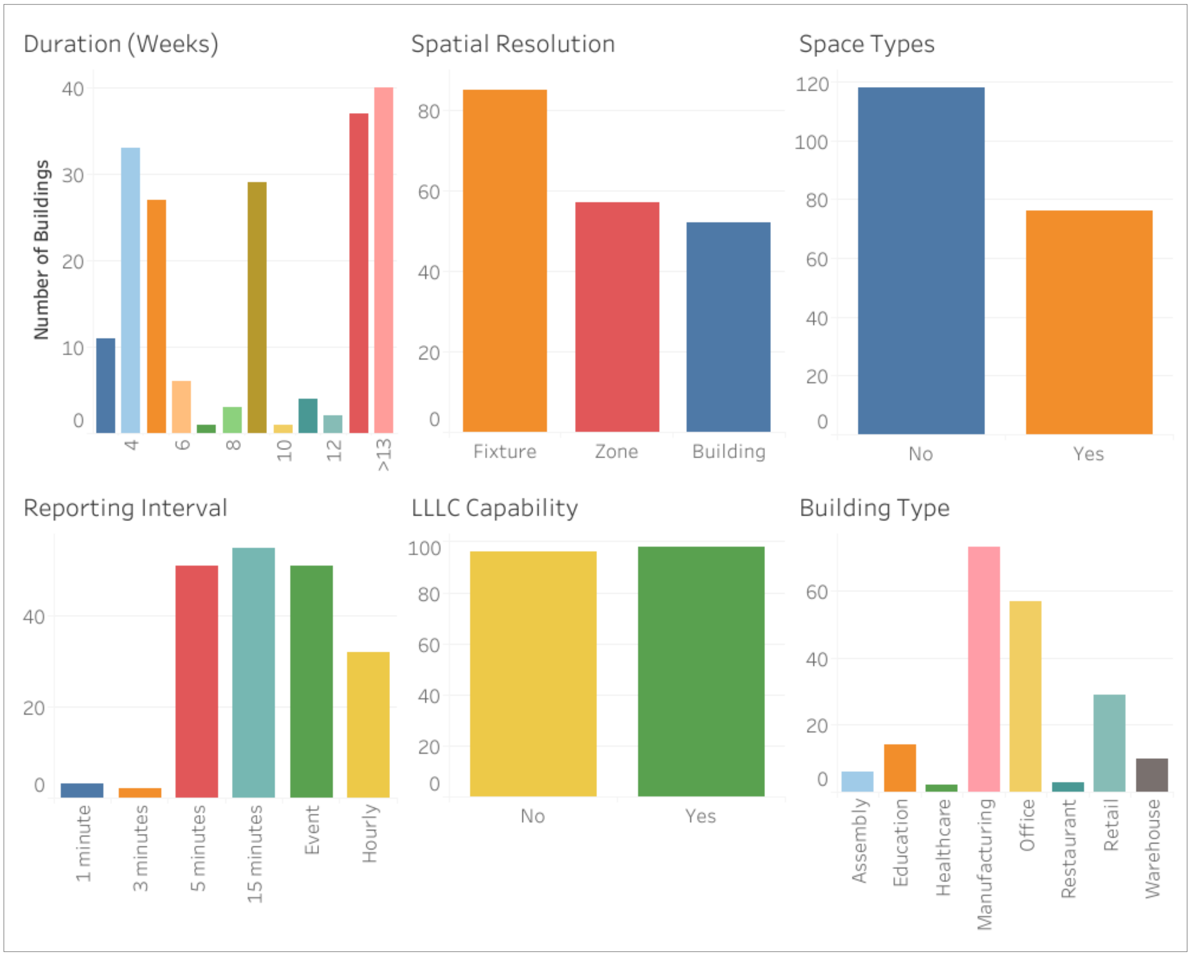


Notes: The buildings analyzed in this study were comprised of buildings from 35 US states, five Canadian provinces, and Mexico. This only includes buildings with high quality data and locational information (n=110). While building locations were generally well distributed across states, there were particular concentrations in the US state of Illinois, California, Ohio, and the Canadian province of Ontario.

Data Normalization and Aggregation

This section of the report outlines the data normalization process, from receiving the data from contributing organizations to normalizing and integrating each dataset into the NLC project database. Due to a lack of existing reporting guidelines, all available data was accepted in disparate formats, which required significant data normalization to integrate it into the database. Figure 7 summarizes the distribution of data formats received across the dimensions described below. The information below describes qualities of the data collected, not about the NLC systems themselves.

Figure 7. Summary characteristics of energy monitoring data collected across all sites.



Duration: The median duration of monitoring data was nine weeks, with a range of twelve days to 122 weeks. On average, this is longer than standard utility and efficiency program M&V monitoring practices, which typically monitor spaces for two to four weeks post-retrofit to estimate energy savings.

Spatial resolution: Data was provided at the whole-building, zone, or fixture levels. In 2017, only a small fraction of the original dataset was whole-building data, which was ultimately discarded from the analysis due to the original design of the baseline estimate methodology. However, during this 2020 round of data collection, 56 of the provided datasets were reported at the building level. This necessitated the development of a building-level analysis baseline estimation methodology, which was adapted from the existing baseline estimation method developed during the 2017 study.

Space types: Mapping zones into meaningful space types was not possible for all the data provided. In some instances, zone descriptions can identify the type of space the lights are in (e.g., "third floor restroom"). However, they more often provide little context (e.g., "zone 18"). The lack of space type information for approximately three fifths of the dataset and the lack of uniformity in the space type descriptions that were available was a barrier to estimating savings by space type within each building.

Reporting interval: Most participants provided data in regular intervals, which were reported hourly or with more granular frequency. About a quarter of the sites include state change information based on irregular, event-based intervals, in which a row of data is recorded for every change in dimming signal or binary on/off status.

LLLC: Luminaire level lighting control was available in a subset of NLCs. LLLC includes sensors and control logics at each individual luminaire, whereas sensors in NLCs without LLLC control groups of fixtures (zones). This dataset includes a nearly even representation of 98 NLCs with LLLC and 96 NLCs without LLLC.

Building type: Data was collected for a variety of building types, with highest representation from manufacturing and office sites, and lowest representation from healthcare and restaurant sites.

Standardization of Data Formats

Data was submitted by six contributors in nine unique data formats, with 18 sub formats within the nine high-level unique formats. Data was normalized into a standard format using the following steps:

- **Anonymize personally identifiable information (PII):** As part of the data intake process, each dataset was reviewed for any references to personally identifiable information, such as site addresses and names of customers and contractors. PII may have appeared either as explicit fields or embedded in zone names or comments. All forms of PII were scrubbed and eliminated from the datasets.
- **Construct time series of energy use over time (as necessary):** Not all the datasets were provided as a time series of wattage or energy ready for analysis. For example, one contributor provided raw data in a time series of cumulative energy, in watt-hour, over the reported period. A time series of average power for each reporting interval was back-calculated before it could be fed into the savings calculations.
- **Determine rated power of each fixture without controls (as necessary):** Correctly identifying maximum power draw without controls is important for accurately attributing high-end trim energy savings to the NLC system. However, not all manufacturers were able to report rated power as a static variable. To identify the rated power of each post-retrofit fixture, post-NLC power used was divided by the dimming level in each interval, generating many estimates of the post-retrofit rated power for each fixture. For each fixture, these estimates were averaged to calculate an assumed rated power without controls.
- **Standardize building and space types:** To create consistency in the reporting conventions, the reported building types and space types were mapped to those in the commonly used Database for Energy Efficient Resources (DEER). Consistent reporting

will play an important role in future data collection, and it is recommended that building types are standardized to facilitate future data collection and analysis.

Data Aggregation into the NLC Database

For each dataset, scripts were used to map normalized project data into fields in the NLC database. This included two overarching data types, each collected at the fixture-, zone- and/or building-level:

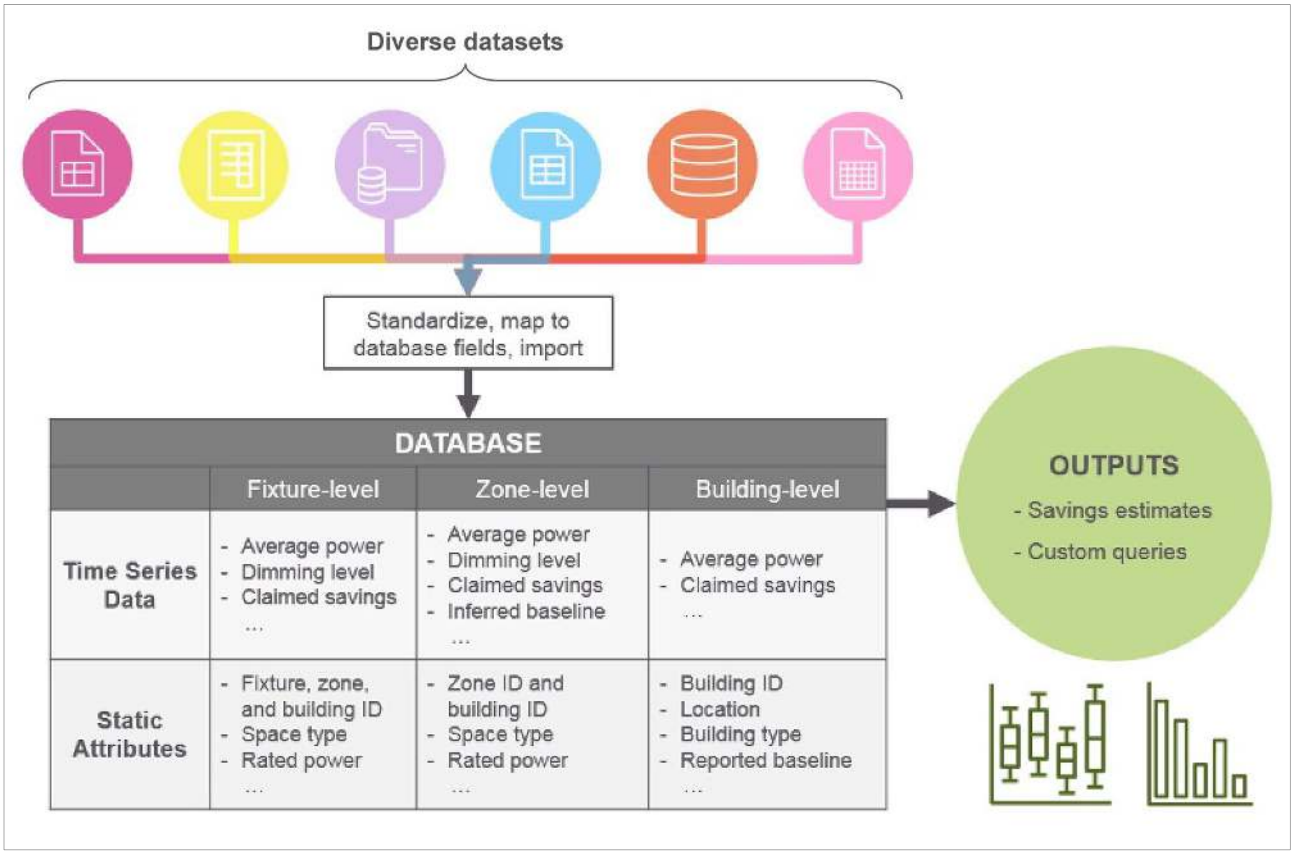
- **Static attributes – fixed attributes of the building, zone, or fixture.** For example, rated power and space type are fixed attributes of a zone or fixture. Geographic location, building type, gross floor area, and NLC system installed (including whether the system has LLLC) are examples of fixed attributes of a building. The reported baseline operating hours were almost always reported at the building level. While in a few cases, some of the static attributes were provided alongside the time series data, in most cases, they were provided in separate files, typically in the form of an Excel spreadsheet.
- **Time series data – interval data with lighting energy use and other time-varying attributes.** This is the time series energy data normalized into the standardized format as described in the previous section. The spatial and temporal granularity was determined by the raw data. For example, the time series data would be five-minute interval data for each fixture for a fixture-level dataset with a five-minute reporting interval.

The database has a hierarchical structure of fixture, zone, and building IDs that enables linkage between static attributes and time series data and across spatial scales. Because data is mapped to space types and building types, it can be rolled up, or aggregated, from:

- Individual fixtures to individual zones
- Individual zones to all zones of the same space type in a building
- Space types in a building to the individual building
- Individual buildings to all buildings of the same building type

The primary function of the database with respect to this report is to generate savings estimates by building type and type of NLC system, but its structure allows for a wide array of custom queries. For example, the database could be queried for savings within a specific geographic region, within certain hours of the day, or relative to other baselines. Figure 8 represents the process of assimilating diverse datasets into the database, provides examples of database fields grouped by spatial scale and whether they change over time, and highlights the primary outputs of the database.

Figure 8. Diagram of data assimilation in the database, example database fields, and resulting outputs.



Calculating Baselines and Energy Savings

Control Factor Definition and Calculation

All results were calculated and presented in terms of a control factor (CF), defined as the fractional energy savings directly attributable to NLC systems. This does not include any increases in luminous efficacy of the light sources due to retrofits. Equation 1 describes the general formula for a control factor: the control factor of an NLC system relative to a given baseline is equal to the change in energy use from baseline to the NLC system normalized to the baseline energy use.

Equation 1:

$$CF_{NLC,Baseline} = \frac{Energy_{Baseline} - Energy_{Post\_NLC}}{Energy_{Baseline}}$$

Where: $CF_{NLC,Baseline}$ is the control factor of the NLC system, relative to some baseline;

$Energy_{Post\_NLC}$ is the post-NLC lighting energy use during the collection period; and

$Energy_{Baseline}$ is the estimated baseline lighting energy use during the collection period.

Baseline Estimation Methodology

The baseline was estimated using the post-NLC inference method, a baselining approach in which data from the NLC system is used to infer the baseline energy use. This approach was selected because it is:

- Unobtrusive
- Yields spatially and temporally granular baseline assumptions
- Project-specific
- Can be systematically scaled across many buildings once the data is in a common format.

Specifically, the "inferred baseline methodology" developed in the 2017 NLC Savings Study was used to estimate the baseline.

Inferred Baseline Methodology

Zone-level data

The inferred baseline methodology was developed for zone-level energy data in the 2017 NLC Savings Study. It was assumed that in the baseline condition, each zone had the same occupied hours as were inferred from the post-NLC data but operated at its rated power. Figure 9 provides a sample savings calculation relative to the inferred baseline for a single zone in a manufacturing facility for a week-long period. If the post-NLC average hourly power (gray) exceeds the "occupied threshold," the zone is assumed to be occupied. To define the occupied threshold, the post-NLC interval data is first normalized by removing any base load.[11] "Occupied hours" were defined as the hourly average power being greater than ten percent[12] of the zone's maximum power draw.[13] During occupied hours, baseline power draw was assumed to be equal to the rated power (which was either provided by the contributor or derived, as discussed above in the "Standardization of Data Formats" section).

As shown in Figure 9, the rated power may be substantially higher than the maximum measured power if the zone employs high-end trim. During unoccupied hours, it is assumed that baseline power draw was the same as the post-NLC power draw. In other words, it is assumed that any ancillary lighting services (such as security and emergency lighting) that use

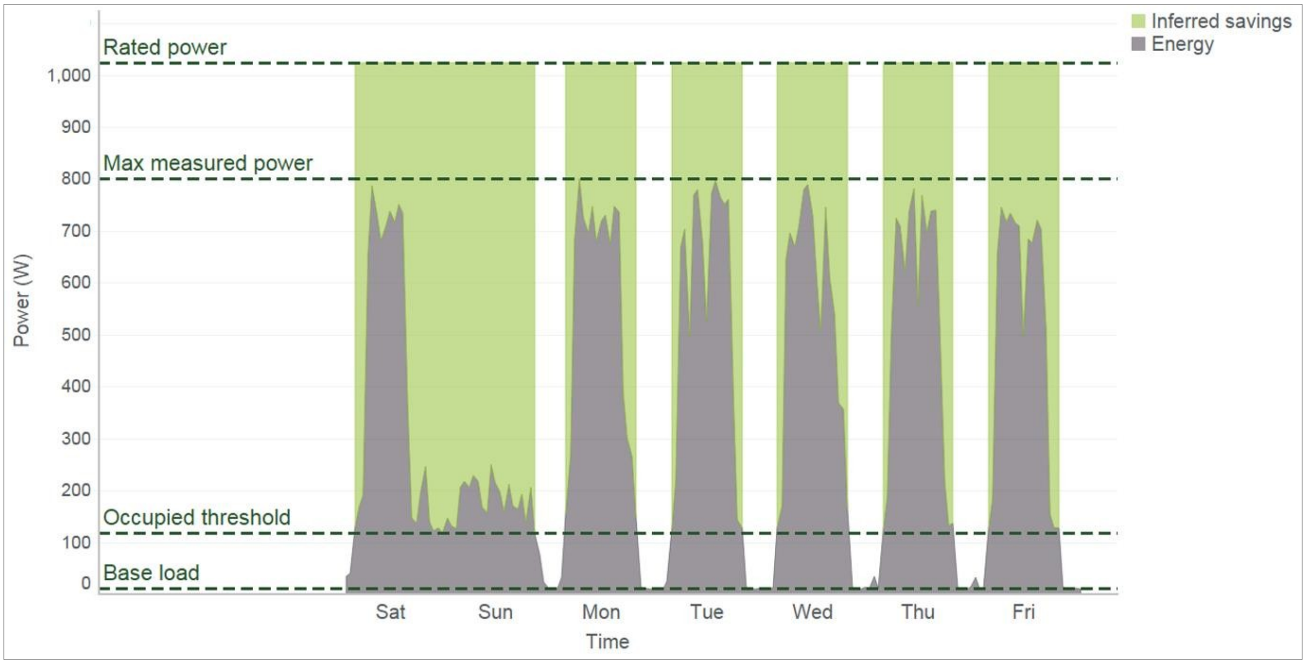
[11] Base load was defined as the 10th percentile of post-NLC average power draw in a zone, when analyzed on an hourly basis. This definition captures the lights that are almost always on in a zone and therefore do not give information about occupancy. Although most zones had minimal or no base load, it was important to remove base load for some zones otherwise the algorithm would assume constant occupancy.

12 For an analysis of how the savings depend on the choice of this parameter, see Appendix C in the 2017 NLC Savings Study (DesignLights Consortium, 2017).

[13] Maximum power draw for each zone was defined as the 98th percentile of power draw attained by that zone during the entire collection period. This is functionally a measure of the highest power draw, excluding outliers due to measurement error.

energy during unoccupied hours were also present in the baseline and thus no savings are achieved during unoccupied times. The inferred savings (green) are simply the difference between inferred baseline energy use and post-NLC energy use during occupied hours.

Figure 9. Sample savings calculation relative to an inferred baseline.



More granular fixture-level data was first rolled up to the zone-level data using the associated zone ID before this baselining methodology was applied. After calculating the inferred baseline and savings for each zone in a building, savings were aggregated across all zones to calculate building-level savings. Figure 10 shows an example of the inferred baseline algorithm being applied to each zone within an office individually, and then aggregated to the building-level.

Figure 10. Example of zone-level inferred baseline rolled up to building level.

Notes: Baseline energy use is inferred at a zone level but can be rolled up to calculate building-level savings. This figure presents seven zones within a building as well as the aggregated profile across the entire building.

Building-level data

A significant number of the datasets that were contributed to this new round of data collection were building-level data, which raised the question whether the same baselining methodology could be applied to calculate control factors with reasonable accuracy. The zone-level data from the 2017 NLC Savings Study was used to verify the predictive power of the inferred baseline methodology on building-level data. The energy data from each zone within the same building was first rolled up to become a time series of building-level data, and the same methodology was applied to estimate the baseline. This first rollup from zone- to building-level data effectively eliminated any zone-level details visible to the inferred baseline methodology. In other words, the control factors were calculated by applying the inferred baseline methodology to the rolled-up energy data as if it were building-level data. The resulting control factors were compared to those generated using the original zone-level data to study the difference.

This exercise showed that the differences between applying the inferred baseline methodology to the zone-level data and to the building-level data were reasonably bounded. With the anticipation that the "occupied threshold" would likely need to be higher when evaluated at the building level, it was determined that the methodology with the "occupied threshold" set to fifteen percent had the optimal baseline predictive power. Incorporating the adjustment, the differences in control factors were within ten percent for seventy-five percent of the datasets[14].

With this positive result, the building-level datasets were included in this study and their corresponding baselines were estimated using this slightly modified methodology. While the modified methodology showed reasonable baseline predictive power on the verification dataset, it should be noted that it still carries uncertainties in predicting the baseline compared to using zone-level data. The lack of zone-level details in the building-level data is still relevant and cannot be completely made up for by the modified methodology in every case. The hope is that, in aggregate, the modified methodology results in reasonable savings estimates when applied to a large number of building-level NLC energy data.

Caveats

There are two key caveats to the inferred baseline approach (affecting the original zone-level, as well as the building-level): (1) it removes all energy savings occurring during non-occupied hours, which may be substantial;[15] and (2) it does not account for existing controls that may have reduced building energy use during occupied times, such as building occupants manually switching lights off. These caveats create opposite sources of bias. Whether they tend to create a net under- or overestimate of savings depends on the details of the baseline controls system, which were rarely included in the data. To the extent that the true baseline had unnecessarily long scheduled hours of operation, this inference method will underestimate savings. To the extent that the true baseline had existing occupancy and daylight sensors or active use of personal controls such as wall switches, this inference method may overestimate savings.

Control Factors Representation

In addition to the overall savings, this study further investigated savings potential from various control strategies. While the type and granularity of collected data did not facilitate complete segregation of each single control strategy, it was possible to separately study the savings resulting from high-end trim and all other control strategies combined.

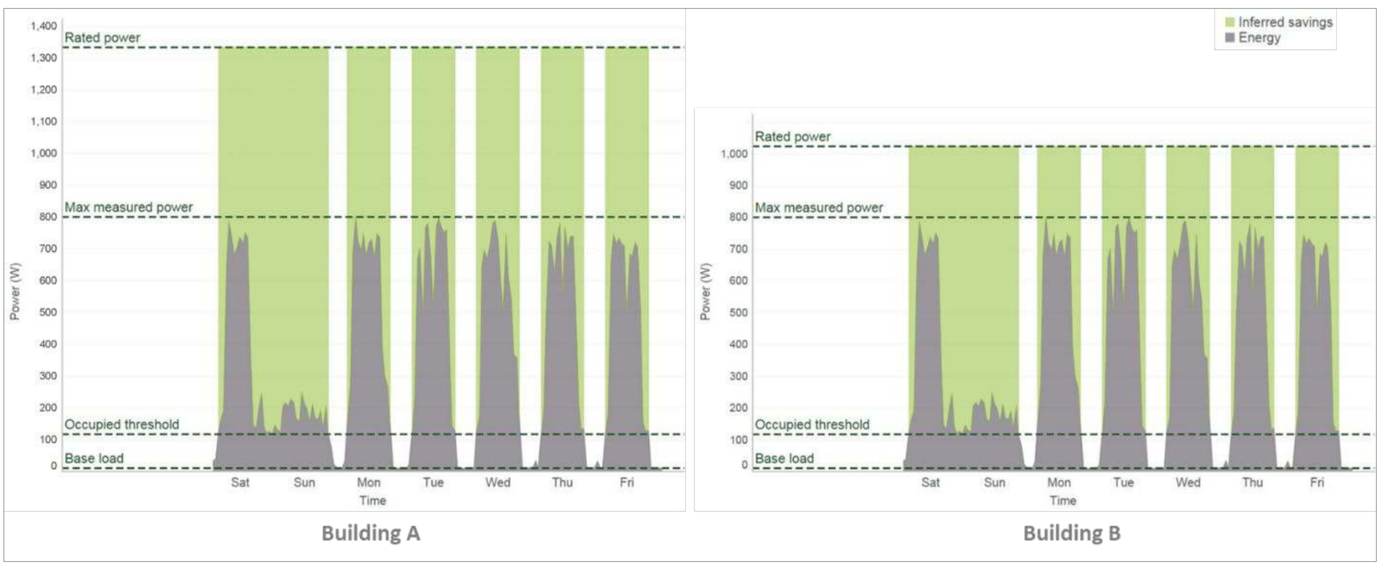
The effect of high-end trim, as illustrated in Figure 9 by the region between the "rated power" and "max measured power", is independent from other control strategies, and the savings for

[14] Seventy-nine datasets from the 2017 NLC Savings Study were included in this verification.

[15] Based on conversations with controls manufacturers across lighting, HVAC, and plug load end uses, anecdotal evidence suggests that a substantial portion of energy savings occur due to unintended equipment operation, such as schedules being overridden or cancelled and not set up again and occupants leaving lights on all night

high-end trim are calculated against the inferred baseline, which is based on the rated power of the system. The effect from other control strategies combined, on the other hand, is dependent on high-end trim when the savings are calculated against an inferred baseline based on rated power. This is because part of the inferred baseline, the region between “rated power” and “max measured power” in Figure 9, represents exclusively the effect of high-end trim. For example, take two buildings with the exact same load profile as depicted in Figure 11. Building A has a lighting system with a higher rated power but is tuned down, via high-end trim, to the same level as Building B. In other words, Building A has a higher inferred baseline. Even if all other control strategies combined saved the exact same amount of energy, i.e. have equivalent savings potential in both buildings, the calculated savings percentage of other control strategies for Building A will appear much lower than that for Building B because the savings are calculated against a much higher inferred baseline based on the rated power of the systems.

Figure 11. Example of two buildings with the exact same lighting load profile after all the controls are implemented.



In this report, to provide a more pertinent picture of the savings potential unbiased of the effect of high-end trim, the control factors for control strategies other than high-end trim, unless otherwise noted, are in comparison to an inferred baseline with savings from high-end trim removed. Specifically, the savings were calculated against the inferred baseline with the region between “rated power” and “max measured power” removed. Because of this alternative representation, the control factors for high-end trim and other control strategies will not add up to the overall control factor. The control factors for other control strategies calculated against the original inferred baseline are included in Appendix A: Representation of Savings for Other Control Strategies. This representation approach is sound because it is a reversable arithmetical process from the control factors calculated against the original inferred baseline, and the derivation is also provided in Appendix A: Representation of Savings for Other Control Strategies.

Quality Control Procedures

To ensure that the underlying data supporting the control factor calculations was robust and the inferred baseline was reasonable, the following analytical filters were applied.

To be included in the final analysis, all buildings had to:

- Have a defined building type
- Have the majority of the NLC controlled area or zones be interior spaces within a building (as opposed to, for example, façade, garage, parking lot, etc.).
- Include a minimum of 10 days of monitoring data
- Have lighting energy reflect usage of the zone or building (instead of a flatlined energy usage throughout the reporting period)
- Contain no data gaps or anomalies upon visual inspection.[16]

All zones and buildings that did not meet the quality control criteria were removed from the dataset. While 323 buildings were initially collected[17], 120 were ultimately removed from the analysis primarily because they did not pass one or more of these criteria, and in a few cases because the amount of time needed to process and normalize several datasets would not have fit within the study scope or timeline.

16 Over 2,500 zones were reviewed to identify data gaps, measurement errors, or other anomalies. The time series of both the post-NLC energy use and the inferred baseline were analyzed for errors or anomalies, visually checking to see whether the inference method was defining occupied hours in an intuitive manner.

17 This number includes both the datasets collected during the 2017 NLC Savings Study and the new datasets obtained through this new round of data collection.

Results and Discussion

The following sections provide an overview of findings, a discussion of how these results can be applied to energy efficiency incentive program design, and comparisons to previous research.

Application of Results

This study provides context on the current state of NLC energy monitoring, including data availability, data quality, and analysis across a portfolio of NLC projects. It also identifies important next steps in standardization, aggregation, and data handling to enhance results in support of greater utility, efficiency program, and market participation. There are two key applications of the results to both efficiency program design and evaluation and the broader industry:

1. **Establishing average energy savings from NLC systems**. Because the buildings included in this study were not identified through a random sample, it is not possible to make statistical inferences about a broader building stock or the drivers of NLC savings in buildings. However, this study represents a largest-to-date sample size of 194 buildings across twelve manufacturers and eight building types. Energy savings vary widely by individual site, and thus energy efficiency program managers should treat the average values found below as a best estimate of what a portfolio of projects might achieve, rather than an individual building.
2. **Establishing consistent data reporting guidelines.** It is recommended that all NLC energy efficiency programs include project reporting of energy monitoring as part of their programs, either as an explicit program requirement or as an optional program element with incentives for sharing data. This will increase the overall sample size of projects with monitoring data, enabling deeper understanding of the building variables correlated with high energy savings. A more detailed discussion is provided in the Project Findings and Recommendations section.

Estimated Control Factors Overview

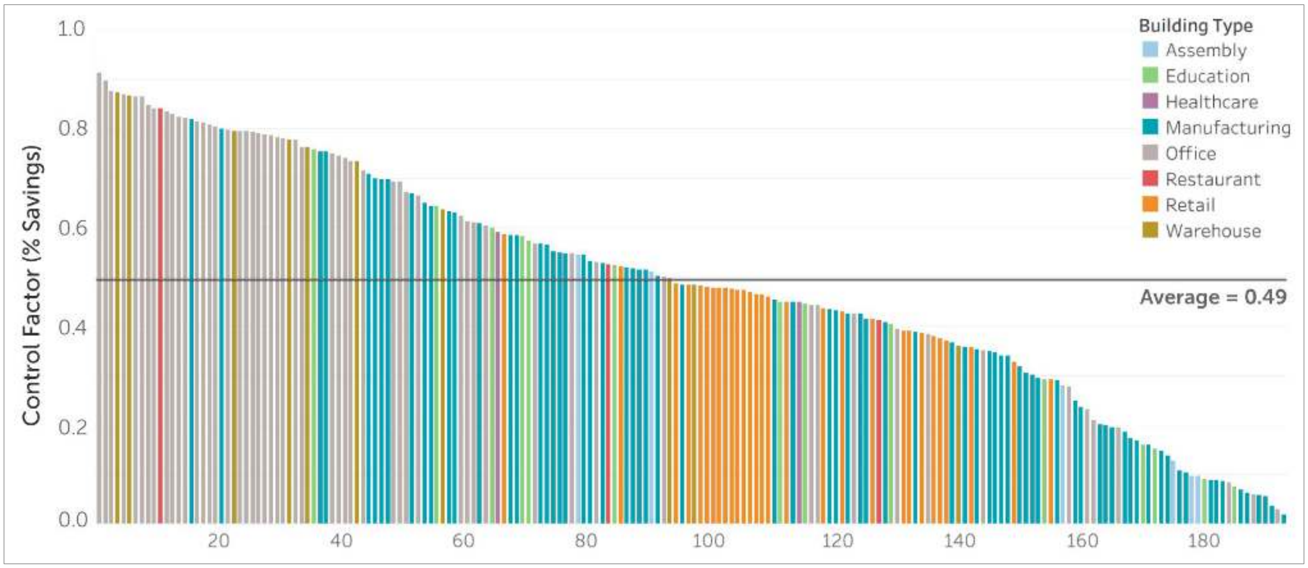
Overall, the results indicated an average control factor of 0.49 across 194 buildings, with a tremendous variation across individual buildings ranging from 0.02 to 0.91 as shown in Figure 12[18].

This wide variation indicates that NLCs can achieve extremely high energy savings but are not guaranteed to do so. As discussed in the section "Major Drivers of NLC Energy Savings," the

[18] A control factor is a number between 0 and 1, representing the fraction of the energy saved through controls. 0 represents no savings, and 1 means all energy is saved. Control factor is equivalent to percent savings (% savings) when presented in percentage. For example, a control factor of 0.49 is equivalent to 49 percent savings (49% savings).

existing literature suggests that savings are highly dependent on-site characteristics, occupancy patterns, which control strategies are enabled, and how control settings are configured.

Figure 12: Distribution of NLC savings across all buildings analyzed (n=194).



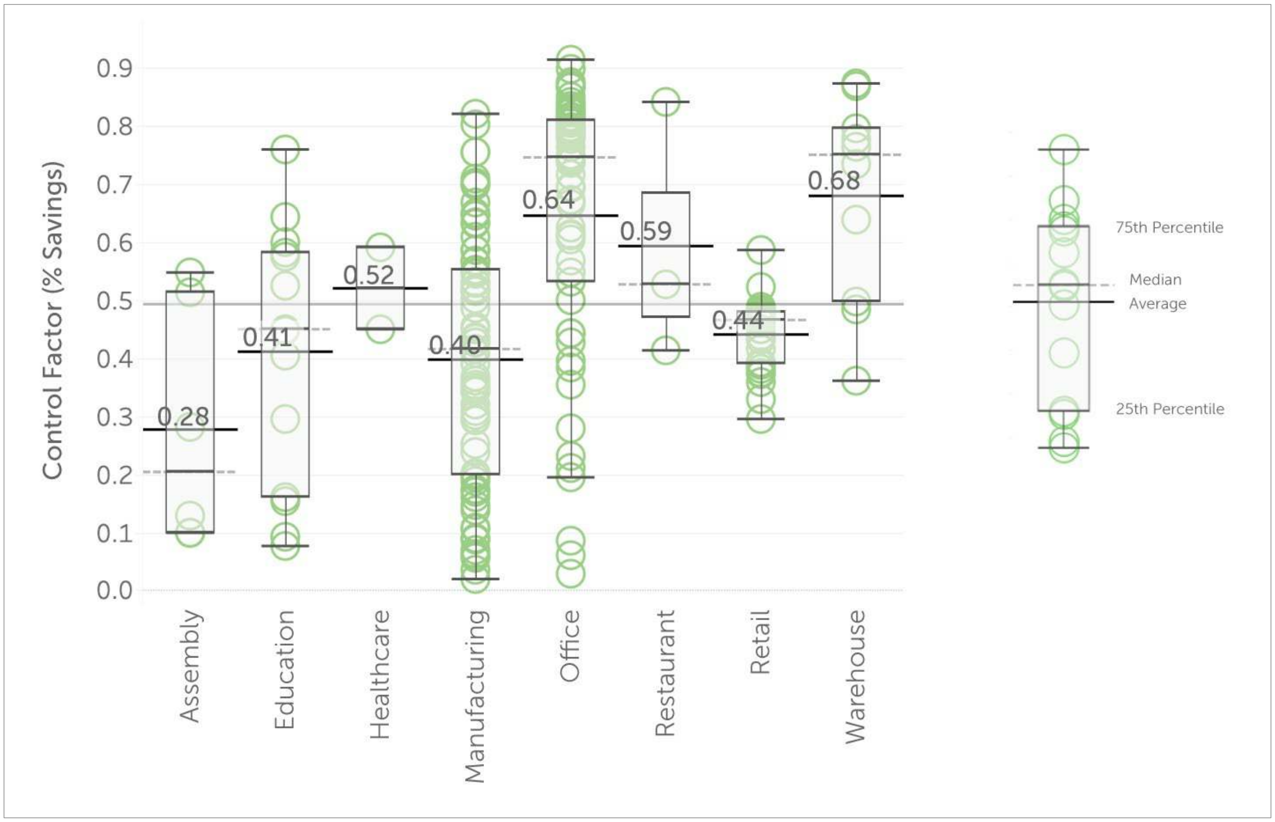
Notes: Figure 12 indicates some patterns of building types within the largest, smallest, and mid-range savings. The largest savings were generally found in warehouses, office buildings, and manufacturing/industrial facilities ("manufacturing"); however, some of the lowest savings were also found in the office and manufacturing building types. Savings in big box retail buildings ("retail") were consistently clustered in the mid-range of the distribution. The consistency of savings in retail applications can most likely be explained by homogeneity of the retail buildings in the dataset: all 29 retail buildings represent a single NLC manufacturer's product and one customer.

Among all the control strategies available in all NLCs, high-end trim contributed the most to the savings. The average savings resulting from high-end trim was estimated at 27 percent across all the buildings analyzed, while other control strategies contributed to a combined savings of 22 percent (Table 5.).

Estimated Control Factors by Building Type

Average savings by building type ranged from 0.28 in the assembly to 0.68 in the warehouse building type. Consistent with previous studies (Williams et al. 2011, Asif ul Haq et al. 2014, and NextEnergy 2020), there was significant variability in energy savings within each building type. Figure 13 shows the distribution of control factors by building type in a box and whisker plot, while Table 5 includes additional information about the sample size, number of manufacturers represented, values for the interquartile range (i.e., the 25th and 75th percentiles), and the savings contributions by high-end trim and other control strategies.

Figure 13. Box and whisker plot of control factors by building type relative to the inferred baseline.



Notes: Each circle represents a building, while the box shows the interquartile range (25th-75th percentile). Whiskers extend to the minimum and maximum values. The solid horizontal line is the average (mean), while the dashed line is the median.

Table 5. Summary of estimated control factors by building type.

Building Type	Total Buildings	Unique Manufacturers	Control Factor* (% Savings)			
			Average	25th–75th Percentile**	High-End Trim Contributions	Other Control Strategies
Assembly	6	2	0.28	0.11 - 0.45	0.07	0.23
Education	14	5	0.41	0.19 - 0.58	0.19	0.32
Healthcare	2	1	0.52	0.48 - 0.56	0.33	0.24
Manufacturing	73	4	0.40	0.20 - 0.55	0.16	0.29
Office	57	8	0.64	0.53 - 0.81	0.46	0.36
Restaurant	3	2	0.59	0.47 - 0.68	0.27	0.30
Retail	29	1	0.44	0.39 - 0.48	0.22	0.27
Warehouse	10	2	0.68	0.53 - 0.79	0.38	0.48
Overall	194	12	0.49	0.35 - 0.69	0.27	0.32

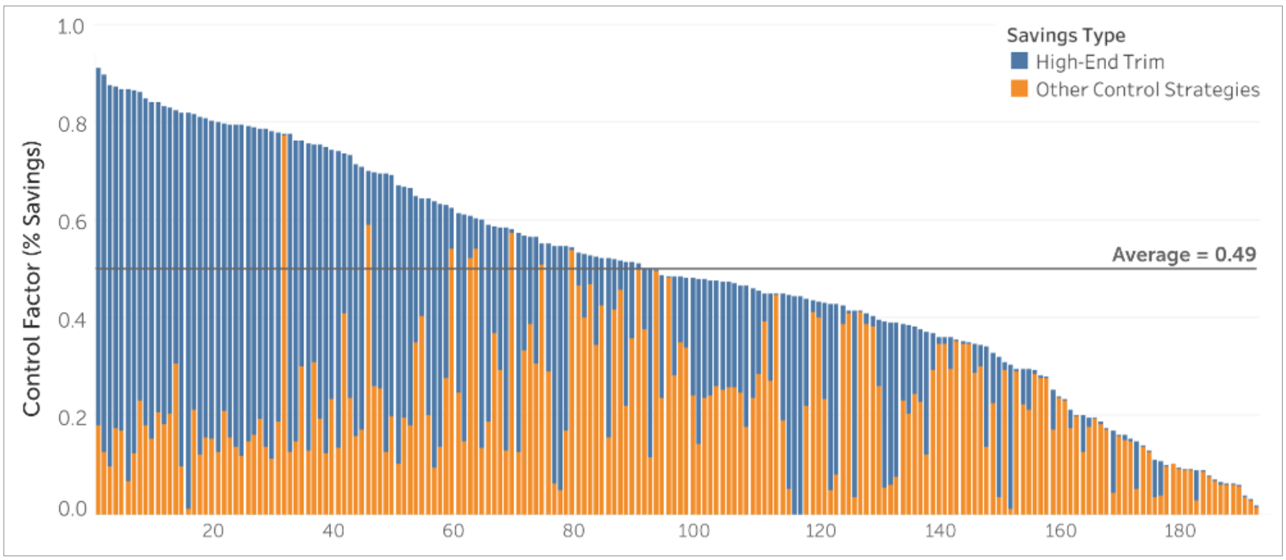
* A control factor is a number between 0 and 1, representing the fraction of the energy saved through controls. 0 represents no savings, and 1 means all energy is saved. Control factor is equivalent to percent savings (% savings) when presented in percentage. For example, a control factor of 0.49 is equivalent to 49 percent savings (49% savings).

** The range for the middle 50% is displayed instead of the full range between the minimum and the maximum to provide a more representative range of savings one can generalize and expect.

The average savings from high-end trim varied significantly across different building types, which seems to suggest, in aggregate, a different savings opportunity for different building types. The average savings from other control strategies, on the other hand, appears relatively consistent across all building types.

Except for one restaurant, the highest savings were found in offices, warehouses, and manufacturing facilities. The breakout of high-end trim savings and other control savings in Figure 14 confirms that these high savings were primarily the result of very aggressive high-end trim[19]. The only high-performing building that was solely due to other control strategies (the tallest orange bar) was an NLC with luminaire-level lighting control in a warehouse, and the savings were likely due to some unique occupancy patterns that resulted in the opportunity for very effective occupancy sensing control.

Figure 14. Control factors per building broken out by contributions from high-end trim and other control strategies.



The highest average savings were found in warehouses (n=10). The largest spread of control factors was within offices, which had an average control factor of 0.64 but a spread of 0.03 to 0.91.[20] Manufacturing had a similarly large spread, with an average of 0.40 but a spread of 0.02 to 0.82. This wide distribution is likely due to the variance in how controls are implemented at each site.

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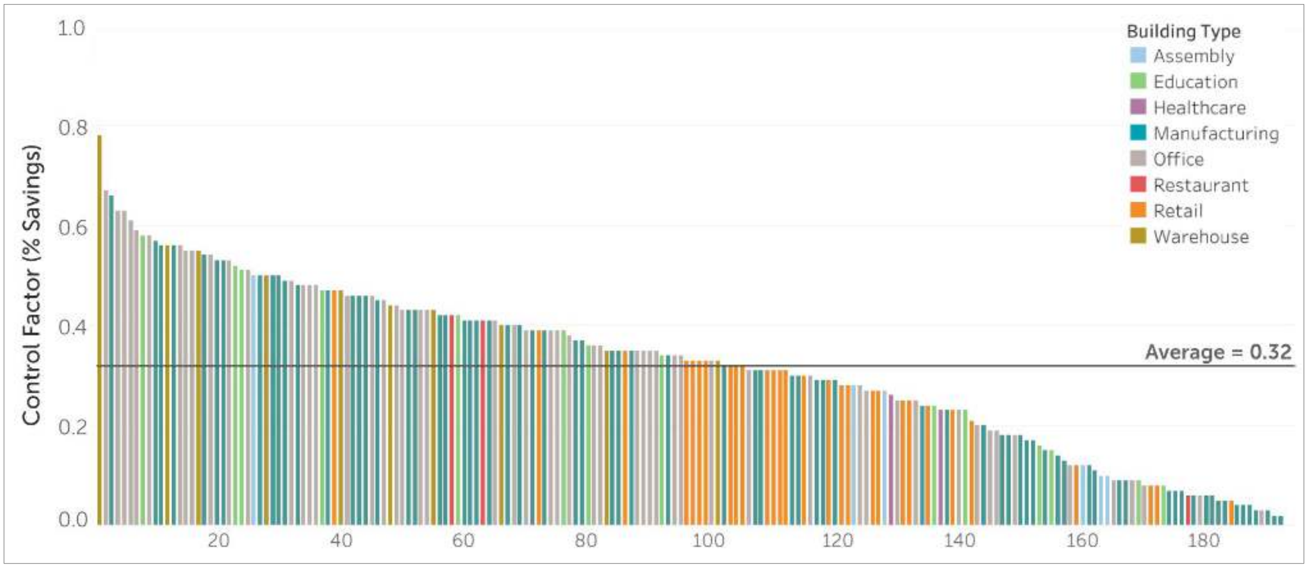
[19] It should be stated that high-end trim settings were not typically provided as part of the NLC energy data time series data. Rather, most high-end trim savings were calculated against the aggregated maximum luminaire wattages provided by the data contributors. In other words, there is a chance that high-end trim savings were underestimated or overestimated in this analysis if the provided maximum luminaire wattage information did not pertinently reflect the actual installation.

[20] This is the spread between minimum and maximum control factors, not the 25th and 75th percentile. The minimum and maximum control factors are not tabulated here but can be observed in Figure 12 and Figure 13.

Zooming in on savings from control strategies other than high-end trim, as illustrated in Figure 15, there seems to be a fairly equal savings opportunity across all building types. In other words, there is not a particular building type with savings clustered at the high or low end of the savings spectrum. Buildings with high savings are likely results of a combination of NLCs implemented with multiple strategies, aggressive settings (e.g., short occupancy shut-off time delays), beneficial site characteristics (e.g., good natural lighting), occupancy patterns, and/or user behavior. In a number of facilities with low savings, it appears—based on visual analysis of the time series data—that the NLC system is acting primarily as a scheduling control without other control strategies enabled, minimizing energy savings.

Figure 15. Percent savings from control strategies other than high-end trim across all buildings.



Estimated Control Factors by the Luminaire-Level Lighting Control Capability

Luminaire-level lighting control (LLLC) is available in a subset of NLCs, where sensors—typically occupancy sensors and photosensors—and control logics are embedded in each luminaire. This study's dataset contains a good mix of NLCs with and without LLLC, from multiple manufacturers, and therefore, it is possible to separately analyze the potential savings that could result from LLLC.

Overall, 98 out of the 194 datasets were from NLCs with LLLC, while the other 96 datasets were from NLCs without LLLC. Offices, warehouses, and manufacturing facilities were the building types where LLLC was the most prominent. Figure 16 shows that savings from NLCs with LLLC, in general, trend higher than from NLCs without LLLC. The average control factor of NLCs with LLLC is 0.63, compared to the control factor of 0.49 achieved by all NLCs in the datasets, as shown in Table 6. The much higher average control factor is a result of both higher savings from high-end trim and other control strategies. It should be noted that this higher savings potential is an average across all buildings for the purpose of a high-level overview, and it does not necessarily imply NLCs with LLLC are universally superior or suitable for all building types and applications. The savings broken down by building type, discussed later in this section, provide better insights on savings potentials.

Figure 16. Control factors of NLCs with and without LLLC across all buildings analyzed.

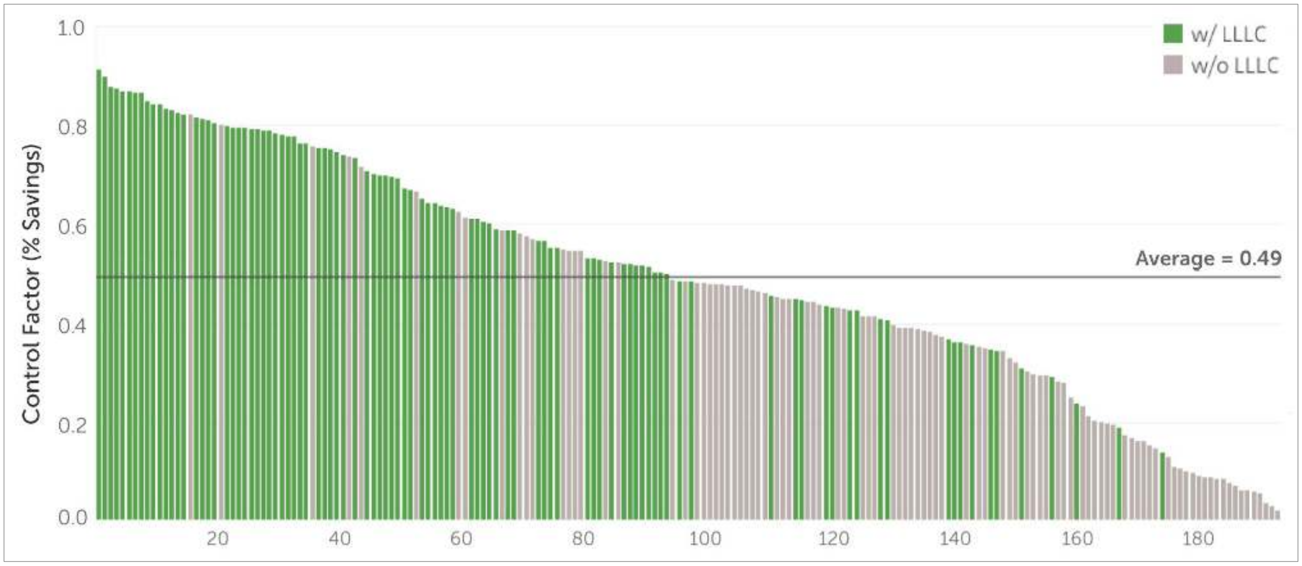


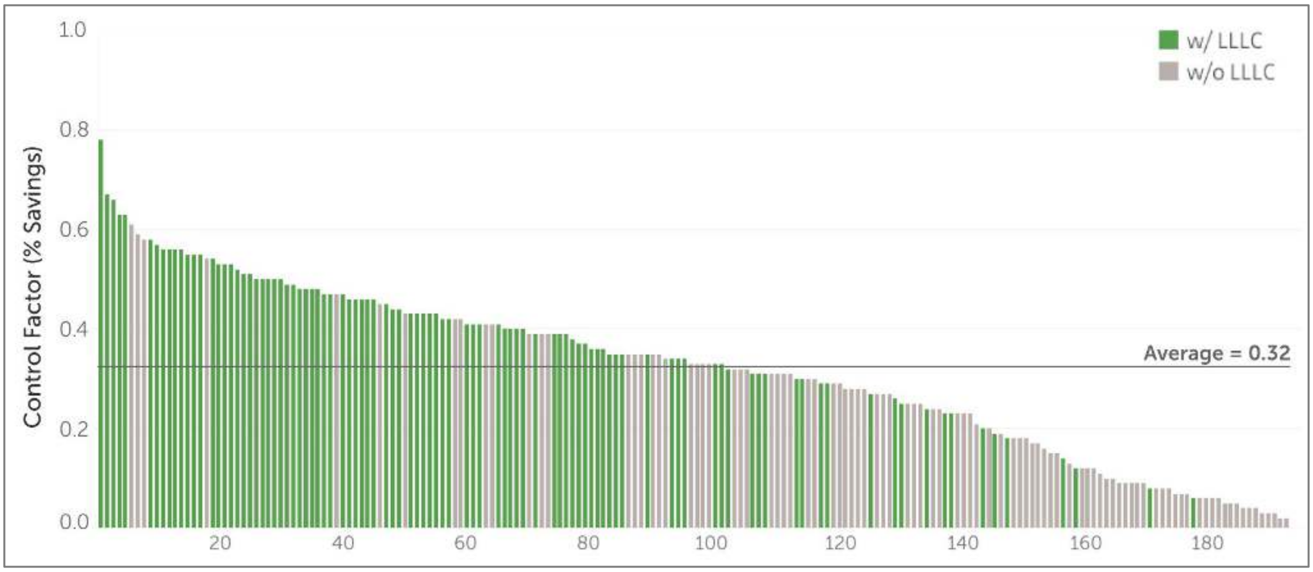
Table 6. Summary of estimated control factors by LLLC and control strategies.

LLLC Presence	Total Buildings	Control Factor (% Savings)			
		Average	25th–75th Percentile	High-End Trim Contributions	Other Control Strategies
NLCs w/ LLLC	98	0.63	0.50 - 0.79	0.37	0.41
NLCs w/o LLLC	96	0.35	0.17 - 0.48	0.17	0.22
All NLCs	194	0.49	0.35 - 0.69	0.27	0.32

Note: The numbers in this table are meant to provide a high-level overview of average savings trends. Additional study is needed to control for potentially confounding variables. At this time, the data does not imply that LLLC is universally superior or applicable to all building types.

The distinctively higher savings from control strategies other than high-end trim is particularly interesting. Figure 17 is a reproduction of Figure 15, showing percent savings from control strategies other than high-end trim for each building, but color-coded by whether or not the NLC has LLLC. The buildings using NLCs with LLLC clearly dominated the high-savings spectrum, and in the highest-savings quartile, 70% of the NLCs had LLLC. This was likely the direct result of more autonomous and localized occupancy sensing control and daylight harvesting at the luminaire level. It is worth noting, however, that there were still NLCs without LLLC achieving comparable savings in this study, as can be observed in Figure 16 and Figure 17. This suggests that proper programming and commissioning to leverage all control capabilities to the fullest extent is key to achieving high savings.

Figure 17. Percent savings from control strategies other than high-end trim across all buildings.



While LLLC showed promising savings potential in the analysis, some intrinsic uncertainties that could be sources of bias should be noted. Part of the datasets from NLCs with LLLC were provided at the building level. Even though the building-level baselining methodology showed good predicting power on the training datasets compared to the zone-level data, the lack of spatial granularity in the data was still relevant and could still introduce biases. The number of datasets for each building type could be another source of bias. The dataset in this study was dominated by office and manufacturing building types, and when put side-by-side with other building types, their savings could skew the overall numbers.

Table 7 shows the average control factors broken down by selected building types. This table represents a subset of the energy data of sufficient diversity within each building type, including a relatively large number of datasets (i.e. buildings), multiple manufacturers, and NLCs both with and without LLLC. Average savings by building type ranged from 0.51 in the manufacturing building type to 0.77 in the office building type for NLCs with LLLC, which represents seventeen percent to twenty-two percent higher savings compared to the average savings of all NLCs in the same building types. This suggests that these three building types and the activities performed within them likely make NLCs with LLLC particularly effective in achieving high savings. It should be noted that this observation cannot be extrapolated to other building types without the support of more robust and diverse datasets, and does not imply that NLCs with LLLC are a universally superior control solution.

Table 7. Summary of estimated control factors by building type and LLLC.

Building Type	Total Buildings	Unique Manufacturers	Average Control Factor (% Savings)		
			NLCs w/ LLLC	NLC w/o LLLC	All NLCs
Education	14	5	0.52	0.35	0.41
Manufacturing	73	4	0.51	0.26	0.40
Office	57	8	0.77	0.40	0.64
Overall	194	5	0.63	0.35	0.49

Note: The building types included in this analysis are those where there was sufficient diversity across NLCs with and without LLLC and across different manufacturers. The "overall" row includes all building types and all NLCs.

Estimated Control Factors by Space Type

Space type was not commonly reported in the collected datasets. As discussed previously, in some cases, the space type could be inferred from the names or descriptions assigned to a zone, such as "third floor restroom". In other cases, the zone names and descriptions provided little context (such as "zone 18") for correctly mapping the space type. As a result, the following analysis included only the space types that were reported from at least three distinct buildings of the same type in the collected datasets. Figure 18 shows the control factors of the space types that match the above criteria and were included in the analysis.

Savings by space type in office buildings

Savings by space type in offices tended to be higher than average building-level savings for all offices. This is because the office buildings that had space type data generally came from the higher-savings cluster of office buildings visible in Figure 18. As previously discussed, one factor that contributed to the high savings for these buildings is their aggressive high-end trim settings.

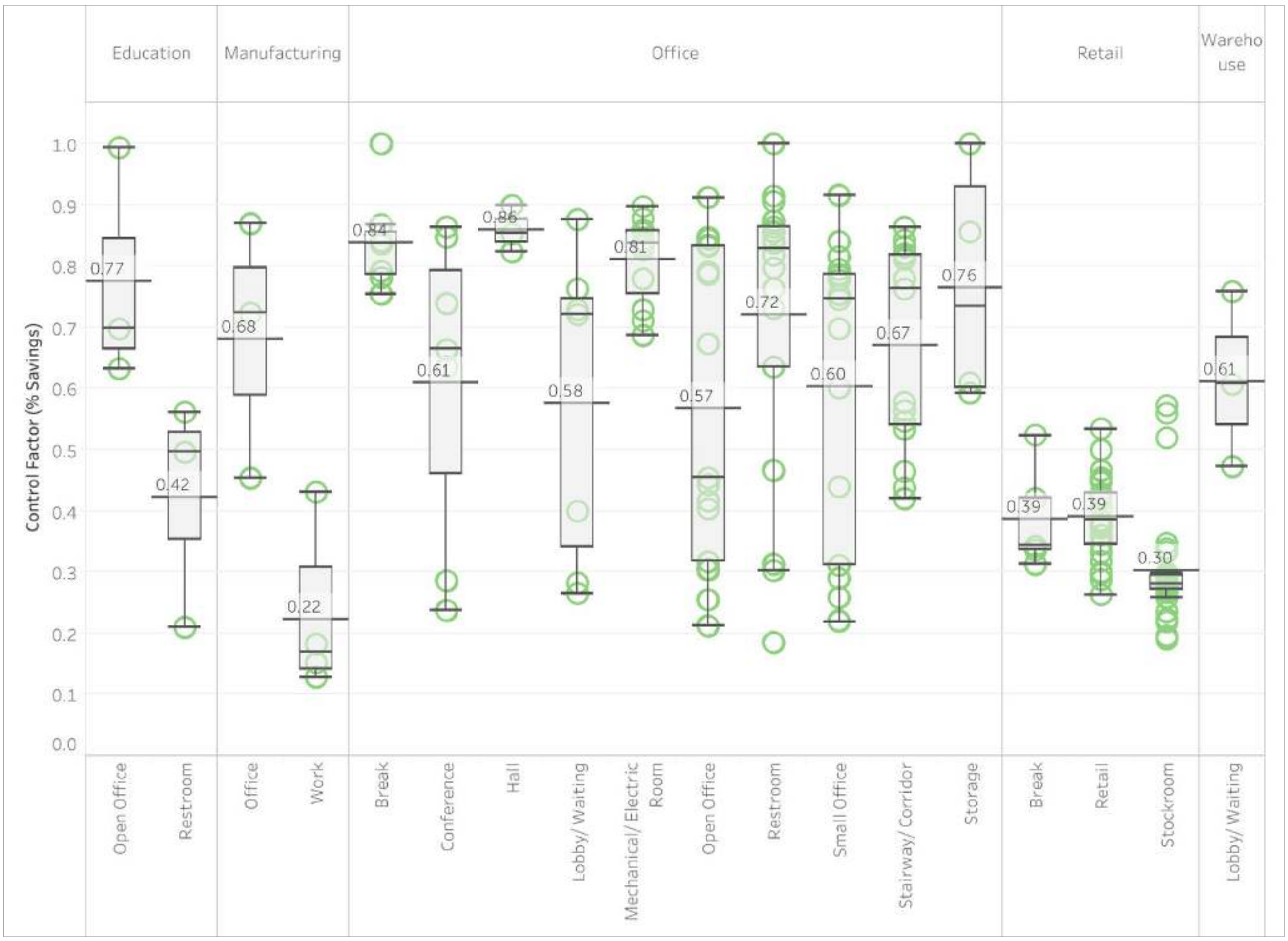
A trend evident in Figure 18 is that office space types with less occupied time tend to have higher savings. For example, break room, hallway, and mechanical/electrical room space types had consistently high savings (81-86% on average), while private office had average savings of 63%, which is on par with the average savings of the office building type. Interestingly, the open office space type had the lowest average savings (50%) and the highest variance among the analyzed space types; while the savings were still quite high in absolute terms (likely due to aggressive high-end trim settings), this demonstrates the impact of highly varied occupancy patterns and schedules on the potential savings.

Savings by space type in education, manufacturing, retail, and warehouse

The small sample size of reported space types for education, manufacturing, and warehouse limits the broader applicability of these findings; however, the findings are similar to those of office buildings: space types with less occupied time generally appear to be ideal for maximizing NLC savings. The work area within manufacturing facilities had the lowest average savings of 30% among the space types of the three building types, which is unsurprising, as work areas are typically highly occupied by shift workers with tight schedules.

The savings results for retail space types run contrary to the trend for office, education, manufacturing, and warehouse, with retail sales saving more than stock room, even though retail sales tend to be a higher occupancy space type. This could be because in the highly homogenous sample of retail buildings in the dataset (29 buildings from a single customer), the retail sales floor is generally daylit and the NLC system employs some daylight harvesting.

Figure 18. Control factor by space type relative to an inferred baseline.



Note: Each dot represents all the zones of a given space type in an individual building (e.g., each dot for private office represents the weighted average of all private offices within a single building). Lines represent the mean savings for a given space type across all buildings.

Comparison to the Most Recent Savings Forecast

The 2017 NLC Savings Study compared the estimated savings with both case studies within the dataset and earlier large-scale studies, and included extensive discussion on the similarity as well as the potential causes of differences. Since then, the most notable large-scale lighting controls savings characterization was conducted by Navigant Consulting and published by the

US DOE in 2019 as part of a larger energy savings forecast of solid-state lighting in general illumination applications (DOE 2019). The estimated NLC savings for each building type from this study are compared to the DOE's 2017 estimates and 2035 forecasts in Figure 19.

Figure 19. Savings comparison with the most recent DOE estimate and forecast.

For the education, healthcare, manufacturing, and retail building types, the DOE's estimated and forecasted energy savings are higher than the present study. On the other hand, the savings for offices and warehouses estimated by the present study are higher than those estimated by the DOE for 2017 and are almost exactly the same as the savings forecasted for 2035.

There are a few likely explanations for the differences in findings between the two studies:

- **Fundamentally different methodologies:** The savings estimates in this study were driven by the actual measurements of NLC energy usage, whereas the DOE study estimated savings from connected lighting[21] as a layered energy reduction from individual control strategies that represent the theoretical achievable maximum savings. This could be a source of the higher savings in the DOE's 2017 estimates and 2035 forecasts for most of the building types.

- **Differences in baseline assumptions:** The baseline lighting load profiles used in the DOE's estimates were provided by the California Public Utilities Commission and were representative of the average lighting load profile of each building type. The inferred baselines used in this study, on the other hand, were derived from the actual energy usage of each NLC installation, and therefore, were site-specific. As discussed in the "Inferred Baseline Methodology" section, the baselines included built-in implicit basic schedule or occupancy controls. In other words, the inferred baseline, in most cases, would likely be the more stringent baseline of the two, resulting in the lower savings estimates in the present study in most of the building types.
- **Difference in control strategies considered:** The control strategies included in the DOE's estimates were dimmer, daylighting, occupancy sensor, and timer. High-end trim was not explicitly considered as one of the control strategies. As discussed previously, high-end trim was found to be a major contributor to the estimated savings in the collected NLC energy datasets. This would likely explain the higher savings estimates for offices and warehouses in this study. The average savings for manufacturing facilities in this study were skewed lower by several sites where only simple scheduling type of controls were implemented.

[21] Instead of networked lighting controls, the DOE study used connected lighting, which broadly includes both connected LED lamps and luminaires. This could be another source for the differences in the savings estimates (while not significant), since the data used in this study did not contain any connected LED lamps.

Project Findings and Recommendations

This project continues the important work started by the 2017 NLC Savings Study to accelerate the move from generalized engineering calculations to a building-specific, data-driven approach to estimating energy savings. There is significant opportunity to build on this analysis and further develop the dataset and insights that can be derived from it. This section provides key findings and recommendations about savings estimates as well as additional findings and recommendations to inform the continued growth of the NLC industry and utility and energy efficiency programs, and to improve how NLC energy monitoring data is collected and analyzed.

Key Findings and Recommendations

Finding #1: The portfolio-level average energy savings across all buildings in this study was 49%.

Similar to the trends observed in the 2017 NLC Savings Study, there does not seem to be a clear correlation between energy savings and building type. Site-specific variation is a much larger driver of energy savings than general factors such as building type. The variation in savings results among buildings within the same building type is likely due to the following factors:

- **NLC system programming and commissioning, and identifying which control strategies are actually used.** Some sites appear to implement aggressive high-end trim and optimize their control strategies to achieve deep savings, while others may be using the systems in a more basic manner. For example, visual analysis of load profiles during the quality control process suggested that many sites with lower savings are simply using NLCs as a zone-level scheduling control with high-end trim, and not implementing other energy-saving control strategies. For these sites, the average hourly power goes from zero to the maximum measured power and back to zero at a predictable time every day without dipping below maximum power. This suggests that occupancy, personal control, or daylighting capabilities were not activated. Any savings derived from zone-level scheduling controls are not accounted for in this analysis due to a lack of pre-NLC baseline data.
- **High variation in settings for the strategies that are used.** There is likely significant differentiation in occupancy timeouts or settings such as auto-on versus manual-on. However, there is not sufficiently granular data to help determine which settings play a primary role in driving lighting efficiency.
- **Variation in site characteristics, occupancy patterns, and user behavior**. The degree of available daylight, occupancy patterns, and individual users' tendencies to turn off the lights when not present all have major impacts on energy savings (Asif ul Haq et al. 2014). To date, such factors generally cannot be accurately compared across buildings, as they are

not easily recorded or measured. A better understanding of the causal factors that influence energy savings is an important consideration for future study. This will require a significantly larger dataset and collection of additional site information, which is feasible if energy efficiency programs for NLCs begin collecting this data in a standardized fashion.

Recommendation #1: Based on this dataset, energy efficiency programs are able to use 49% as the best estimate of average portfolio-level energy savings for NLC programs.

The portfolio-level average energy savings across all 194 buildings in this study was 49%. This estimate is 2% higher than the estimate from the 2017 NLC Savings Study. Because the buildings included in this study were not identified through a random sample, it is not possible to make statistical inferences about a broader building stock. For the same reason, it is also not possible to definitively determine if the 2% gain in the savings estimate is due to increased familiarity with the technology and improved programming and commissioning. However, 49% represents the average savings from NLC systems across twelve manufacturers, eight building types, and 194 buildings, and is therefore the best available estimate of average NLC performance. A reasonable interpretation of the results is that "across a portfolio of buildings, NLC is likely to save roughly half of the lighting energy".

Finding #2: The NLC systems with LLLC showed overall higher savings in this set of data.

NLC systems with LLLC showed overall higher savings than systems without LLLC (see Table 8 below). While this finding suggests that more granular control may lead to higher savings, it should not be inferred at this time that LLLC is universally superior in all applications, building types, and design criteria. A larger study including more diverse NLC systems with LLLC and controlling for potentially confounding variables is still needed to confirm this finding at the portfolio level. Future study should also address the potential "checkerboard[22]" effect and the potential issues related to user perception and satisfaction.

Table 8. Summary of estimated control factors by LLLC and control strategies.

LLLC Presence	Total Buildings	Control Factor (% Savings)			
		Average	25th–75th Percentile	High-End Trim Contributions	Other Control Strategies
NLCs w/ LLLC	98	0.63	0.50 - 0.79	0.37	0.41
NLCs w/o LLLC	96	0.35	0.17 - 0.48	0.17	0.22
All NLCs	194	0.49	0.35 - 0.69	0.27	0.32

Note: The numbers in this table are meant to provide a high-level overview of average savings trends. Additional study is needed to control for potentially confounding variables, and thus at this time the data does not imply that LLLC is universally superior or applicable to all building types.

[22] The "checkerboard" effect refers to the scenario where a connected space is unevenly lit, and the ceiling is showing dark spots as some luminaires are turned off or dimmed significantly. This occurs when each fixture turns off or dims itself in the absence of an occupant in its field of view while other locations within the same space are still occupied and the luminaires above the occupied areas are at a much higher light output level.

Recommendation #2: Based on this dataset, it may be worthwhile to explore programs around LLLC for greater average energy savings.

Further study is still needed to create more robust savings estimates for NLCs with LLLC at the portfolio level and for each building type. However, it may be worthwhile to pilot programs targeting the building types where LLLC seems to exhibit significantly higher savings, such as offices, manufacturing facilities, and other similar building types (see Table 7). Other aspects around LLLC can also be investigated through the pilot programs, including suitable applications (e.g. luminaire layouts, space configurations, etc.) and occupant perception, as noted in Finding #2.

Additional Findings and Recommendations

Finding #3: Ownership of, management of, and access to NLC energy data varies from NLC manufacturer to manufacturer.

During the outreach and data collection period of this study, NLC manufacturers were the first outreach target in hopes of gaining access to a large amount of NLC data from a few centralized sources. It quickly became evident that each manufacturer had varied knowledge on the whereabouts and details of its NLC installations and varied ability to provide viable data to the study due to different sales models. Some manufacturers centrally manage energy data in the cloud and had contractual agreement with customers to access the data. Other manufacturers enable energy monitoring by default or as an option and store energy data locally within the system. Most of these manufacturers rely on sales representative agencies, distributors, and contractors for sales, installation, and commissioning; and therefore, have little or no direct access to or knowledge about the installations.

This translated to a high level of effort in outreach and collecting NLC energy data for this study. More importantly, from the energy efficiency program perspective, it may not always be practical to expect involvement of and support from manufacturers in submitting NLC energy data as part of an energy efficiency program. Recommendation #3 specifically advocates for energy efficiency programs for NLCs to be the primary drivers for collecting NLC energy data as part of their energy efficiency programs.

Recommendation #3: Energy efficiency programs for NLCs should drive the sharing and use of anonymized NLC energy data for all participating projects.

While the 49% portfolio savings for NLCs may be used as deemed savings in the near term, the most accurate savings claims will always be the savings measured at each installation. With energy reporting becoming ubiquitous in NLCs, evaluating savings at each installation should be the ultimate direction energy efficiency programs move towards. As pointed out in Finding #3, administrators of energy efficiency programs for NLCs, instead of manufacturers, are the only market actor that has direct engagement with NLC program participants in all cases. Energy efficiency programs for NLCs should strongly consider including clauses in their customer participation agreements that authorize the sharing of anonymized data.

Anonymized data sharing is common in many software applications, and authorization is typically written into the usage terms and conditions or specifically requested during the installation process. It is recommended that program administrators either (a) explicitly require reporting as a condition to receiving incentives[23], or (b) incentivize energy monitoring and data reporting by providing an additional per-kWh "adder" for data sharing[24].

In addition to collecting NLC energy data submitted by program participants, this recommendation also advocates for the energy efficiency program administrator's active use of the collected data, either for savings verification on a per-project basis or for performance evaluation at the program or portfolio level. A standardized data submission format and process (detailed in Recommendation #4) should be specified and included as part of the customer participation agreement such that the data can readily be plugged into a calculation template or script without significant manual processing. This recommendation is consistent with and reinforces the recommendation in the DLC report, *Interoperability for Networked Lighting Controls* (DLC 2020), that the program administrator should be the primary driver and promoter for the use case of energy data reporting for incentive savings verification.

Finding #4: The process for exporting static attributes of the energy data, such as the post-NLC rated power, is more error-prone than for time-series data and can skew the estimated savings.

As discussed in the "Data Aggregation into the NLC Database" section, the NLC data is comprised of two parts: the static attributes and the time series data. For energy data directly reported by NLCs (as opposed to measured using separate data loggers), the time series data is a direct export from the NLCs. The static attributes, on the other hand, were typically provided in a separate document during the data collection period, which is much more susceptible to human data entry and transcription error. Some NLCs may be able to export static attributes, but they are still only as accurate as the information manually entered into the NLC by the commissioning providers at the time of system startup, programming, or commissioning.

One example identified during the data processing and analysis exercise of this study is the post-NLC rated power provided in several datasets. High-end trim settings are typically not part of the energy reporting time series data, and therefore, the savings calculations rely on the post-NLC rated power reported by the data contributor to determine savings from high-

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[23] At the time of this report writing, examples of utilities that already require NLC energy reporting as a criterion for program eligibility include AEP Ohio and Consumers Energy.

[24] At the time of this report writing, examples of utilities that provide an incentive adder for NLC energy reporting include ComEd and Focus on Energy.

end trim. Inaccurate post-NLC rated power could lead to both underestimates and overestimates of the savings:

- Underestimate (scenario 1) – For the NLC energy data without a reported rated wattage, either at the system level, zone level, or luminaire level, the analysis defaults to the approach described in the "Standardization of Data Formats" section. This means the post-NLC rated power was derived either from other information, e.g. dimming level, or from the observed maximum power in the time series data. This is likely to penalize the actual effect of high-end trim and result in an underestimate of the high-end trim implemented at the site.
- Underestimate (scenario 2) – There were a few cases where the reported post-NLC rated power was lower than the occurrences of the maximum power observed in the time series energy data. These post-NLC rated powers provided by the data contributors were most likely to be erroneous, and the savings calculations would default to the approach described in the "Standardization of Data Formats" section, thereby penalizing the assessment of high-end trim savings.
- Overestimate – The post-NLC rated power information reported by the data contributors could be erroneously higher than the actual installation. It was not possible for this analysis to accurately discern if the reported rated wattage was unreasonably high. In this case, the estimated high-end trim savings would be an overestimate.

Another example is the gross square footage of the NLC installation. While not utilized in the analysis, some of the gross square footages were clearly inaccurate, resulting in unrealistically low installed lighting power densities according to a simple calculation. This would become problematic if the utility or energy efficiency program for NLCs determines incentives or verifies project savings based on operational lighting power density or energy use intensity.

Recommendation #4: As part of the NLC energy data, essential static attributes of an NLC installation should be required and verified carefully to ensure accuracy and quality of the analyses.

Whether or not NLC energy data is collected as part of an energy efficiency program or for future savings characterizations like this study, the static attributes, such as the post-NLC rated power, gross building area of the NLC installation, etc., need to be carefully verified by the data collector for accuracy. This is critical in ensuring the accuracy and quality of estimated savings, as discussed in Finding #4. What constitute an "essential" static attribute depends on the intended use and analysis of the NLC energy data. For a similar study to this one, the post-NLC rated power is one of the essential static attributes. If an energy efficiency program intends to evaluate NLC energy performance using metrics such as operational lighting power density or energy use intensity, then the gross building area of the NLC installation would be another essential static attribute[25].

From the energy efficiency program perspective, the best time to accurately collect these essential static attributes is at the completion of the NLC installation. Some static attributes may be collected during project scoping or initial application submission, but they are typically subject to change as projects progress and should be re-confirmed when the project installation is completed. If the NLC allows, these static attributes should also be entered or programmed into the system during programming and commissioning.

Finding #5: The size of NLC energy data, and thereby the required database storage and processing time and power, grows rapidly as spatial and temporal granularities increase. Data requirements specified in accordance with the actual needs and use of the NLC energy data is key to ensuring program success and scalability.

The savings analysis performed in this study is primarily for research purposes with the goal of characterizing typical NLC savings. For this reason, the study sought data at the highest possible spatial and temporal granularities with the longest possible duration. The size of a dataset grows rapidly as the spatial and temporal granularities and the overall duration of measurement increase. A dataset reported at the building level for two weeks at a 15-minute interval could be as small as a few hundred kilobytes (KB), and in contrast, a dataset at the fixture level for six months at a 5-minute interval could easily be several gigabytes (GB). After all data included in this study was processed and loaded into the database, the overall size of the database had grown to over 200 GB. These highly granular and long duration datasets presented the following challenges during this study:

- Took a long time for data contributors to transfer the data to the project data repository online. In some instances, this discouraged the contributors from providing the most granular data.
- Required an extensive amount of time, measured in days, to process and normalize the raw data and load it into the database.

The challenges encountered in this study suggest that it would not be a scalable model for utility and energy efficiency programs to require the most granular energy data for NLCs. Program data requirements will need to strike a balance between accuracy and scalability as suggested in Recommendation #5 in the next section.

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[25] For these example metrics, the spatial and temporal granularity as well as the required duration of the time series data will also need to be specified. Such considerations are omitted here since they are not directly relevant to this discussion and will be addressed in Recommendation #5.

Recommendation #5: Energy efficiency programs for NLCs should standardize the NLC energy data reporting format and requirements to facilitate program participation and streamline the process. Based on these reporting guidelines, manufacturers should consider developing administrator-specific reporting functionality to support the energy-efficiency program data intake process.

While NLC energy data with the highest granularity and longest duration may result in the most accurate representation of the actual performance, as Finding #5 points out, the large size of the NLC data files makes data intake, processing, and analysis very challenging and unscalable for efficiency programs. It is critical for energy efficiency programs for NLCs to specify and standardize the spatial and temporal granularity and duration requirements based on the metrics and methodology that will be used to assess or verify NLC energy performance. When considering performance metrics and evaluation methodology, the key is to strike a balance between accuracy and scalability.

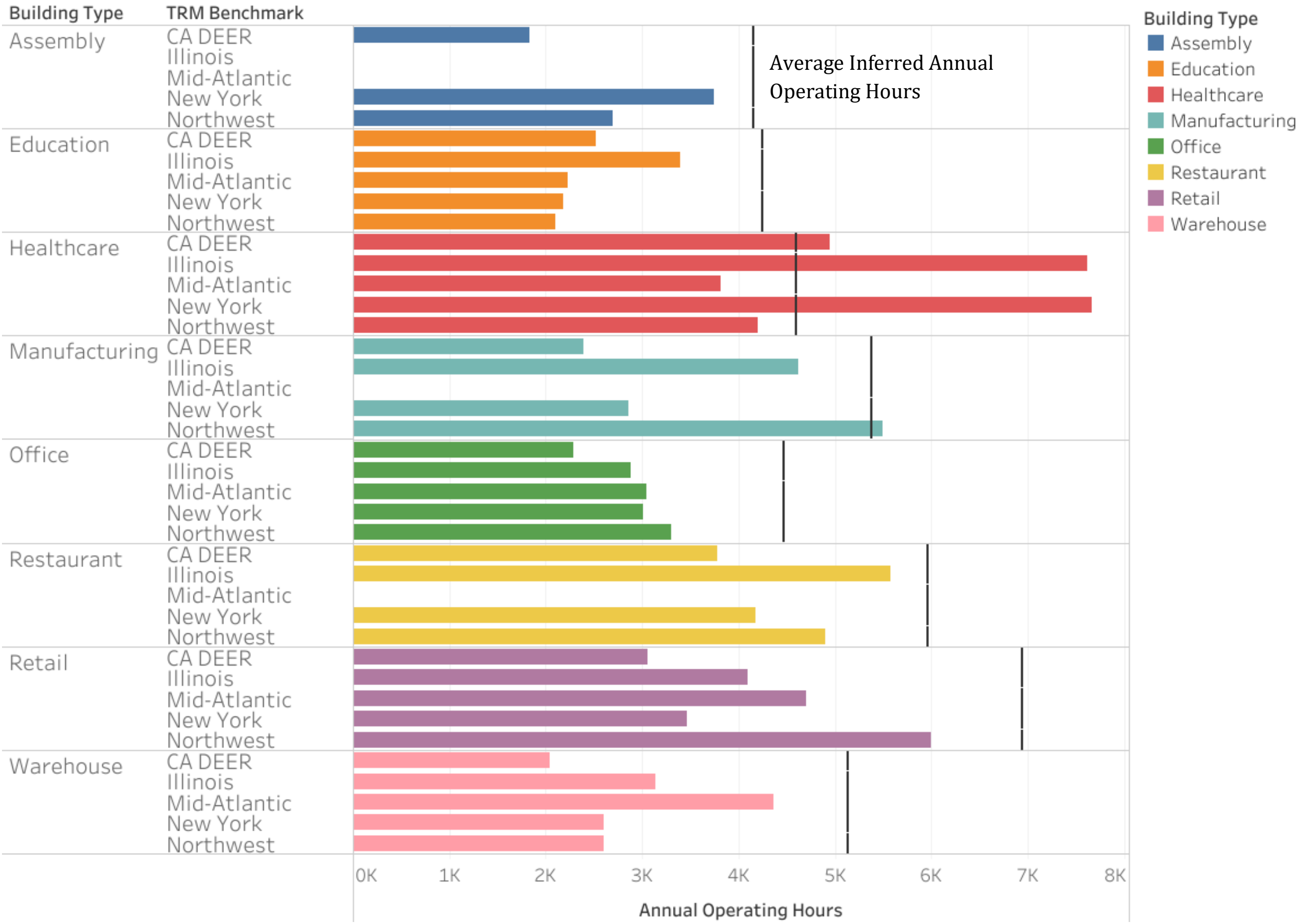
When the data reporting format and requirements are standardized, at least within the program, there will be an opportunity to automate not only the data intake process, but also the performance evaluation calculations, as suggested in *Interoperability for Networked Lighting Controls* (DLC 2020) in the energy monitoring use case. A standardized data reporting format and requirements will also provide manufacturers clear guidance and motivation to develop NLC energy reporting functionalities that support efficiency program needs.

The DLC is supporting progress on Recommendations #4 and #5 through the NEMA ANSI C137 committee. This progress will enable the DLC and program administrators to encourage the installation of products with standardized data reports, as per Recommendation #3.

Finding #6: In this study, buildings with NLC systems had significantly longer inferred operating hours than typical prescribed TRM estimates of building operating hours.

The average inferred occupied hours for buildings in this study's dataset are substantially longer than the average deemed lighting system operating hours assumed by many utility and efficiency programs throughout the US in their Technical Reference Manuals (TRMs). This is consistent with previous findings from the 2017 NLC Savings Study. Figure 20 compares inferred hours found in this study and deemed operating hours for fixtures across several TRMs, including California, Illinois, Mid-Atlantic, New York and the Northwest regions.

Figure 20. Comparison of sample deemed TRM operating hours and inferred operating hours.



The discrepancy between inferred hours calculated in this study and TRM assumptions could be due to one or more of the following reasons:

- For Assembly, Healthcare, and Restaurant building types, small sample sizes (n=3, n=2, n=3 respectively) may not form a representative sample of typical operating hours.
- Buildings with longer core hours are more likely to implement NLC systems because of the stronger value proposition associated with longer operating hours.
- The methodology of this study might have a systematic bias, although a systematic underestimate of operating hours appears more likely than an overestimate.
- This study's methodology likely underestimates baseline hours when the lights are on. This is because it only accounts for actual detected presence and does not consider the possibility of unnecessarily long lighting schedules where time clocks turn the lights on well before or after occupants are in the building.
- This study's methodology could overestimate baseline occupied hours because occupancy and energy use are analyzed on an hourly basis. If the lights go on halfway through an hour, the average power draw during that hour will exceed the 10% threshold and that

whole hour will be assumed to be on in the baseline. This approach gives some credit for scheduling and was based on discussion with industry experts. However, it is unlikely that this is a major driver of the observed differences in operating hours, as work schedules tend to start and end on the hour, so the potential for overestimating hours in this manner is relatively low.

The large discrepancy between inferred hours and deemed operating hours found in TRMs may result in lower overall savings for projects using deemed operating hours. This study, and any future updates to this study, could serve as additional data points for the TRMs to calibrate the deemed operating hours.

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Appendix A: Representation of Savings for Other Control Strategies

Control Factors

The control factors for control strategies other than high end trim, calculated both against the original inferred baseline and the inferred baseline with savings from high-end trim removed, are shown in Table 9 and Table 10.

Table 9. Summary of estimated control factors by building types.

Building Type	Total Buildings	Unique Manu-facturers	Control Factor (% Savings)				
			Average	25^{th}–75^{th} Percentile	High-End Trim Contributions	Other Control Strategies[1]	Other Control Strategies[2]
Assembly	6	2	0.28	0.11 - 0.45	0.07	0.21	0.23
Education	14	5	0.45	0.19 - 0.63	0.21	0.24	0.32
Healthcare	2	1	0.56	0.51 - 0.62	0.42	0.14	0.24
Manufacturing	73	4	0.40	0.20 - 0.55	0.16	0.24	0.29
Office	57	8	0.63	0.50 - 0.80	0.46	0.18	0.36
Restaurant	3	2	0.57	0.47 - 0.65	0.31	0.26	0.30
Retail	29	1	0.44	0.39 - 0.48	0.22	0.22	0.27
Warehouse	10	2	0.69	0.56 - 0.79	0.38	0.31	0.48
Overall	194	12	0.49	0.35 - 0.69	0.27	0.22	0.32

1. *Control factors were calculated with respect to the inferred baseline.*
2. *Control factors were calculated with respect to a baseline where influence and savings from high-end trim were removed.*

Table 10. Summary of estimated control factors by LLLC and control strategies.

LLLC Presence	Total Buildings	Control Factor (% Savings)			
		Average	High-End Trim Contributions	Other Control Strategies[1]	Other Control Strategies[2]
NLCs w/ LLLC	98	0.63	0.37	0.37	0.41
NLCs w/o	96	0.35	0.17	0.17	0.22
All NLCs	194	0.49	0.27	0.27	0.32

1. *Control factors were calculated with respect to the inferred baseline.*
2. *Control factors were calculated with respect to a baseline where influence and savings from high-end trim were removed.*

Note: The numbers in this table are meant to provide a high-level overview of average savings trends. Additional study is needed to control for potentially confounding variables, and thus at this time the data does not imply that LLLC is universally superior or applicable to all building types.

Relationship Between Control Factors

The table below defines the variables that are used to explain the relationship of the two representations of control factors for other control strategies in Table 9 and Table 10.

Variable	Unit	Definition
$\boldsymbol{CF_{NLC,Baseline}}$	%	The overall control factor of the NLC system calculated against the inferred baseline
$\boldsymbol{CF_H}$	%	Control factor for high-end trim calculated against the inferred baseline
$\boldsymbol{CF_O}$	%	Control factor for other control strategies calculated against the inferred baseline
$\boldsymbol{CF'_O}$	%	Control factor for other control strategies calculated against the inferred baseline where the savings from high-end trim (CF_H) are removed
$\boldsymbol{Energy_{Baseline}}$	kWh	Inferred baseline energy usage
$\boldsymbol{Energy_{NLC}}$	kWh	Post-NLC lighting energy usage
$\boldsymbol{Energy_{O_{max}}}$	kWh	Inferred baseline energy usage with the savings from high-end trim removed
$\boldsymbol{Savings_H}$	kWh	Energy savings from high-end trim
$\boldsymbol{Savings_O}$	kWh	Energy savings from other control strategies combined

The two different representations of control factors for other control strategies, $\boldsymbol{CF_O}$ and $\boldsymbol{CF'_O}$, follow the arithmetic relationship below: $CF'_O = CF_O/(1 - CF_H)$, and the derivation is provided as follows.

Overall control factor ($CF_{NLC,Baselind}$):

$$CF_{NLC,Baselind} = \frac{Energy_{Baseline} - Energy_{NLC}}{Energy_{Baseline}}$$

$$= \frac{Savings_H + Savings_O}{Energy_{Baseline}}$$

$$= CF_H + CF_O$$

Control factor for high-end trim (CF_H):

$$CF_H = \frac{Savings_H}{Energy_{Baseline}}$$

Energy savings from high-end trim ($Savings_H$):

$$Savings_H = CF_H \times Energy_{Baseline}$$

Control factor for other control strategies calculated against the inferred baseline (CF_O):

$$CF_O = \frac{Savings_O}{Energy_{Baseline}}$$

Energy savings from other control strategies ($Savings_O$):

$$Savings_O = CF_O \times Energy_{Baseline}$$

Inferred baseline with savings from high-end trim removed ($Energy_{O_{max}}$):

$$\begin{aligned} Energy_{O_{max}} &= Energy_{Baseline} - Savings_H \\ &= Energy_{Baseline} - CF_H \times Energy_{Baseline} \\ &= (1 - CF_H) \times Energy_{Baseline} \end{aligned}$$

Control factor for other control strategies calculated against the inferred baseline with savings from high-end trim removed (CF_O'):

$$CF_O' = \frac{Savings_O}{Energy_{O_{max}}} = \frac{CF_O \times Energy_{Baseline}}{(1 - CF_H) \times Energy_{Baseline}} = \frac{CF_O}{1 - CF_H}$$