CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

**FINAL PROJECT REPORT**

# Pilot-Scale Evaluation of Integrated Building Control System for Commercial Buildings

**June 2023 | CEC-500-2023-039**

**PREPARED BY**:

**Primary Authors**:
Keith Graeber
Andrew Harper
Philip von Erberich

California Lighting Technology Center, University of California - Davis
633 Peña Drive
Davis, California 95618
Phone: (530) 747-3838
https://cltc.ucdavis.edu

**Contract Number**: EPC-16-003

**PREPARED FOR**:
California Energy Commission

Felix Villanueva
**Project Manager**

Virginia Lew
**Office Manager**
**ENERGY EFFICIENCY RESEARCH OFFICE**

Jonah Steinbuck, Ph.D.
**Deputy Director**
**ENERGY RESEARCH AND DEVELOPMENT DIVISION**

Drew Bohan
**Executive Director**

## DISCLAIMER

# PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.
- Using ratepayer funds efficiently.

*Pilot-Scale Evaluation of an Integrated Building Control System for Commercial* Buildings is the final report for the Pilot Scale Evaluation of an Integrated Building Control Retrofit Package project (Contract Number: EPC-16-003) conducted by the California Lighting Technology Center at University of California, Davis. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

# ABSTRACT

The California Lighting Technology Center, in collaboration with the California Energy Commission, conducted research to refine and deploy technology strategies that integrate and optimize automated controls for heating, ventilating, and air conditioning, electric lighting, and dynamic fenestration (window and door) systems. Project objectives were:

1. Refine and publish an integrated building control system specification for commercial applications including necessary hardware and software components.
2. Evaluate the system under controlled laboratory conditions to ensure readiness for real-world deployment.
3. Install and evaluate the system in an existing building to validate performance and adjust as needed to ensure the system was commercial-ready.
4. Document expected system costs, energy use, nonenergy benefits, and other relevant elements when installed in prototype commercial buildings.

Field deployment and evaluation results from the project verified the system design, procurement, installation, and commissioning under real-world conditions for the new technology at scale. The project showed that the integrated building control system technology can reduce heating, ventilation, and air conditioning, lighting, and shading loads by 10 to 40 percent compared to typical baseline systems, depending on building application, size, location, geometry, and climate zone. Additionally, integrating basic heating, ventilation, and air conditioning and lighting systems using occupancy-based control is relatively inexpensive and expected to result in simple payback periods of fewer than three years.

The project team worked closely with multiple fenestration and lighting control manufacturers to refine their products for inclusion in the project. After the demonstration in this EPIC project, these new products are commercially available and ready for use in current integrated building control systems by system designers, installers, and integrators. Outcomes from this project provide the groundwork for additional research that, if successful, could support adoption of more aggressive energy standards related to integrated building control systems.

**Keywords:** algorithm, buildings, comfort, commercial, daylighting, efficiency, electricity, energy, fenestration, HVAC, integration, lighting, optimization

Please use the following citation for this report:

Graeber, Keith, Andrew Harper, and Philip von Erberich. 2021. *Pilot Scale Evaluation of Integrated Building Control System for Commercial Buildings*. California Energy Commission. Publication Number: CEC-500-2023-039.

# TABLE OF CONTENTS

Page

# LIST OF FIGURES

# LIST OF TABLES

# EXECUTIVE SUMMARY

## Introduction

California's clean energy goals include reducing greenhouse gas emissions to 40 percent below 1990 levels by 2030 and achieving carbon neutrality no later than 2045. Integrated building control systems can help California achieve these goals by reducing commercial building energy use, associated greenhouse gas emissions, and peak electricity loads.

Integrated management of commercial lighting and heating, ventilation, and air conditioning (HVAC) systems is among the most promising building energy-efficiency and demand management strategies. The traditional approach to building automation includes independent control systems for each building energy end use (energy directly consumed by the user). In commercial buildings, these control systems typically involve security, electric lighting, shading, fenestration (windows and doors), some process loads (for example, plug loads and electronics), and HVAC systems. However, there is little or no communication among the individual systems or devices.

With respect to the largest energy end-uses of a commercial building, significant research has improved the overall energy efficiency of end-use devices and reduced operating hours through automated control. Research and development efforts during the past decade focused on improving electric lighting or fenestration control methods to increase system reliability and reduce energy used for lighting. However, few of these efforts accounted for the interdependence of lighting, fenestration, and HVAC systems in improving the overall indoor environment. To achieve this improvement, a common communication platform is needed to integrate individual building systems.

Individual manufacturers typically do not provide hardware or software to integrate their products with those of other manufacturers or building systems that are unrelated to their core focus areas. This means that integrated and optimized systems have not reached the commercial market, due in part to manufacturers prioritizing private research and development funds in areas that serve their products and in part to a general lack of collaboration among competing manufacturers. Ratepayer-sponsored research is, therefore, essential to address barriers to the use of integrated and optimized systems and support collaborative efforts among key technology providers.

## Project Purpose

To help California meet its clean energy goals, the California Lighting Technology Center, in collaboration with the California Energy Commission (CEC), analyzed the market, refined the products, and conducted a pilot-scale demonstration of a new technology platform that integrates HVAC, electric lighting, shading, and operable fenestration under a single control system to improve whole-building energy performance and indoor environmental quality. This integrated approach increases whole-building energy efficiency, demand flexibility, and occupant comfort; is highly flexible in terms of building applications, location, and geometry; and can be deployed using currently available, off-the-shelf control hardware and software at substantially lower cost than using traditional building energy management systems.

The project goal was to refine, install, and evaluate a precommercial integrated building control system under real-world conditions to demonstrate the feasibility of an integrated controls approach and validate its potential for improving commercial building energy efficiency and demand flexibility. The project team achieved these goals by addressing four primary project objectives:

1. Refine and publish an integrated building control system specification for commercial applications including necessary hardware and software components.
2. Evaluate the integrated system in the laboratory under controlled conditions to ensure its readiness for real-world deployment.
3. Install and evaluate the system in an existing building under general occupancy and operating conditions to validate control system performance and adjust as needed to ensure the system was commercial-ready.
4. Document expected costs of the new platform, energy use, nonenergy benefits, and other relevant elements when installed in prototypical commercial buildings.

Key audiences for project outcomes included building management system and addressable device manufacturers, as well as system designers, installers, system integrators, and policy makers. Small changes to each audience's common practice can result in substantial energy savings and greenhouse gas emission reductions statewide.

## Project Process

The California Lighting Technology Center is dedicated to advancing energy-efficient lighting, daylighting, and building control technologies and strategies. Collaborating with the CEC and industry partners helped the research team achieve the project goals. The team focused on four key activities:

1. **Control system assessment:** The project team updated an existing market assessment to identify commercially available building control systems and components appropriate for use in an integrated building control system.
2. **System-level integration and refinement:** Based on a market assessment, the team updated then tested existing integrated building control system control algorithms developed by the California Lighting Technology Center to ensure compatibility with newly identified hardware.
3. **Field deployment and evaluation:** The researchers used testing outcomes to further refine and prepare the system for deployment in an existing office building on the University of California, Davis campus. The intent of the field demonstration was to validate system performance under real-world conditions and address any remaining issues prior to commercialization.
4. **System cost and performance analysis:** The project team analyzed energy and costs to identify expected system costs, energy performance, and similar outcomes for prototypical commercial California buildings.

Through this process, the project team established these goals to address market barriers:

- Establishing a communication platform that lighting, fenestration, and HVAC industries were able to successfully implement thereby enabling integration.
- Refining the control algorithms to optimize the performance of the individual building systems with respect to energy savings and occupant comfort.
- Verifying system operation and costs in a real-world building.
- Extrapolating field system characteristics to a broader portfolio of commercial buildings.

Additionally, the COVID-19 pandemic and associated social changes during the final year of the project presented challenges to the field deployment and evaluation activities, including 1) delays in the preconstruction process; 2) delays due to additional requirements on the demonstration job site to reduce risk of exposure for the construction crew; 3) delays in the manufacture and procurement of various system components; and 4) altered occupancy patterns due to shelter-in-place orders. To meet these challenges, the project team supplemented field activities by estimating building energy use post-retrofit through collection and analysis of the energy and savings performance achieved from similar projects under similar conditions.

## Project Results

Overall, the field deployment and building energy modeling results supported the project goals and objectives to develop new technologies and system integration strategies to improve system performance and save energy.

Field deployment and evaluation results verified system design, procurement, installation, and commissioning under real-world conditions for the new technology at pilot scale in one demonstration building. Building energy modeling results show that the integrated building control system technology can reduce HVAC, lighting, and window shading loads by 10 to 40 percent compared to typical baseline systems, depending on building application, size, location, geometry, and climate zone. Adding integrated shading and operable fenestration can dramatically reduce peak energy demand associated with cooling and reduce annual energy use by up to 30 percent depending on conditions and climate zone.

The researchers used procurement cost information from the field deployment combined with building energy modeling results to analyze economic measurements for the integrated building control system. The research showed that basic HVAC and lighting system integration using occupancy-based control can be relatively inexpensive and could result in a simple payback period of less than three years.

Peak demand reductions ranged from less than 5 percent for integrating lighting and HVAC systems to as much as 15 percent for an integrated building control system that incorporates natural ventilation and building precooling.

These project results lay the groundwork for additional research that, if successful, could support adoption of more aggressive energy standards related to integrated building control systems. Specifically, long-term energy monitoring of the field deployment once building occupancy returns to normal will provide the real-world energy use data needed to verify system performance. Supplemental research on the integration of additional technology categories, such as automated demand response, variable air volume and actuated dampers, security, and skylights, could increase the energy savings potential of integrated building control systems.

## Technology Transfer

The goal of technology transfer for this project was promoting best practices for retrofitting commercial buildings with integrated building controls. To communicate these practices and better ensure continued product use, the California Lighting Technology Center focused on developing design guidelines and standardized specification, installation, and building code language that could be used by manufacturers, system designers, system integrators, and installers and be considered for adoption by policy makers.

The California Lighting Technology Center worked closely with multiple fenestration and lighting control manufacturers to refine their products for inclusion in an integrated system. The center supported its manufacturing partners to update device drivers, communication requirements, and similar hardware and software elements to make products compatible with existing communication bridges and controllers. These new or updated product models are commercially available and ready for use in integrated building control systems. Automated window products (for example, Winco Series 3350 by Winco Window) are already commercially available.

Additional technology-transfer activities aimto introduce integrated building control system strategies and articulate specific benefits associated with integrated building control. Technology transfer opportunities included publishing design guidelines—*Daylight Harvesting for Commercial Buildings* (now available at [Daylight Harvesting for Commercial Buildings | California Lighting Technology Center (ucdavis.edu)]—and completing advocacy activities with industry standards development committees for integrated demand side management and daylighting.

Near-term target markets for the integrated building control system technology include building owners with green building or occupant wellness goals, such as Leadership in Energy and Environmental Design (LEED) or WELL Building Standards certifications. The researchers anticipate this market to represent around one percent of California's commercial building stock. Project results will be made available to LEED and WELL membership. Midterm target markets include buildings located in regions with reach codes (local building energy code that reaches beyond the state minimum requirements for energy use in building design and construction) and local ordinances that exceed California's building energy efficiency standards. Project outcomes from this project may be used in future advocacy activities to update voluntary integration measures in Title 24, Part 11, or "CALGreen," which is often used as a reach code. This market currently consists of 37 communities registered with the CEC. Project outcomes will be made available to building departments, Illuminating Engineering Society  membership via Lighting Design and Application (LD+A) articles, and Building Owners and Managers Association membership. The long-term target market for this technology is California's commercial building stock via codes and standards enhancement activities. Advocacy activities will focus on updating Title 24, Part 6 requirements to include integration options, as well as further the development of outcome-based energy code approaches that use integrated building control systems. Project outcomes will be shared with organizations, such as Title 24 Stakeholders and the California Energy Alliance*,* to help promote the strategy.

## Benefits to California Ratepayers

The project results validated the technologies and strategies that can benefit ratepayers through more reliable and less expensive electricity. California ratepayers who adopt this technology can expect to save about 10 to 40 percent in building energy use and associated costs. These savings come from the integrated control of controllable devices that contribute to electricity loads in a typical commercial building, with most savings attributed to the integration and optimization of lighting and HVAC systems. Estimated electricity savings translate directly to cost savings of $7.9 million to $31.6 million annually assuming a one percent adoption rate throughout California's commercial buildings.

This project demonstrated comprehensive, optimized, and integrated control of multiple building devices using commercially available technology obtainable at 19 percent lower cost than traditional solutions used for integrated building control by minimizing the use of additional sensors and controls and installation of these devices. For example, in a 5,744 square foot building that complies with the current building code, the project costs to integrate addressable lighting and HVAC devices totaled $5,474. When combined with the average 27 percent energy savings from this integration approach, California ratepayers can expect a simple payback of three years.

For the same 5,744 square foot building, the greenhouse gas emission reductions associated with the annual energy savings range from 7.2 metric tons to 26.1 metric tons of carbon dioxide equivalent. In 2013, the CEC estimated that commercial buildings in California use about 50,474 gigawatt hours annually for heating, ventilation, cooling and indoor lighting.

Estimated statewide emission reductions associated with a one percent adoption rate in California's commercial buildings range from 35,687 metric tons to 142,748 metric tons of carbon dioxide equivalent annually. This is equivalent to removing 7,710 to 30,840 typical gasoline-fueled passenger vehicles (as defined by the United States Environmental Protection Agency) from California roads each year.

The project results also set the groundwork for related research topics such as:

- Long-Term Energy Monitoring of the Pilot-Scale Deployment.
- Automated Demand Response Integration.
- Occupancy-Based Optimization of Ventilation.
- Load Shifting.
- Variable Air Volume and Actuated HVAC Dampers.
- Advanced Security Integration.
- Mobile Integration.
- Venting Skylights Pilot Study.
- Work with Industry to Identify Integrated Building Control System Cost Reductions.

# CHAPTER 1:
# Background and Project Purpose

Integrated management of commercial building systems including lighting and heating, ventilation, and air conditioning (HVAC) is among the most promising building energy-efficiency strategies, especially for buildings with daytime operating hours. However, the traditional approach to building automation includes a collection of independent control systems, one for each building end use, with limited or no communication among the individual devices. Independent control systems found in existing commercial buildings typically address security, electric lighting, shading, and HVAC. Existing solutions are limited to integrate any subset of these individual control systems to form a single, intelligent, control system. While several research and development efforts during the past decade were aimed at improving electric lighting or fenestration[1] control methods to increase system reliability and reduce lighting energy use. Few efforts accounted for the interdependence of lighting, fenestration and HVAC systems and the consideration of HVAC status in an integrated approach to improve whole building energy-efficiency.

In 2015, the California Lighting Technology Center (CLTC) completed prototype development and testing of smart and ultrasmart luminaires (lighting units), smart windows, advanced skylights, occupancy sensing technologies, control algorithms, and preliminary system integration solutions with very promising results. These technologies were then leveraged to create a precommercial, integrated building control system (IBCS) that considered the operational state of each device in the network, as well as the surrounding environment, to better control lighting and fenestration as a single system.

The 2015 project demonstrated that integrated systems could an reduce building system energy use by as much as 26 percent compared to buildings using traditional, nonintegrated control systems and strategies. The project also demonstrated the feasibility of deploying these integrated control solutions using off-the-shelf hardware and software at substantially less cost than that of a traditional building energy management system. However, the IBCS had yet to include HVAC units or be installed in actual buildings and evaluated under real-world conditions.

Based on the 2015 project and its potential benefits, the California Energy Commission (CEC) funded CLTC to complete a pilot-scale IBCS demonstration, including HVAC integration, in an existing commercial building at the University of California (UC) campus in Davis, California. The project goal was to refine, install, and evaluate the precommercial IBCS under real-world conditions to demonstrate the feasibility of the lower-cost, integrated controls approach and validate its potential for improving commercial building energy efficiency and demand flexibility.

---

[1] Fenestration refers to windows, doors, skylights, and any other openings in a building.

## COVID-19 Pandemic

The COVID-19 pandemic and associated social changes during the final year of the project adversely affected the evaluation of the IBCS pilot demonstration by significantly slowing IBCS installation and commissioning. This was due to several factors including a delay in the preconstruction process, additional requirements on the demonstration job site to reduce risk of SARS-COV2 exposure for the construction crew, and delays in the manufacture and procurement of various system components.

In addition, UC Davis moved nonessential staff off campus to work from home. This alteration in occupancy patterns at the test site affected the traditional pre- and post-retrofit energy and performance evaluations. The project team was also unable to collect occupant feedback on the pilot IBCS.

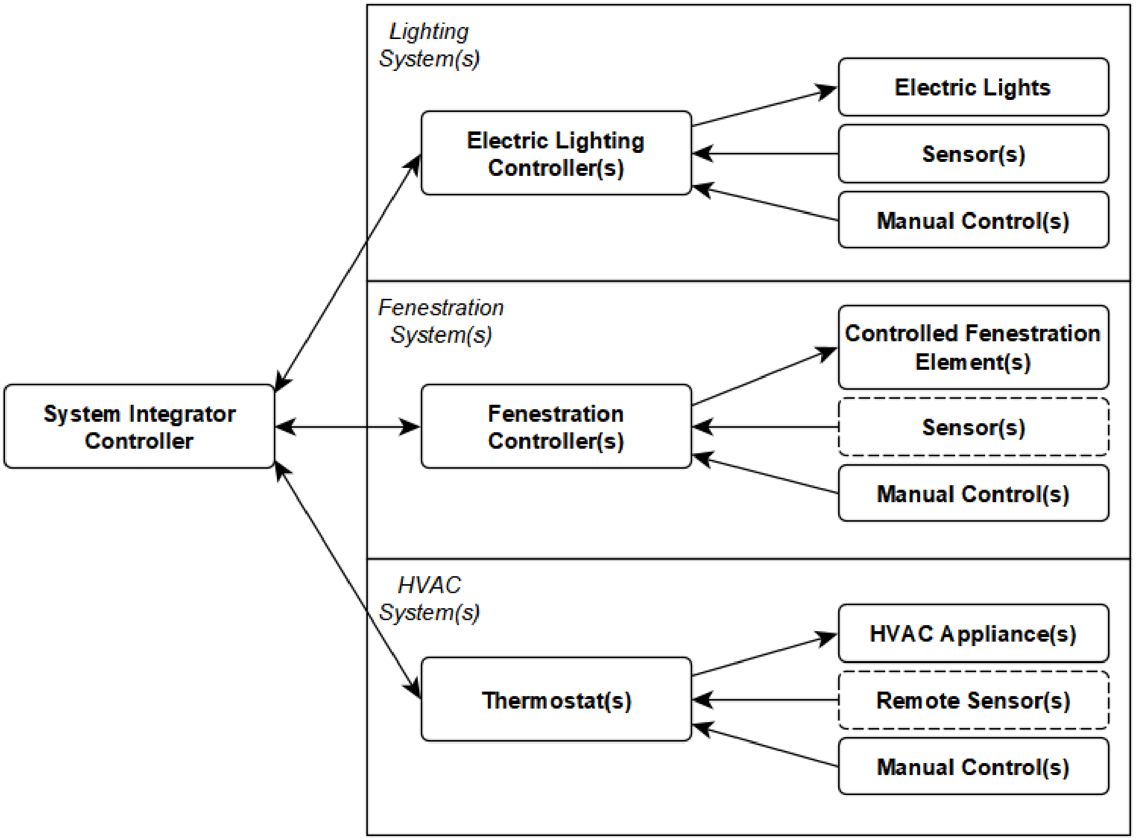
To meet these challenges, CLTC took a two-part approach. First, CLTC did a supplementary estimation of building energy use post-retrofit. This was accomplished by collecting and analyzing the energy and savings performance achieved in similar projects under similar conditions. The researchers used savings from existing literature and primary building energy modeling to estimate relative IBCS performance, savings, and benefits. Second, CLTC expanded the scope of technology transfer activities in this project to work with additional manufacturers to incorporate their technology into the integrated building control system concept making more products commercial ready for post-pandemic retrofit and new construction projects.

# CHAPTER 2:
# Applied Research Outcomes

CLTC identified and tested commercially available technologies as possible components of the pilot-scale IBCS. During the evaluation, the project team refined the preliminary IBCS system and incorporated new commercial technologies that improved performance or expanded the IBCS capabilities.

The IBCS conceptual structure is a collection of building systems connected to a system integrator (Figure 1), a high-level, overarching controller that promotes communication between individual building systems. Individual building systems include a system-level controller, system appliances (such as luminaires and operable windows), sensors, and user-input. The system controller controls connected appliances based on input from the sensors, users, and system integrator.

**Figure 1: Conceptual Structure of an Integrated Building Control System**



**Arrows point in the direction of data flow between components.**

Source: California Lighting Technology Center

Manufacturers may use one or more proprietary controllers for their individual appliances, which means any integrated control system must be able to adapt to various types of inputs and communication protocols. The IBCS's ability to be used with different individual system controllers demonstrates its versatility and enables a building owner to include individual building systems that best fit the needs of a specific site.

To demonstrate the concept's technical feasibility using commercially available systems, CLTC installed, commissioned, and tested an IBCS in its laboratory under controlled conditions. The IBCS controlled the following building appliances, each with its own unique controller:

1. LED luminaires.
2. In-room air-conditioning heat pump.
3. Actuated skylight with integrated shades.
4. Windows with electrochromic glazing.
5. Window with integrated roller shade.
6. Actuated, operable window.

For each system controller, CLTC evaluated the ability of the IBCS's system integrator to communicate with the device. The researchers identified technical limitations such as inability of a controller to provide the bidirectional communication required for satisfactory integration. CLTC worked with building system manufacturers to overcome these limitations and increase the system readiness and availability for use of each device as part of a commercial IBCS. Appendix A provides details on the specific systems and communication protocols evaluated for use with the IBCS, and Appendix B provides details regarding system integration activities.

The primary results of the IBCS laboratory testing were:

- Demonstration of the technical feasibility of the IBCS in a controlled setting.
- Identification of individual device barriers that hampered use as part of an integrated control system and development of solutions for overcoming those barriers.
- Demonstration of IBCS operation with a cross-section of commercial building controllers and subsystems.
- Partnership with building system manufacturers to increase product readiness for inclusion in an IBCS.

## Integrated Building Control System Control Strategy Development

The CLTC developed integrated control strategies for the building control systems in the IBCS. The automated operation of the IBCS was further developed by extending CLTC’s recently completed prototype development and testing of smart and ultra-smart luminaires, smart windows, advanced skylights, occupancy sensing technologies, control algorithms, and preliminary building management system integration solutions. The IBCS algorithms integrate control of electric lighting, HVAC, and dynamic fenestration devices. CLTC tested these algorithms in its daylighting laboratory to ensure the feasibility of deploying them in the pilot IBCS study.

The control logic for the lighting, fenestration and HVAC operation is based on key environmental and internal state parameters of building system controllers. The control logic for each building system improves the building’s energy performance with a focus on occupant comfort and energy efficiency. The algorithms are different for occupied and vacant periods to prioritize comfort during occupancy and energy efficiency during vacancy.

The primary results of these activities were:

- Production of a refined IBCS control algorithm.
- Identification of key environmental and state parameters such as occupancy that can be shared between system controllers.
- Validation of commercial building systems' ability to respond to the IBCS signals.

### Algorithms Followed During Occupancy

When the space is occupied, the control strategy focuses on maximizing comfort. The control logic adjusts lighting output, fenestration visible light transmittance (VLT), fenestration solar heat gain coefficient (SHGC) and venting, and HVAC output:

- Electric lighting output is adjusted based on available daylight.
- Fenestration VLT is adjusted based on the status of the lighting system and the HVAC system. If the lighting is not fully dimmed, the fenestration is adjusted to provide maximum daylight penetration without producing glare. If the lighting is fully dimmed, the fenestration is adjusted to support the HVAC system by maximizing SHGC if the HVAC is in heating mode and minimizing SHGC if HVAC is in cooling mode.
- Fenestration venting is adjusted based on HVAC status and outdoor conditions including temperature, wind, rain, and carbon dioxide ($CO_2$) levels.
- HVAC is adjusted to maintain indoor temperature within a preset, user-specified range.

### Algorithms Followed During Vacancy

When the space is vacant, the control strategy focuses on maximizing energy efficiency. The control logic aims at adjusting lighting output, fenestration SHGC and venting, and HVAC output:

- Lighting output is set to off or minimum.
- Fenestration SHGC is adjusted based on HVAC status.
- Fenestration venting is adjusted based on HVAC status and outdoor conditions including $CO_2$ levels, temperature, wind, and rain.
- HVAC is adjusted based on preset space temperature.

Appendix C provides a detailed description of the IBCS control strategies.

## Laboratory Validation of Control Performance

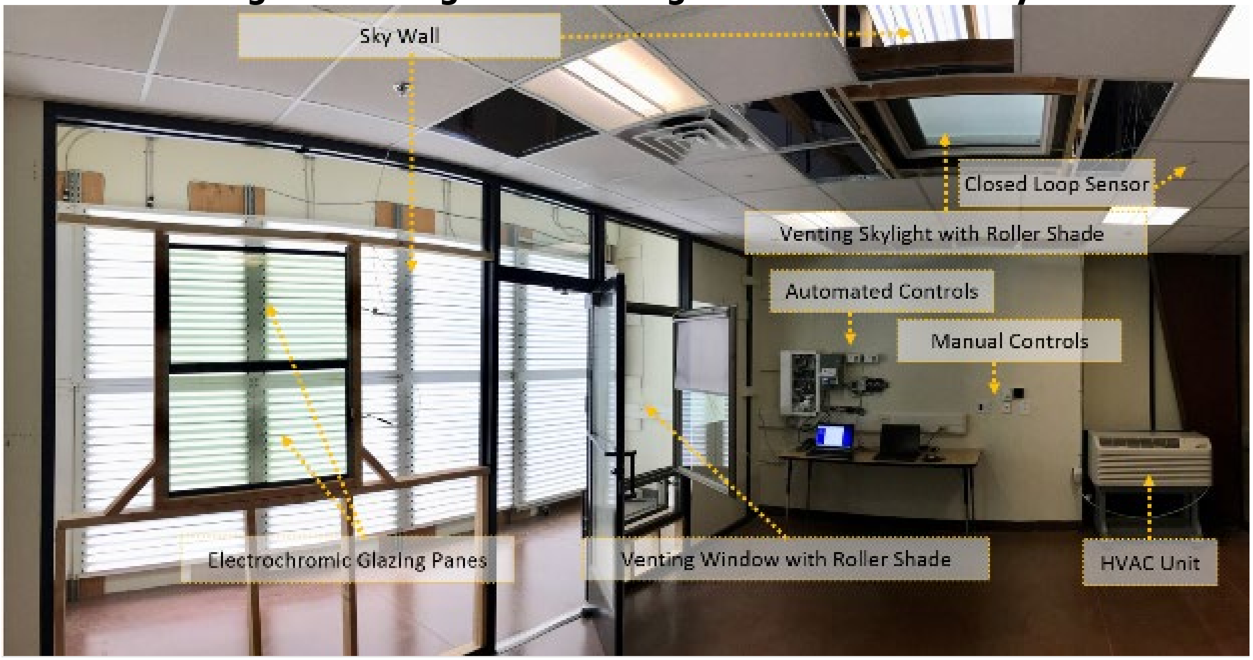
Prior to installing the IBCS at the demonstration site, the project team installed and tested a small-scale IBCS in a CLTC laboratory space. The space was equipped with an HVAC unit, an actuated window, actuated roller shades, four 2x4 LED troffers,[2] and a suite of various monitoring and control devices. Additional technologies not included at the campus

---

[2] A troffer is a rectangular light fixture that fits into a modular dropped ceiling grid.

demonstration site, such as electrochromic windows and venting skylights with a roller shade, were also installed and tested to demonstrate the system's versatility. To create repeatable, real-world simulations, additional HVAC vents were routed into the room for environmental control, and a wall of dimmable fluorescent lamps external to the room provided artificial "daylight".

**Figure 2: Integrated Buildings Controls Laboratory**



**The image shows CLTC's laboratory IBCS test space, which included controlled devices, the automated and manual controls hardware, and the sensors used to determine indoor and outdoor environmental conditions.**

Source: California Lighting Technology Center

The project team tested the IBCS control algorithm as it was developed and programmed to ensure that its behavior matched the desired environmental control behavior while still allowing for appropriate occupant override. The IBCS algorithm was broken down into smaller subalgorithms, which aided in defining specific tests to verify algorithm performance. These subalgorithms are directly tied to the various control systems integrated as part of the IBCS and are referred to by their respective names. This includes lighting, HVAC, natural ventilation, and dynamic shading. The testing of each algorithm is discussed below. Appendix E provides test results.

## Lighting Algorithm

Typically, lighting control is handled by local controls, a centralized zoned control system, or a networked lighting control system. However, to explore advanced lighting control techniques, CLTC used the IBCS system integrator's programmability to implement dual loop lighting control. Dual loop control uses interior and exterior facing photosensors to determine the appropriate light levels for a space. This specific implementation features self-calibration levels to improve the lighting system's response based on changes in a space's internal reflectance and incident daylight angles.

To test the various features and characterize the lighting algorithm's response, CLTC engineers subjected the algorithm to multiple stimuli under various extremes. The goal was to make the algorithm as robust as possible while ensuring adequate lighting when needed.

Initial testing included simple approaches to ensure that the algorithm's basic functionality was accurate and reliable. This included ensuring that occupants had control of the lights when desired, lights turned off when the room was vacant, and interior light levels changed inversely to available daylight. The team simulated multiple daylight profiles using the laboratory's artificial daylight source, which allowed for multiple test repetitions under identical conditions. After the basic tests, the researchers completed more strenuous testing to test the algorithm's limits. Given that changes in the interior reflectance of the room can significantly distort the response of typical lighting algorithms, the IBCS lighting control algorithm was designed with self-calibration techniques to improve response to these issues. To simulate a change in interior reflectance, the team modified the room by moving the furniture and then blanketing the room with black or white cloth to simulate minimum and maximum interior reflectance. The researchers measured quantitative lighting levels in the space to verify that the illuminance was always at a sufficient level for the intended tasks in the space.

## Heating, Ventilation, and Air Conditioning Algorithm

The HVAC algorithm has two primary functions in the IBCS: $CO_2$ management and occupant setback adjustment. For $CO_2$ management, the building automation controller reads in $CO_2$ levels from multiple sensors and, if the $CO_2$ levels are beyond the specified threshold, the HVAC fan is turned on to increase building air changes in the building. To test this, the researchers artificially increased the $CO_2$ levels at the sensors to ensure that the command to turn the fan on was sent to the HVAC thermostat.

For occupant setbacks, the building automation controller also pulls in occupancy data from the HVAC zones. When the zone is vacant, the building automation controller sends a command to the thermostat to change the heating and cooling setpoints to predetermined setback values to prevent the HVAC from running while the space is unoccupied. Conversely, the algorithm restores the last occupied heating and cooling setpoints when the space becomes occupied. Testing for this feature was accomplished by monitoring the occupancy status and verifying that the corresponding setpoints were pushed to the thermostat when the occupancy status changed.

Beyond basic functionality testing, the researchers discovered that the thermostat's behavior did not follow expectations under certain scenarios. Affected scenarios included those where multiple commands were simultaneously sent to the thermostat, those sent when the HVAC was set to “off” on the thermostat, and those sent when the thermostat was not connected its cloud server. To correctly address these cases, the team designed the IBCS algorithm to include confirmation of commands sent and connection detection. With this design in place, the algorithm was able to recognize when the thermostat behavior was incorrectly set, and to reapply the settings once the thermostat returned to typical operation.

## Natural Ventilation Algorithm

The natural ventilation algorithm is designed to support building heating, cooling, and $CO_2$ management. For heating and cooling, the building automation controller makes control decisions based on internal and external environmental factors and the status of the central HVAC system. To avoid occupant discomfort, operable windows will not open when external environment factors are unfavorable. These factors include precipitation, wind speed, and temperature. If there is detectable precipitation or winds that exceed a preset threshold, the window remains closed.

Additionally, the outdoor ambient dry bulb temperature,[3] as compared to the indoor ambient dry bulb temperature, must be such that adding outdoor air through open windows reduces the need for heating or cooling, depending on the HVAC mode selected. For example, if the HVAC system is in cooling mode, the outdoor air temperature must be lower than the internal air temperature for the window to open. Otherwise, the window stays closed to insulate the building. While it was not possible to directly control the outdoor environmental conditions to test window operation, the researchers simulated various conditions by programmatically overriding the environmental data in the building automation controller and then logged window response to ensure that it matched intended operation.

The operable windows can also be automatically opened to increase fresh air in the control space when $CO_2$ levels make it necessary. The building automation controller first runs the fan on the HVAC to lower internal $CO_2$ levels. When $CO_2$ levels remain high even after fan operation, the windows are opened, assuming favorable weather conditions. Like the HVAC test, the project team verified this feature by artificially increasing the $CO_2$ levels in the test case and logging automated window operation. The natural venting algorithm is also designed to prevent cycling of windows due to frequent changes in environmental conditions. Window actuation is suppressed for a user-defined period after the window is automatically closed.

## Dynamic Shading Algorithm

The dynamic shading algorithm is designed to support building heating and cooling by daylight and associated solar heat gains. The building automation controller first determines the HVAC operating mode—heating or cooling—then ensures that shades are raised during heating mode to maximize solar heat gain and lowered during cooling mode to minimize solar heat gain. The algorithm is designed with occupant comfort as the leading design factor, so this feature is only implemented during room vacancy. During occupied periods, shades may be manually controlled to permit outdoor views or control glare. To test this feature, the researchers modified the occupancy status and HVAC mode to verify that shades responded accordingly.

For daylight management, the building automation controller lowers the shades when incident daylight surpasses a user-defined threshold. This is another feature designed for occupant comfort. The building automation controller reads daylight levels provided by local photosensors and lowers the shades when the value surpasses the threshold. To test this feature, the project team simulated excessive daylight using an artificial daylight source and verified the automated shade response.

---

[3] Dry-bulb temperature is the air temperature measured by a thermometer exposed to the air but shielded from radiation and moisture.

## Complete Integrated Building Control System Algorithm Testing

After the specific feature testing was completed, the researchers tested the entire IBCS algorithm. This was done by adding occupants in the laboratory space who worked on common office tasks for several weeks. Occupants interacted with the system to verify that it was functional and operated without issues. This test was more qualitative and explorative without documentation of rigorous results. Instead, the team allowed the algorithm to operate in a typical office setting while the occupants were mindful of the general IBCS expectations to ensure that it was operating according to system design goals.

# CHAPTER 3: Pilot-Scale Deployment Outcomes

## Demonstration Site Conditions

The UC Davis main campus facilities staff provided CLTC with a demonstration building and test site for IBCS installation and evaluation. The project team installed the IBCS in 13 spaces throughout the first floor of the facility, informally called The Barn (Figure 3), for a total of 2,068 square feet (36 percent of the conditioned building floor space). Six demonstration spaces were located along the West building façade and seven spaces along the East façade (Figure 4). The team selected these spaces to encapsulate complete HVAC zones and allow for a detailed evaluation of HVAC, lighting, and fenestration connected to and controlled by the IBCS under typical real-world conditions. The Barn is equipped with a smart power meter that monitors energy use at the whole-building level. This data was used to produce the baseline energy usage numbers of one year for the cost-effectiveness calculations.

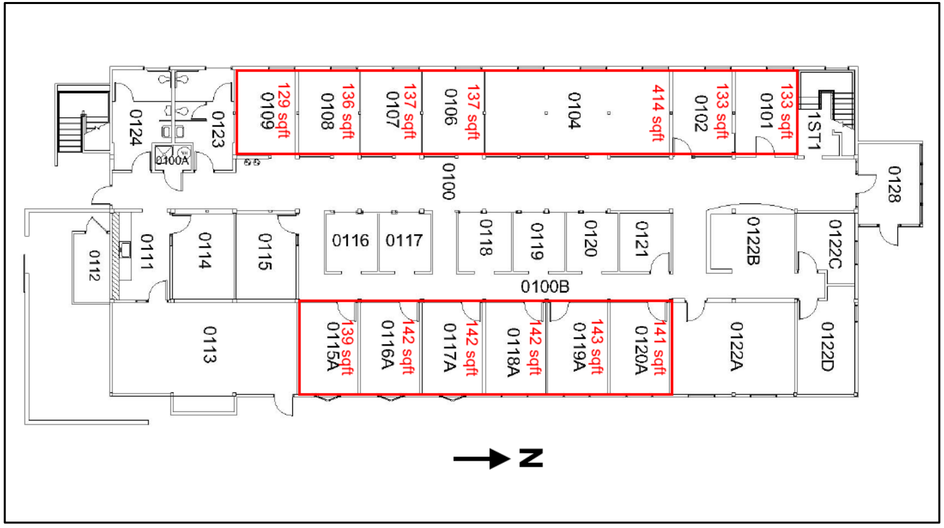
Appendix D provides a detailed description of the existing site conditions at demonstration facility. The researchers completed IBCS installation and commissioning in the summer of 2020. The system is currently fully functional and operating at the facility.

**Figure 3: North Facade of the Demonstration Building**

**John Muir Institute of the Environment, informally named “The Barn”**

Source: California Lighting Technology Center

**Figure 4: Selected Demonstration Area**



**Selected demonstration area on the first floor of The Barn on the UC Davis campus.**

Source: California Lighting Technology Center

## Lighting

The linear LED lamps and drivers were highly efficacious and relatively inexpensive. The lighting controls included fixture controllers, open and closed loop photosensors, occupancy sensors, and various gateways to translate the lighting control signal into BACnet signals. The pre-retrofit lighting in the demonstration area consisted of 24 – 2′x2′ and 38 – 1′x4′ recessed T8 fluorescent luminaires. The wattage ranged from 32 watts per luminare for the 2′x2′ and 34 watts per luminaire for the 1′x4′.

To integrate the retrofitted lights within the IBCS, the team installed a wireless lighting control system. Using lighting controls will ultimately reduce the total lighting load through personal tuning, daylight harvesting, and occupancy-based controls. The daylighting and occupancy-based lighting control strategies that these devices employ typically result in 38 percent energy savings as compared to uncontrolled lighting.

## Heating, Ventilation, and Air Conditioning

Prior to this study, the existing central HVAC of the demonstration building included a wireless thermostat as the main controller. Due to the various communication protocols supported by the IBCS, the site needed no modifications to integrate with the existing thermostats. The HVAC appliances in the test site are constant-volume air handlers, packaged central air conditioning units, and a gas furnace for heating.

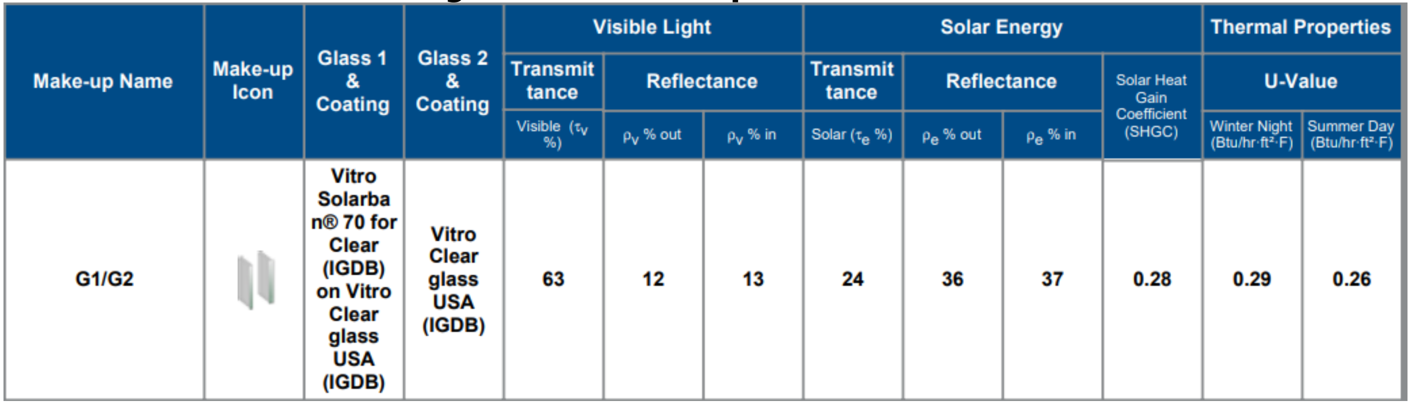
The team designed the IBCS algorithm for the HVAC system to include occupancy-based controls using the occupancy sensor from the lighting system to reduce HVAC use while the space is unoccupied. Multiple studies have analyzed occupancy-based HVAC controls with savings estimates from 10 percent to 43 percent for HVAC, with a median of 20 percent. In addition to the controls savings, this study looked at improving the thermal insulation of the building by replacing the windows, adding variable VLT and SHGC characteristics through actuated roller shades, and including alternative cooling methods with actuated windows.

## Window Glazing

According to the U.S. Department of Energy (USDOE), the most important factors for Energy Star qualified windows are their U-Factor and SHGC. The U-Factor measures how well the window insulates the building from the outside environment, and SHGC measures how much thermal energy from the sun comes through the window.

The windows in the IBCS demonstration zone face east and west, so both the U-Factor and SHGC should be minimized for ideal energy savings. Representative values for these parameters of the preretrofit windows are approximately 1.09 and 0.81, respectively,[4] and the actual performance of the window is likely even worse when considering the air leakage present with the old framing and hardware of the windows causing imperfect seals. According to documentation from the manufacturer, the retrofit windows have a U-Factor of 0.29 and an SHGC of 0.28 (Figure 5).

**Figure 5: Window Specifications**



| Make-up Name | Make-up Icon | Glass 1 & Coating | Glass 2 & Coating | Visible Light | | | Solar Energy | | | | Thermal Properties | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Transmittance | Reflectance | | Transmittance | Reflectance | | Solar Heat Gain Coefficient (SHGC) | U-Value | |
| | | | | Visible ($\tau_v$ %) | $\rho_v$ % out | $\rho_v$ % in | Solar ($\tau_e$ %) | $\rho_e$ % out | $\rho_e$ % in | | Winter Night (Btu/hr·ft²·F) | Summer Day (Btu/hr·ft²·F) |
| G1/G2 | | Vitro Solarban® 70 for Clear (IGDB) on Vitro Clear glass USA (IGDB) | Vitro Clear glass USA (IGDB) | 63 | 12 | 13 | 24 | 36 | 37 | 0.28 | 0.29 | 0.26 |

**Window specifications for the windows installed in the selected demonstration area at The Barn at the UC Davis campus.**

Source: Window Company

The researchers used the USDOE "Energy Savings Window Worksheet" to calculate the potential energy savings due to the improvements in the thermal properties of the window. The cooling and heating degree days values needed for this worksheet were obtained using the most recent year of historical weather data from the KSMF Sacramento Airport Weather station.

## Dynamic Shading

In addition to the improvements attributed to upgrading the window glazing, each window was equipped with actuated roller shades that can provide additional energy savings by rejecting solar radiation that enters the conditioned space in the building through the windows. These shades have a transmittance of 3 percent, meaning they prevent 97 percent of solar radiation from entering the building when used. Historically, roller shades played an architectural role in the built environment and were marketed as an aesthetic upgrade. Using roller shades with metalized films is a recent development and the research team expects that, as more studies show the energy saving potential, the product costs will be optimized based

---

[4] Representative window specifications by window type reported by Whole Building Design Guide.

on energy economics to improve sales volume. Previous research by Eleanor S. Lee and Stephen Selkowitz[5] indicate that dynamic shading can reduce daily cooling loads by 22 to 24 percent.

### Precooling through Natural Ventilation

The last feature of the windows installed in this retrofit package was natural ventilation. The specified window was equipped with a single-chain motor that can open the window to a maximum length of 13.8 inches. The goal of this feature was to offset HVAC loads by using natural ventilation when outside environmental conditions are favorable. While there are multiple situations in which natural ventilation can reduce energy loads, the most noted example is precooling the building. Opening windows at night to let cooler air into the building delays the start of the building's mechanical cooling thereby decreasing daily HVAC usage. Precooling using natural ventilation can significantly outperform precooling strategies that use air handlers.

Multiple studies have modeled buildings to determine the potential energy savings by using precooling through natural ventilation. The results of these studies range from 5 percent to 23.5 percent when considering various parameters such as relative humidity, the duration of venting, whether using actuated windows or the building's air handlers, and the thermal mass of the building. A 2015 modeling study by Christopher Iddon and Nikhil ParasuRaman[6] that closely matches the control algorithm used in this implementation found precooling through natural ventilation reduce annual cooling energy usage by 15.7 percent.

## Modeled Economic Performance

IBCS economic performance depends highly on existing conditions, the use type, and the specific implementation of IBCS deployed. While IBCS can include any number of controllable building systems such as lighting, HVAC, fenestration or plug load controls, IBCS cannot happen without some level of building integration work. This work may consist purely of programming a site-specific sequence of operations or it may include physical installation of communications hardware such as cabling, wireless transceivers, or protocol gateways.

Due to this variability in possible IBCS embodiments, the researchers modeled four scenarios to understand the cost benefit of the most common incremental steps of IBCS as estimated by the team. Modeled scenarios considered combinations of lighting, HVAC, and shading integration. The researchers did not consider savings due to natural ventilation in the modeling. Code compliant and legacy construction scenarios were both considered. The team determined energy savings and project costs considering a mix of existing publications, site conditions at the project demonstration site, and the team's energy modeling. All energy

---

[5] Lee, Eleanor, and Stephen Selkowitz. 1997. Design and Performance of an Integrated Lighting Envelope/Lighting System. https://eta-publications.lbl.gov/sites/default/files/39729.pdf. Lawrence Berkeley National Laboratory

[6] Iddon, Christopher, and Nikhil ParasuRaman. 2015. Nightly Purge as a Means to Reduce Cooling Load in an Office in Pune, India. http://www.ibpsa.org/proceedings/BS2015/p2323.pdf. Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015

savings and cost numbers are specific to the 5,744 square foot building on UC Davis campus called "The Barn" using a flat rate of $0.18 per kW-hr. Table 1 summarizes the results.

The economic performance discussed only includes cost savings from conservative flat electrical rates. IBCS enables future realization of advanced building control strategies that not only improve whole building energy usage and occupant comfort but also consider and adjust appliance operation based on real-time pricing signals and demand events. The research team anticipates future broad adoption of time-of-use-based tariffs to greatly improve the economic performance of the IBCS.

**Table 1: Cost Effectiveness Results**

| IBCS | Baseline Annual Energy Use (kW-Hr) | Energy Conservation Measures | % Savings (Specific Systems) | Annual Energy Saved (kW-Hr) | % Total Building Energy Savings | Project Cost | Simple Payback |
|---|---|---|---|---|---|---|---|
| Lighting + HVAC Integration in a code compliant building | 89,588 | 1. Occupancy-based temperature setbacks<br>2. Occupancy-based ventilation setbacks | 27% HVAC (based on model considering local weather conditions) | 10,240 | 11% | $5,474 | 3.0 |
| Lighting + HVAC + Shading Integration in a code compliant building | 89,588 | 1. Occupancy-based temperature setbacks<br>2. Occupancy-based ventilation setbacks<br>3. Occupancy-based SHGC control of Windows | 38% HVAC (based on model considering local weather conditions and published shading impacts) | 14,412 | 16% | $47,099 | 18.2 |
| Lighting + HVAC Integration including lighting retrofit | 89,588 | 1. Occupancy-based temperature setbacks<br>2. Occupancy-based ventilation setbacks<br>3. Lighting retrofit<br>4. Lighting controls | •27% HVAC (based on model considering local weather conditions)<br>•63% Lighting Retrofit (based on site conditions and published savings estimates) | 32,769 | 37% | $72,579 | 12.3 |
| Lighting + HVAC + Shading Integration including lighting retrofit | 89,588 | 1. Occupancy-based temperature setbacks<br>2. Occupancy-based ventilation setbacks<br>3. Occupancy-based SHGC control of Windows<br>4. Lighting controls | •38% HVAC (based on model considering local weather conditions and published shading impacts)<br>•63% Lighting Retrofit | 36,941 | 41% | $114,203 | 17.2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | (based on site conditions and published savings estimates) | | | | |

**Cost effectiveness of IBCS from modeled economic performance scenarios.**

Source: California Lighting Technology Center

### Scenario A

The first IBCS scenario modeled consisted of adding building integration hardware to an existing code compliant building and implementing temperature and ventilation setbacks based on occupancy signals from the lighting controls. This scenario was titled "Lighting + HVAC Integration in a Code Compliant Building". The researchers modeled energy savings in EnergyPlus (USDOE's whole building simulation program) using weather data from Sacramento, California. The model resulted in annual savings of 27 percent of HVAC energy use for a total of 11 percent savings of whole building energy use. Project costs were determined using information collected from the field demonstration construction project. The team estimated total project cost, including materials and labor, at $5,474. This scenario has an estimated simple payback of 3.0 years.

### Scenario B

The second IBCS scenario consisted of adding building integration hardware and metalized film roller shades to an existing code compliant building and implementing seasonal shade control and temperature and ventilation setbacks both based on occupancy signals from the lighting controls. This scenario was titled "Lighting + HVAC + Shading Integration in a Code Compliant Building". The project team modeled energy savings in EnergyPlus using weather data from Sacramento, California and combined them with existing shading case studies. The analysis resulted in annual savings of 38 percent of the HVAC energy use for a total of 16 percent savings of whole building energy use. The researchers determined project costs using information collected from the field demonstration construction project. Total project cost including materials and labor were estimated at $47,099. This scenario has an estimated simple payback of 18.2 years.

### Scenario C

The third IBCS scenario consisted of adding building integration hardware and a lighting and lighting controls retrofit to an existing building and implementing temperature and ventilation setbacks based on occupancy signals from the lighting controls. This scenario is titled "Lighting + HVAC including Lighting Retrofit." The team modeled energy savings in EnergyPlus using weather data from Sacramento, California, combined with existing lighting case studies. This resulted in an annual savings of 27 percent of the HVAC energy use and 63 percent lighting energy use for a total of 37 percent savings of whole building energy use. The researchers determined project costs using information collected from the field demonstration construction project and RS Means (construction cost estimating software). Total project cost including materials and labor was estimated at $72,579. This scenario has an estimated simple payback of 12.3 years.

### Scenario D

The fourth IBCS scenario modeled consisted of adding building integration hardware, metalized film roller shades, and a lighting and lighting controls retrofit to an existing building and implementing seasonal shade control and temperature and ventilation setbacks both based on occupancy signals from the lighting controls. This scenario is titled "Lighting + HVAC + Shading Integration including Lighting Retrofit." The research team modeled energy savings in EnergyPlus using weather data from Sacramento, California and combined them with existing lighting case studies. This resulted in an annual savings of 38 percent of the HVAC energy usage and 63 percent lighting energy usage for a total of 41 percent savings of whole building energy usage. Project costs were determined using information collected from the field demonstration construction project and RS Means. Total project cost including materials and labor are estimated to be $114,203. This scenario has an estimated simple payback of 17.2 years.

## Nonenergy Benefits

Beyond the direct energy savings, the IBCS provides additional nonenergy benefits. These benefits focus on building safety and occupant satisfaction and well-being. While some of these benefits may come at additional energy cost, it is possible to moderate the impact of each individual aspect as needed by adjusting the IBCS algorithm.

### Building Safety

With the addition of smart sensors and controllers, building safety can be actively monitored. Monitoring the actuators for the windows removes the concern of unintentionally leaving windows open during building vacancy, while the ability to draw the shades obscures the building contents from view. These actions can strengthen building security. Additionally, it is possible to control the lights during after-hours to maintain a minimum lighting level if needed for advanced security options, such as video surveillance.

### Air Quality Management

Given the disastrous wildfires that California has experienced in the last few years, air quality is an important consideration for advanced control systems and has guided development of the natural ventilation algorithm to consider air quality. With the $CO_2$ sensors equipped inside and outside of the building and queries to weather API's, the IBCS can ensure that windows stay closed during bad air quality events. Beyond this, certain standards, such as the WELL Building certification standards, require that indoor $CO_2$ values remain under 800 ppm.

The IBCS algorithm has been taken a step further by also managing interior $CO_2$ levels. This management is achieved by using the building's central air handlers to mix air and bring in additional fresh air. If this action is not sufficient, the algorithm can also decide to open the windows if exterior weather conditions are right. $CO_2$ management is important for occupant well-being and productivity because it correlates with drowsiness, headaches, and nausea. The IBCS is well-suited to ensure that occupants are provided with fresh air.

## Lessons Learned

### Best Practices for Building Control System Logic

During this project, the CLTC identified several best practices for programming building control systems:

- Data reporting can be a programmatically expensive feature. Best practices are to keep the CPU usage of the controller to less than 80 percent. Monitoring of the busy time while determining the optimal reporting rates will be necessary.

- Control for a building system appliance should be as close to the appliance as possible, except for when the system can benefit from system integration. This means the system integrator controller should only be responsible for integration operations. Individual building system performance may be improved by moving programming closer to the devices where possible.
- Best practices for network security suggest keeping the BACnet IP network local and only exposing the necessary devices to the internet. Devices which are exposed to the internet must follow all appropriate network security protocols including, but not limited to, message encryption and user authentication as described in ASHRAE-132-2020.

## Potential Security Issues with Automated Windows

One significant energy-savings measure the IBCS enables is precooling the building by opening the windows at night. However, this can pose a security risk since it is likely to occur when the building is unoccupied. Three proposed strategies to address potential security concerns are to mechanically limit the stroke of the window, only enable venting on windows not accessible from the ground, or only vent the windows when the building is occupied.

## Additional Issues for Historic Buildings

Historic buildings such as The Barn pose an additional unique set of challenges for IBCS deployment. Examples include:

- Maintaining the building’s exterior historical aesthetic.
- Likely presence of hazardous materials that require abatement.
- Lack of drawings or inaccurate drawings.
- Mislabeled electrical circuit panel.
- Lack of high-quality retrofit lighting kits that maintain historic lighting form factors.

# CHAPTER 4:
# Technology Transfer

Successful technology transfer requires articulating the energy savings and nonenergy benefits associated with IBCS use. For instance, improved visual and thermal environments, controllability, and ease-of-use all add value. The overall technology transfer goal was to promote best practices for retrofitting commercial buildings with integrated building controls by demonstrating the value of both energy and nonenergy benefits. Tools that communicate these practices and better ensure continued product use include design guidelines and industry standards. This section provides an overview of the technology-transfer activities that have reinforced IBCS benefits and introduced new opportunities to improve the energy and overall performance of California's commercial buildings.

## Production Readiness

### Product Optimization

Throughout the course of this project, CLTC worked with companies across multiple markets. Through these interactions, CLTC helped make these companies aware of the requirements of building automation such as language protocols to ultimately advance the marketplace for integrated building control systems.

### Automated Window System

CLTC engaged with Winco Window, an automated window company, throughout the design, manufacture, and installation of the automated window system installed in The Barn. Prior to this project, Winco Window manufactured and installed a similar product in only one location. The novelty of the product and the unique historic aesthetic of The Barn presented a set of distinctive design criteria that were met through collaboration between CLTC and Winco Window.

The Barn is a designated historic building. As such, the building owners and operators communicated that maintaining its historic appearance was a critical design criterion. Specifically, the new automated windows needed to match the original window aesthetic as closely as possible while adding a second pane, internal roller shade, and an actuator. CLTC communicated this design criterion to Winco Window, who proposed a double pane, single casement window design with sash and muntin that closely matched with original windows. Additionally, these windows were designed to open via automated actuator from the same side hinge as the original windows opened with a hand crank. Furthermore, another design criterion designated by the building owners was the inclusion of screens to keep squirrels, insects and other unwanted material or debris from entering the building. This resulted in the development of a novel screen with a cutout for the actuator chain drive mechanism allowing the window to be opened while the screen remained in place. Ultimately, the proposed design satisfied all aesthetic requirement, maintained all required functionality for the research project and became a new product in Winco Window's portfolio.

Once the aesthetic and mechanical design of the windows had been approved, CLTC worked in conjunction with the electrical contractor and Winco Window to inform the routing of the shade motor wiring from inside the window casement to outside the frame where it could be connected to the building electrical system. Upon reviewing electrical schematics, the electrical contractor suggested that the control and power wiring for the internal shade motor be routed to the upper right corner of the frame such that the wiring could pass from the window frame, through the drywall and directly into the conduit.

**Figure 6: Electrical Wiring for the Internal Shade Motor**

**The electrical wiring for the internal shade motor was routed to the edge of the frame so that the wiring passed directly from the window to the conduit.**

Source: California Lighting Technology Center

CLTC communicated this design change to Winco Window, who implemented it appropriately resulting in a cleaner interior aesthetic and a simpler wiring layout. During laboratory testing, CLTC identified a potential safety issue with the automated windows. The sample window delivered to CLTC for laboratory evaluation had no controls in place to identify if an obstruction had entered the window's path during opening or closing. This could result in appendages getting stuck between the windowsill and the moving window presenting a pinch point hazard. Laboratory testing revealed that the actuator closed the window with enough force to cause or serious injury to any body part in the way. CLTC communicated this issue with Winco Window, who resolved the problem by implementing a pinch sensor around the entire window frame. When compressed, the pinch sensor sends a signal to the actuator causing it to fully open to relieve the pinch point. CLTC and Winco Window installed, tested, and verified the operation of this pinch sensor in the field.

### Electrochromic Glass

CLTC collaborated with a manufacturer of fast-tinting electrochromic glass technology, referred to as Manufacturer A. The response time and low transmissivity of the glass makes the product a prime candidate as a dynamic fenestration option for heat rejection. However, while working with the company, it was identified that their technology could only be integrated with RESTful API queries. While it is possible for such queries to be handled by the JACE 8000, the central controller used in the IBCS, it requires specific programming that has limited documentation. Instead, the common way to integrate with specialized devices is through Niagara drivers. Through the course of the project, CLTC provided pressure to expedite the delivery of such a product and encouraged the company to offer alternative communication protocols such as BACnet IP, a common protocol used in building control system integration. The primary reasoning for using BACnet IP is that it allows the windows to be controlled programmatically on a local level instead of relying on internet connectivity to cloud web-services. Beyond this, CLTC has made plans with Manufacturer A to help both partied better understand the features of the Niagara driver and provide feedback on improvements to the installation and integration process of their electrochromic glazing windows.

### Wireless Lighting Niagara Driver

CLTC collaborated with a wireless lighting control option, referred to as Manufacturer B. While working directly with the company to test their advanced lighting control system within the IBCS, we discussed potential integration options. Initially, it was believed that the system offered a BACnet IP integration option, especially since the wired controllers use Ethernet cabling for communication. However, upon investigation, CLTC identified that BACnet IP communication was not a supported protocol. Manufacturer B instead offered their typical integration option, RESTful APIs. Ultimately, this presented a difficult programming task for integration that would best be handled with a Niagara driver. Since lighting controls may need more frequent querying, especially for lighting and occupancy sensors, drivers can provide steady requests without overloading the API requests server of the lighting control system. CLTC recommended that Manufacturer B investigate BACnet IP integration and further recommended that they develop Niagara drivers to integrate with building control systems.

### Integration with Existing Building Design and Construction Pathways

CLTC collaborated with luminaire manufacturers and manufacturer representatives to broaden the product form factor offerings that met CLTC’s high-quality performance specification.

While retrofit kits that meet this standard exist for some common form factors such as 2′x4′ recessed troffers, CLTC found that some other common form factors such as 1′x4′ and 2′x2′ recessed troffers do not have existent retrofit kits that meet the standard. CLTC worked with industry partners to increase the range of form luminaire factors, including linear LED lamps.

## Other Technology Transfer Activities

CLTC leveraged multiple advocacy tools to make the knowledge gained, experimental results, and lessons learned from this effort available to the public and key decision makers. Advocacy tools include:

- Technical Advisory Committee.
- Outreach Portals and Materials.
- Education and Workforce Development.

## Technical Advisory Committee

The technical advisory committee (TAC) consisted of key stakeholders who are a cross section of professionals related to the research topic. Members of the TAC were from the following areas of expertise:

- Partners in manufacturing.
- Researchers in the same field as the research effort.
- Members of trades that will apply the results of the project.
- Product developers relevant to the project.
- Utility representatives.

The TAC's purpose was to guide and direct the research team. The research team leveraged the TAC's technical area expertise, knowledge of market applications, and links with industry to inform various stages of the research.

The research team hosted annual TAC meetings during which the team updated the TAC members on project progress and solicited their input on outstanding questions. Additionally, the research team reached out to individual TAC members to solicit input on specific questions and methods leveraged to execute the research.

## Outreach Portals and Materials

The research team used a variety of outreach portals and materials to inform key stakeholders and the public on how to participate in the research, gain public exposure, and accelerate adoption of resulting technologies and strategies. Outreach portals and materials include:

- Attending sustainability conferences to present findings of research efforts and incorporate new products into ongoing research.
- Website and newsletter announcements of findings.
- Tours at CLTC for key stakeholders and the public of research test areas.
- Publishing journal articles, press releases, and other documents on research findings on CLTC website (https://cltc.ucdavis.edu).
- Social media updates on project-related topics using Facebook, Twitter, and LinkedIn platforms.

## Education and Workforce Development

CLTC developed education and workforce materials by writing research articles for lighting-industry publications and developing curriculum for lighting fundamentals courses. Efforts included:

- Contributing content to the Illuminating Engineering Society's industry publication, *LD+A Magazine*, in the Research column.

- Providing lighting educational courses for investor-owned utility partners and energy-efficiency associations. Curriculum for the courses includes information about ongoing research from this effort.
- Develop and publish *Daylight Harvesting for Commercial Buildings* Guide highlighting daylight management and integrated building control systems in tandem with the Building Energy Efficiency Standards (Title 24, Part 6).

# CHAPTER 5: Conclusions and Recommendations

Overall, the field deployment and building energy modeling outcomes in this project supported the project goals and objectives to develop new technologies and system integration strategies that improve building system performance while saving energy.

## Conclusions

Field deployment and evaluation results verified system design, procurement, installation, and commissioning under real-world conditions for the new technology at scale. The project showed that the IBCS can reduce HVAC, lighting, and shading loads by 10 percent to 40 percent compared to typical baseline systems depending on building application, size, location, geometry, and climate zone. Estimated electricity savings translate to cost savings of $7.9 million to $31.6 million annually if there is a one percent adoption rate throughout California’s commercial buildings.[7]

For the selected demonstration site, analysis showed that basic integration of HVAC and lighting systems using occupancy-based control is relatively inexpensive and expected to result in simple payback periods of less than three years. The addition of integrated shading and operable fenestration can significantly reduce peak demand associated with cooling loads and was shown to reduce annual energy use by up to 30 percent depending on conditions and climate zone.

Based on this range of energy savings, estimated statewide emission reductions associated with a one percent adoption rate of IBCS in California’s commercial buildings range from 35,687 to 142,748 metric tons of carbon dioxide equivalent annually. This is equivalent to removing 7,710 to 30,840 typical gasoline-fueled passenger vehicles (as defined by the U.S. Environmental Protection Agency) from California roads each year.

Additionally, peak demand reductions ranged from less than 5 percent for lighting and HVAC systems integration to as much as 15 percent for an IBCS incorporating natural ventilation and building precooling.

Nonenergy benefits of the IBCS for California ratepayers include improved building performance and amenity; improved air quality management; and improved building safety features.

The project team worked closely with multiple fenestration and lighting control manufacturers to refine their products for inclusion in the field deployment. These new products are commercially available and ready for use in today’s integrated building control systems by system designers, installers, system integrators. Outcomes from this project set the

---

[7] In 2013, the California Energy Commission’s demand forecast model estimated that commercial buildings in California use approximately 50,474 GWh annually for heating, ventilation, cooling, and indoor lighting end uses.

groundwork for additional research that, if successful, may support the adoption of more aggressive energy standards related to integrated building control systems.

## Future Research Recommendations

Multiple strategies were analyzed during CLTC's implementation of the IBCS, but there are additional strategies that could yield additional energy savings. These strategies are prime candidates for future research.

### Long-Term Energy Monitoring of the Pilot-Scale Deployment

During this project, CLTC developed a test protocol for a year-long monitoring and verification plan for the pilot-scale deployment. Due to project delays and substantial occupancy changes in the test building caused by the COVID-19 pandemic, the research team could not perform this plan.

Continued monitoring of the IBCS in-situ will enable validation of the performance of the IBCS compared to its expected performance. Validation will provide a firmer basis for adoption of this technology in the commercial building space, which will in turn aid in the reduction of energy usage in the commercial sector in California.

As the demonstration site is already instrumented for the necessary monitoring and verification activities, this monitoring and validation will be straightforward once building occupancy has returned to a typical occupancy pattern.

### Automated Demand Response Integration

Automated demand response is a readily available technology that could be easily integrated to control the IBCS in a way that reduces building energy use during peak energy levels on the electricity grid. Not only does this reduce the total energy usage of the building, it also does so during peak energy prices which would provide additional economic savings. As with so many other aspects of the IBCS, one critical advantage is that energy savings can be found by curtailing multiple energy loads interconnected by the IBCS. This includes plug loads, lighting, and HVAC.

### Occupancy-Based Optimization of Ventilation

Traditionally, building ventilation ensures that the number of fresh-air change overs will be adequate for a worst-case occupancy rate. Integrating an occupancy sensor from the lighting system into the HVAC system can safely reduce the level of ventilation during vacancy periods. This has potential for significant energy savings, as ventilation accounts for 16 percent of energy usage in U.S. commercial buildings.

### Load Shifting

Load shifting is an important topic when discussing energy grid stability. While load shifting strategies do not necessarily save energy, they do provide the benefit of reducing energy costs by limiting energy usage during times of peak energy prices and limit the total peak load on the energy grid. One implementation of this strategy involves running the HVAC before the expected peak energy demand to precool the building so the HVAC is used less during the energy peaks. Beyond this, thermal rejection methods, such as dynamic shading, can also be used to decrease the expected thermal load on the building during energy peaks.

## Variable Air Volume and Actuated Heating, Ventilation, and Air Conditioning Dampers

Often the HVAC for a building has one or two setting levels to control how much heating and cooling it provides for a building, and heating and cooling is dispersed across the entire HVAC zone. One potential drawback of this implementation is that the HVAC is unaware of which parts of its zone need temperature control. In buildings with private offices, it is possible to restrict air flow to the unoccupied offices to potentially limit the thermal load of the HVAC. This restriction would require adding additional hardware and sensors to the HVAC system, which may make it difficult in retrofit scenarios, but it provides the opportunity to focus HVAC output where it is needed. This strategy would also allow for more personalized occupant control since they could limit the amount of air flow into their office area, which would increase occupant comfort while decreasing the thermal load on the HVAC.

## Advanced Security Integration

While the IBCS can inherently provide some important first levels of security, such as ensuring windows are closed and minimum illumination levels are met during the night for surveillance, it is possible to expand the security features by integrating with commercially available security systems.

## Mobile Integration

As mobile devices become ever-present in modern life, options for integrating with them continue to expand. With this integration, building managers could quickly see the status of any integrated building with a user-friendly app on their phone. Moreover, as additional control systems become integrated, occupants will have more override options to personalize their workspace to their liking. Instead of investing in additional wall switches and other hardware, occupants could instead define room wide personalized user-overrides programmable from their phones.

## Venting Skylights Pilot Study

The inclusion of motorized skylights in an IBCS has the potential to increase the energy savings associated with natural ventilation. This is due to the ability to increase the area affected by natural ventilation by providing additional paths for airflow. The energy savings of such a strategy should be evaluated in a pilot-scale application to determine the actual savings from this application.

## Work with Industry to Identify Cost Reductions of Integrated Building Control System

While the installation of an IBCS enables significant savings in terms of energy usage, the widespread adoption of integrated building control systems in retrofit applications is currently cost-limited. Studies indicate that the cost of a technology typically reduces as a function of increased market penetration. This is likely due to a combination of factors including installer familiarity, as well as technological and manufacturing process maturity.

To aid the adoption of the IBCS, the CLTC proposes additional studies focused on the installation of individual systems, especially dynamic fenestration systems, in retrofit applications. This will enable the identification of the factors that may be controlled to enable cost-effective deployment of IBCS systems.

# CHAPTER 6:
# Benefits to California Ratepayers

Project outcomes led to validation of technologies and strategies capable of increasing ratepayer benefits such as greater electricity reliability and reduced electricity costs, while also providing nonenergy benefits to California ratepayers.

## Energy Benefits

California ratepayers that adopt this technology can expect to save an estimated 10 percent to 40 percent in their building energy use. These savings are achieved through the integrated control of the addressable devices that contribute to electricity loads in a typical commercial building, with most of these savings attributed to the integration and optimization of lighting and HVAC systems. Estimated electricity savings will translate directly to cost savings of $7.9 million to $31.6 million annually if there is a one percent adoption rate throughout California's commercial buildings.

This project demonstrated comprehensive, optimized, integrated control of multiple building devices using commercially available technology available at 19 percent lower cost than traditional solutions used for integrated building control. For example, in a 5,744 square foot building that is compliant with today's building code, the project costs using the traditional method would cost about $428,000. The IBCS control strategy developed in the project cost about $360,000. When combined with the average 27 percent energy savings associated with this integration approach, California ratepayers can expect a simple payback of three years. For the same 5,744 square foot building, the greenhouse gas emission reductions associated with the annual energy savings range from 7.2 to 26.1 metric tons of carbon dioxide equivalent.

Estimated statewide emission reductions associated with a one percent adoption rate of this technology in California's commercial buildings range from 35,687 to 142,748 metric tons of carbon dioxide equivalent annually.

## Nonenergy Benefits

Nonenergy benefits of the IBCS for California ratepayers include improvements in building performance, air quality management, and building safety features.

Beyond the automated performance improvements to the building, increased amenities from adding addressable devices provided users with more granularity when manually controlling their lighting and fenestration systems. The increased granularity provided users complete control of each system if needed to fit their own personal comfort. Updated fenestration systems also resulted in improved building safety in two ways:

1. Window status monitoring via the window actuators input into the building control system.
2. IBCS algorithm allows shades to be drawn on a schedule to obscure the view of the inside of the building when vacant.

Improved air quality management is also due to implementing additional monitoring devices that are part of the IBCS, including installation of a local weather sensing station to detect real-time weather occurrences, connecting to a regional weather service to understand predicted weather patterns and installation of local indoor and outdoor carbon dioxide sensors.

# LIST OF ACRONYMS

| Term | Definition |
|---|---|
| AC | Alternating Current |
| ANSI | American National Standards Institute |
| API | Application Programming Interface |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| BACnet IP | Building Automation and Control Network Internet Protocol |
| BMS | Building Management System |
| CAT5 | Category 5 Cable |
| CLTC | California Lighting Technology Center |
| CO2 | Carbon Dioxide |
| COVID-19 | Coronavirus Disease 2019 |
| CPU | Central Processing Unit |
| DC | Direct Current |
| EPIC | Electric Program Investment Charge Program |
| US DOE | United States Department of Energy |
| HVAC | Heating, Ventilation, and Air-Conditioning |
| I/O | Input/Output |
| IBCS | Integrated Building Control System |
| JACE | Java Application Control Engine |
| LED | Light-emitting Diode |
| LD+A | Lighting Design and Application Magazine of the Illuminating Engineering Society |
| Mbps | Megabits per second |
| MS/TP | Master-Slave/Token Passing |
| RESTful | Representational State Transfer Protocol |
| RF | Radio Frequency |
| SARS-COV2 | Severe acute respiratory syndrome coronavirus 2 |
| SHGC | Solar Heat Gain Coefficient |
| TAC | Technical Advisory Committee |

| Term | Definition |
|---|---|
| UC Davis | University of California – Davis campus |
| VLT | Visible Light Transmission |
| WELL | WELL Building Standard that measures, certifies, and monitors features of the built environment that impact human health and well-being |

# REFERENCES

Williams, Allison, Barbara Atkinson, Karina Garbesi, and Francis Rubinstein. 2011. A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings. https://eta.lbl.gov/sites/default/files/publications/a_meta-analysis_of_energy_savings_from_lighting_controls_in_commercial_buildings_lbnl-5095e.pdf. Lawrence Berkeley National Laboratory

Lee, Eleanor, and Stephen Selkowitz. 1997. Design and Performance of an Integrated Lighting Envelope/Lighting System. https://eta-publications.lbl.gov/sites/default/files/39729.pdf. Lawrence Berkeley National Laboratory

Iddon, Christopher, and Nikhil ParasuRaman. 2015. Nightly Purge as a Means to Reduce Cooling Load in an Office in Pune, India. http://www.ibpsa.org/proceedings/BS2015/p2323.pdf. Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015

For further information on Appendices, please contact Virginia Lew at Virginia.Lew@energy.ca.gov.