Laboratory Evaluation of a Commercial, Whole-Building, Integrated Control System

Final Report

ET22SWE0044

Prepared by:

Keith Graeber, CLTC

Andrew Harper, CLTC

Jonathan Bryant, CLTC

Andrew Norman, CLTC

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Disclaimer

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Abbreviations and Acronyms

Acronym	Meaning
API	Application Programming Interface
BACnet	Building Automation and Control Network
BAS	Building Automation System
CDD	Cooling Degree Day
CLTC	California Lighting and Technology Center
CO_2	Carbon Dioxide
DAC	Disadvantaged Communities
EE	Energy Efficiency
ET	Emerging Technology
F	Fahrenheit
FC	Foot-candle(s)
GHG	Greenhouse Gas
HP	Heat Pump
HTR	Hard-to-Reach
HVAC	Heating, Ventilation, and Air Conditioning
I/O	Input/Output
IP	Internet Protocol
IOU	Investor-Owned Utility
JACE	Java Application Control Engine
kW	Kilowatt
kWh	Kilowatt-hour
m	Minute
mph	Miles Per Hour
MS/TP	Master-Slave Token Passing Protocol
M&V	Measurement and Verification
PA	Program Administrator
PG&E	Pacific Gas & Electric
RF	Radio Frequency
RH	Relative Humidity
s	Second
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TPM	Technology Priority Map

UCD	University of California Davis
W	Watt
WH	Water Heating
g	Gram
Ton	Imperial ton
Kg	Kilogram
wH	Watt hour
ft	Foot
CT	Current transformer

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Executive Summary

The *Laboratory Evaluation of a Commercial, Whole-Building, Integrated Control System* project aims to quantify the incremental benefits of integrating and sharing information among building subsystems such as lighting, HVAC, dynamic fenestration, and plug loads under a central building automation system (BAS). The performance of one subsystem often influences others—lighting can increase the building's thermal load, while shading systems can reduce both cooling and lighting needs. When each subsystem communicates performance metrics with others, the building's overall performance can be improved, resulting in greater energy savings and occupant satisfaction, relative to buildings with systems operating in isolation.

The project's primary objectives are:

- **Cost-Effectiveness and Incremental Energy Efficiency Analysis**: Assess the cost effectiveness of each integration strategy by comparing its energy use to the energy use of the baseline system.
- **Demand Flexibility and GHG Reduction**: Evaluate each integration strategy to determine its load reduction potential, overall load flexibility under normal operating conditions, and impacts on greenhouse gas emissions (GHGs).
- **Evaluate Occupant Comfort and Acceptance**: Document occupant comfort and acceptance through periodic surveys and ongoing feedback on message boards.

In this project, the research team equipped an existing building at UC Davis, referred to as the Barn, with networked building controls, a wi-fi-enabled heat pump hot water heater, and plug load controllers. The team devised seven integrated control strategies involving the cross-communication of two or more building subsystems and tested them over a one-year period. All seven integration strategies were tested and five showed significant energy savings, ranging from five to 35 percent. Each control strategy, except for precooling, was tested during both the heating and cooling seasons to evaluate performance under various operating conditions. The test duration for each strategy depended on several factors, including weather variability, occupancy patterns, and data quality. Figure 1 provides a visual representation of the total run-time in workdays for each strategy, highlighting the differences in test duration based on these factors.

Integration of electric lighting and shading subsystems resulted in an annual reduction of 5.4 percent compared with the baseline (Figure 2). During the cooling season, the window shades were closed when sunlight was incident on the windows, either in the morning or afternoon, depending on the building facade (east or west). This strategy reduced the solar heat gain, which lowered cooling demand, though it required more electric lighting. In contrast, during the heating season, the shades were opened when sunlight was incident to allow solar heat gain to warm the space and natural daylight to offset electric lighting use.

The integration of lighting and HVAC systems yielded energy savings of 15.9 percent. Cooling and heating setpoints were raised based on occupancy data received from the lighting system, allowing the HVAC to operate more efficiently during vacant periods. This strategy was most effective in spaces with fluctuating occupancy patterns.

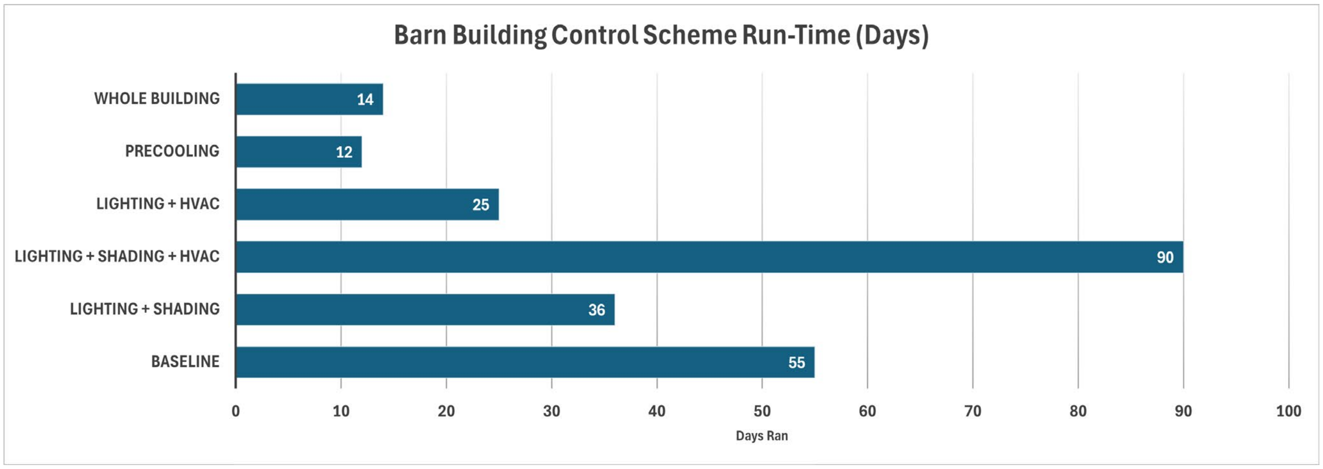


Figure 1. Testing duration for each integration strategy.

Source: CLTC

A precooling strategy, which utilized outdoor air to cool the building before occupancy, resulted in 8.7 percent energy savings. By delaying mechanical cooling for several hours, this approach significantly reduced HVAC energy use during peak mid-day cooling periods.

The most substantial savings came from the whole-building integration strategy, which combined lighting, shading, HVAC, and water heating and plug loads. This fully integrated approach achieved a 35.1 percent reduction in annual energy consumption, highlighting the benefits of coordinating multiple building systems, using shared environmental and operational data under a central control system. The integration of lighting, shading, and HVAC systems together also showed notable savings of 23.4 percent, largely due to optimized control of shading and HVAC systems, which reduced cooling demand and improved overall building energy efficiency.

The research team also implemented occupancy-based plug load control within select office spaces to assess both the technical feasibility of the integration and its potential energy savings. The goal was to reduce vampiric or redundant receptacle loads by controlling devices such as air purifiers and personal heaters using occupancy signals from the lighting system. Through this project, the team successfully verified that integrating the plug load controller with the lighting system, leveraging shared occupancy data, was technically feasible. However, the study revealed that occupants were not comfortable turning off most receptacle-based loads, and the devices they did agree to have switched off when they left the room were not significant energy users. For example, devices like monitors and personal workstations typically feature auto-off or sleep mode functions, limiting their savings potential as controllable plug loads.

Nevertheless, devices such as electric scooter chargers and other charging devices, while not significant for direct energy savings, still present an opportunity for demand shifting. By controlling these loads to operate during off-peak hours or when demand flexibility is needed, there is potential to contribute to grid management goals. Thus, while these loads may not reduce overall energy consumption, they can still be valuable in achieving demand flexibility, a key objective of this project.

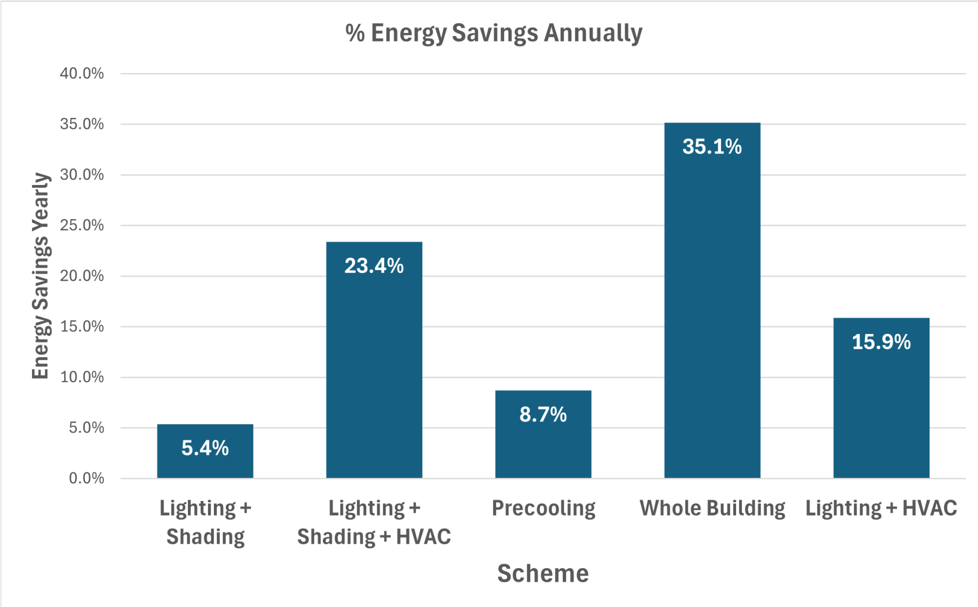


Figure 2. Energy savings for each integration strategy.

Source: CLTC

As a result, while the integration itself was validated, significant energy savings were not demonstrated in The Barn due to the nature of the controllable loads. That said, this plug load control strategy could offer greater savings in buildings with more suitable loads, such as space heaters or air purifiers, where occupancy-based control would have a more meaningful impact on energy consumption.

Finally, the integration of the lighting and smart water heater systems focused on adjusting the heat pump water heater's operation based on occupancy, with the goal of reducing energy consumption. Before integration, the baseline water heater consumption averaged 0.37 kWh per day. Following the integration, the average consumption slightly increased to 0.47 kWh per day, suggesting that the low demand for hot water in the building limited the potential for energy savings. The water heater primarily served bathroom sinks and one central kitchen sink, and, as a result, the building's low hot water demand offered little opportunity for significant savings.

While the water heater's operation was shifted to align with occupied hours, allowing it to cool down overnight or during unoccupied periods may reduce its efficiency. The energy required to reheat the water may offset any potential savings from the integration. It is important to consider hot water demand when evaluating smart water heater integration in commercial buildings. For buildings with higher or more consistent demand—such as gyms, hotels, or restaurants—a controllable smart water heater could offer more significant energy savings. In such settings, strategies like preheating during off-peak hours could be used for load shifting and demand reduction, improving overall energy efficiency while reducing peak demand.

Introduction

The 'Laboratory Evaluation of a Commercial, Whole-Building, Integrated Control System' project assessed the overall energy savings achieved by integrating various building subsystems into a centralized building automation system (BAS), using a custom algorithm to optimize their control. These algorithms were designed to optimize each system's performance in terms of energy efficiency and occupant comfort by considering all relevant control parameters from each subsystem that influence the performance of other building systems.

The research team devised and deployed seven distinct integration strategies that involved cross-integration of two or more building systems. To evaluate the effectiveness of each strategy, the team collected data from a measurement and verification (M&V) system installed in parallel with the control system’s sensors. The collected M&V data during each control strategy was used to estimate total energy consumption, which was then compared to a baseline scenario where each building system operated independently, without any cross-integration or data sharing. This comparison provided insights into the incremental energy savings attributable to each integration strategy.

Test Bed

The test bed, referred to as The Barn, is a two story, wood frame building located at 501 Engineering Bikeway, Davis, California at the University of California – Davis main campus (Figure 3).

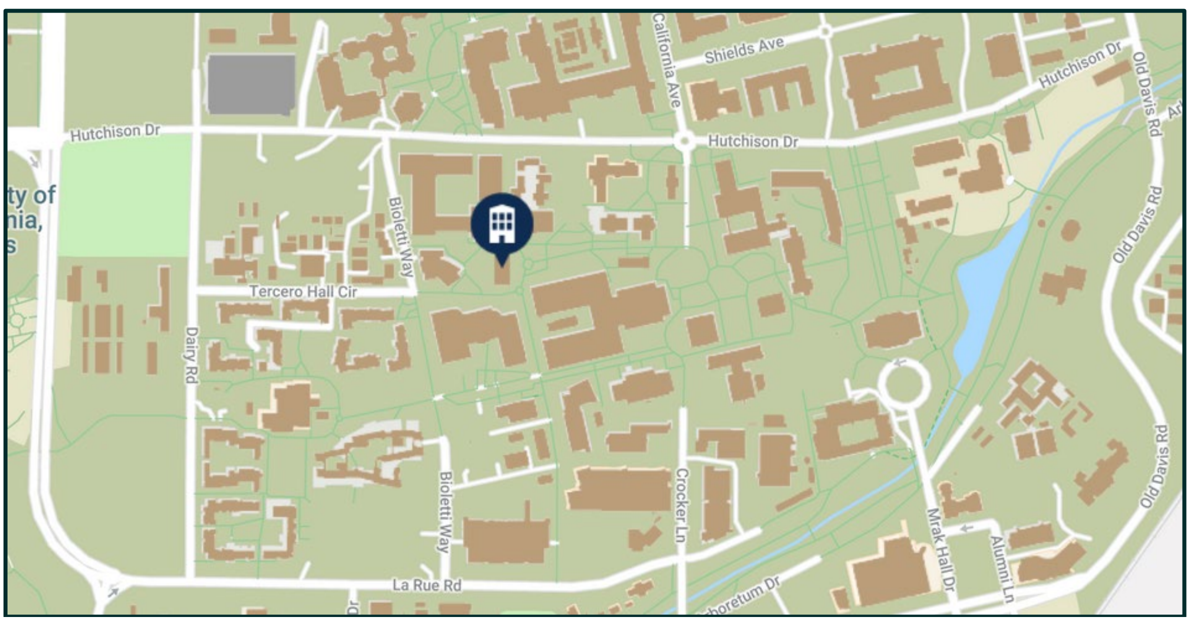


Figure 3. Location of the test site on the UCD main campus.
Source: UC Davis

The Barn (Figure 4), was constructed in 1914 and originally served as a cattle barn. In 1968, the Barn was remodeled to serve as office space for the UC Davis Architects and Engineers (A&E), while preserving the barn aesthetic. A&E moved to a new location in 2004, leaving the Barn empty until 2014, when the UC Davis John Muir Institute of the Environment assumed occupancy. Since then, the research team has been using The Barn as an on-campus laboratory evaluation space for multiple studies and the development of building control technologies, with the cooperation of the Institute of the Environment. The Barn has integrated into our research activities, effectively functioning as an extension of our lab, providing the necessary infrastructure and environment for implementing and assessing building control systems. Equipped with measurement and verification (M&V) equipment, The Barn allows the team to manage and control all metrics required for evaluating specific control strategies, without outside influence. The support from the Institute's staff has further ensured a controlled environment. This cooperative effort has made The Barn an ideal space for testing and refining control methodologies, bridging the gap between a formal laboratory setting and a practical demonstration environment.

Figure 4. The north façade of the John Muir Institute of the Environment. The building is also called "The Barn".
Source: CLTC

The test space is 2,068 square feet and consists of 13 private office spaces on the east and west sides of the building's first floor. Six offices are located along the building's west façade and the remaining seven along its east façade (Figure 5).

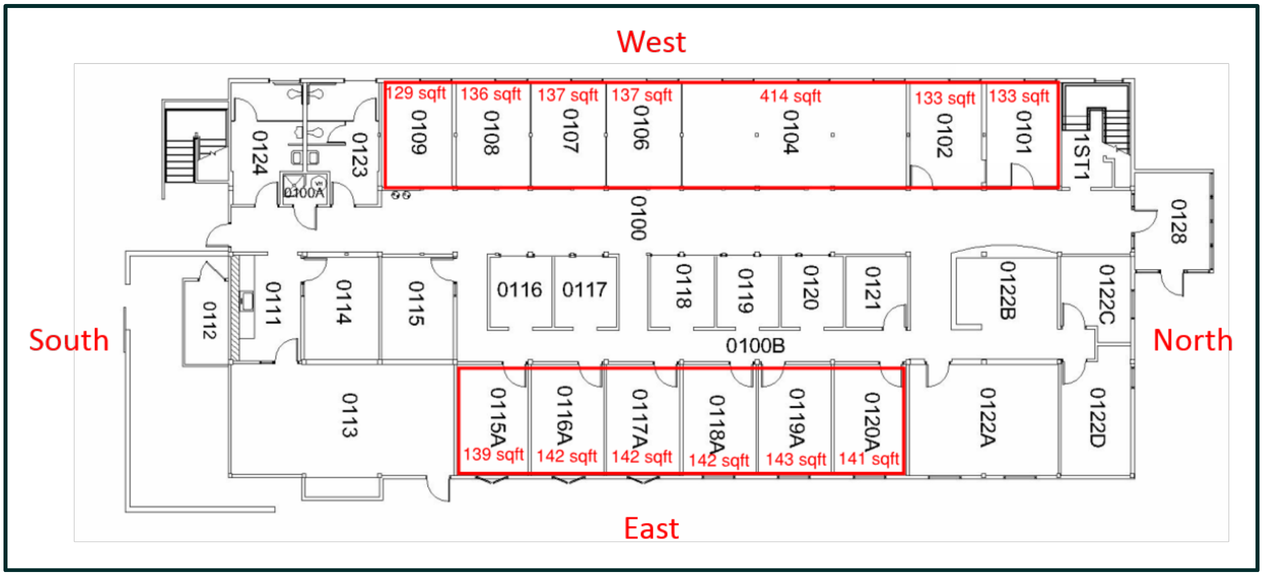


Figure 5. First-floor building plan identifying the test area.
Source: CLTC

Building Systems

The primary goal of a whole-building integrated control system is to use data from all connected building subsystems to inform and optimize the control of each system individually, while ensuring that their interactions enhance overall building energy performance and occupant comfort. This cross-system integration is essential, as the operation of one building system can directly influence the performance of others. Permitting was not required to implement these control strategies at The Barn because the retrofit primarily involved integrating additional networked control systems with the existing Building Automation System. The original water heater was replaced with a networked heat pump water heater by campus facilities, who handled all necessary permitting and ensured compliance with relevant regulations. There were no permits required for the research team. There were no additional structural or electrical modifications that would require regulatory oversight. Since The Barn already had a functional BAS, the adjustments focused solely on optimizing the operation of existing subsystems.

To achieve this, the building was retrofitted with networked control systems (Figure 6). These systems were integrated with the BAS using BACnet IP and MS/TP protocols or web-based application programming interfaces (API). The BAS serves as the central integrator, housing the control logic that coordinates the operation of all connected subsystems. It collects real-time data from each subsystem to determine the appropriate operating mode for each system.

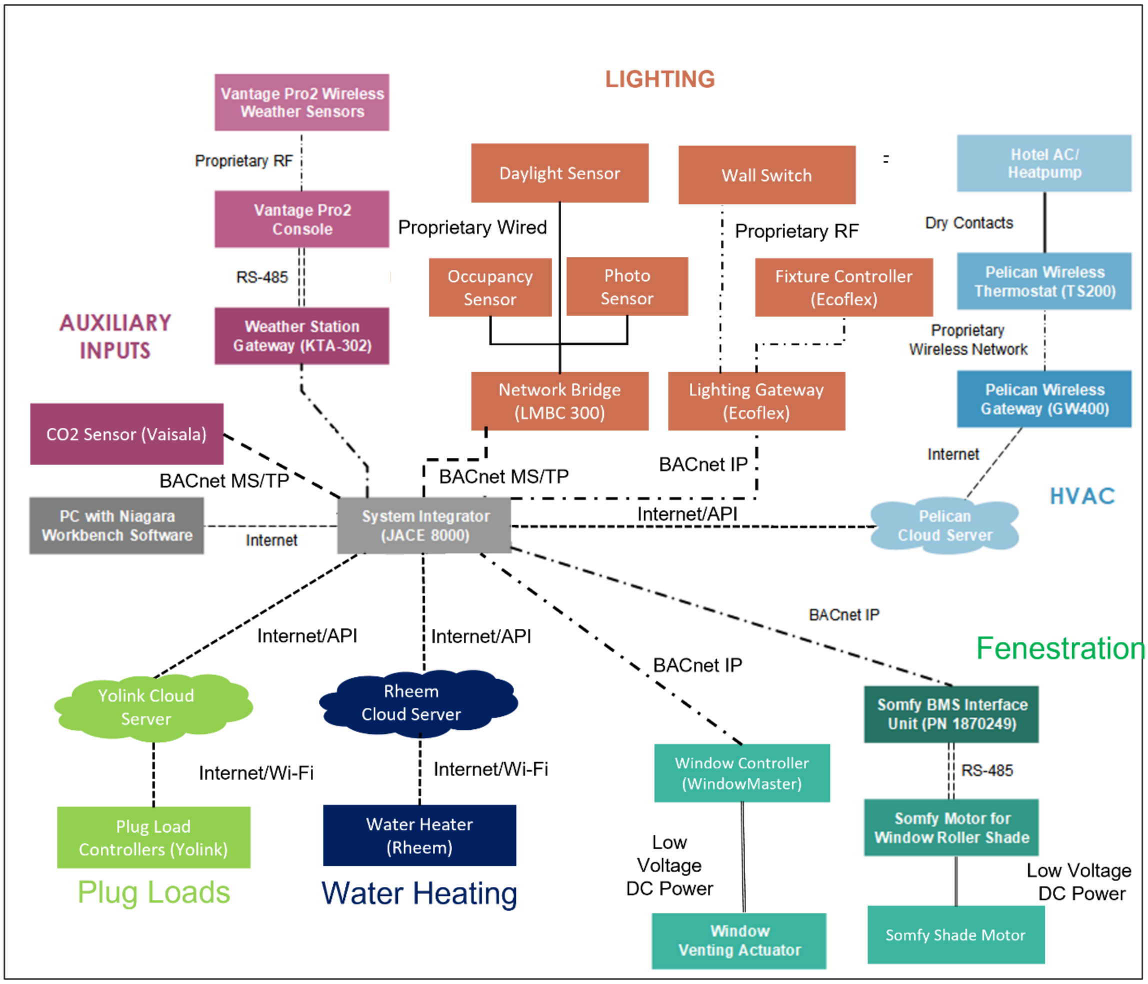


Figure 6. The Barn's control system network diagram.
Source: CLTC

Lighting

The Barn's lighting system consists of 0-10V dimmable tubular LEDs (TLEDs) installed in existing linear fluorescent fixtures, controlled by a networked lighting control system integrated with the BAS. This control system uses a hybrid wired/wireless setup. In each room within the test bed, photosensors and occupancy sensors measure light levels and occupancy, transmitting the data to a network bridge, which then relays it to the BAS via the BACnet MS/TP. The BAS uses this information to determine the appropriate lighting operation and sends control commands to the lighting gateway using BACnet IP (Figure 7). The gateway, in turn, wirelessly sends signals to a controller in each luminaire.

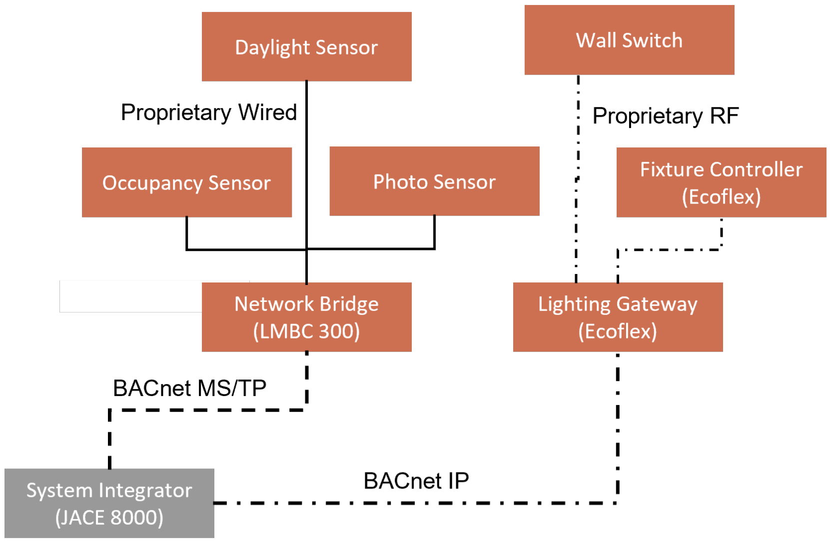


Figure 7. The Barn's hybrid lighting system architecture.
Source: CLTC

Manual adjustments can be made through a wall switch that also communicates with the lighting gateway. The test space includes 60 luminaires with a maximum nominal power of 1,488 Watts (W) (Table 1).

Table 1. Lighting System Components Installed at the Test Site

Luminaire Type	Luminaire Power (W)	Luminaire Quantity	Total Power (W)
2' TLED	17	24	408
4' TLED	30	36	1,080

Source: CLTC

Windows and Shades

The motorized, double-pane casement windows at the test site feature internal motorized shades and are equipped with actuators for automated venting and shade control. Both the window actuators and shade motors are individually addressable via BACnet MS/TP or IP, enabling direct control of each unit (Figure 8). The actuated window operation enables automated natural ventilation and precooling, helping to reduce HVAC loads. The motorized shades are designed to regulate solar radiation, effectively managing both solar heat gain and daylight availability (Figure 9).

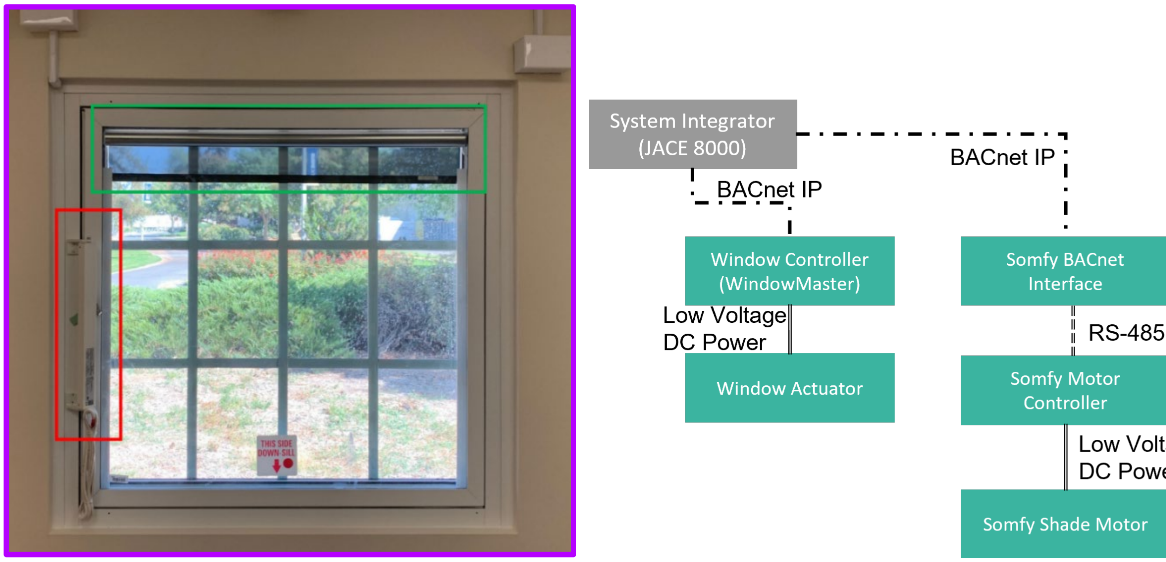


Figure 8. Casement windows feature an internal, motorized, metal shade and an actuator for automated operation (left) and system diagram (right).
Source: CLTC

HVAC

The test bed consists of two distinct HVAC zones, each controlled by its own unit, with internet-enabled thermostats and gateways directly integrated into the BAS. The thermostats manage fan and temperature settings and come with a web-based user interface for scheduling and system management. They are also controllable via an API, allowing the BAS to communicate directly with the devices (Figure 10). The gateways ensure seamless communication between the thermostats and the web server, enabling efficient HVAC operation in response to control system commands, occupant overrides, and external conditions. The two HVAC zones, referred to as the East Zone and the West Zone, are controlled by separate thermostats. The East Zone is conditioned by an electric heat pump with a nominal power rating of 2.4 kW, while the West Zone uses a gas furnace paired with a traditional split-system air conditioner rated at 6.4 kW. The East Zone thermostat is located in room 0119A, and the West Zone thermostat is positioned in the hallway outside room 0104 (Figure 11).

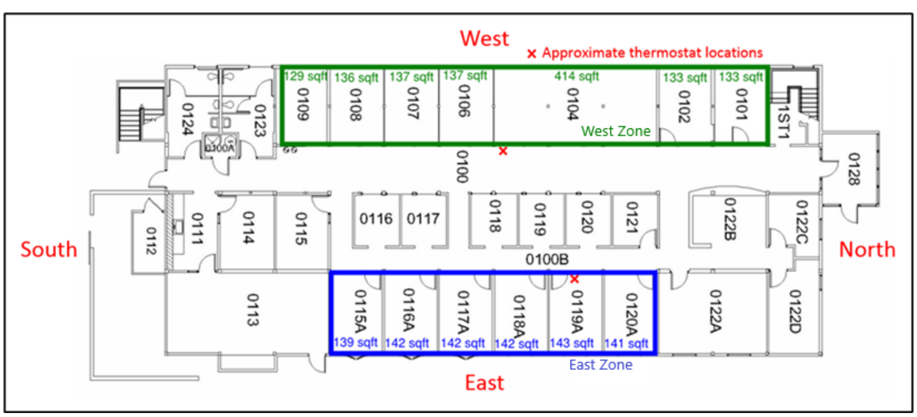


Figure 9. HVAC zones and thermostat locations.
Source: CLTC

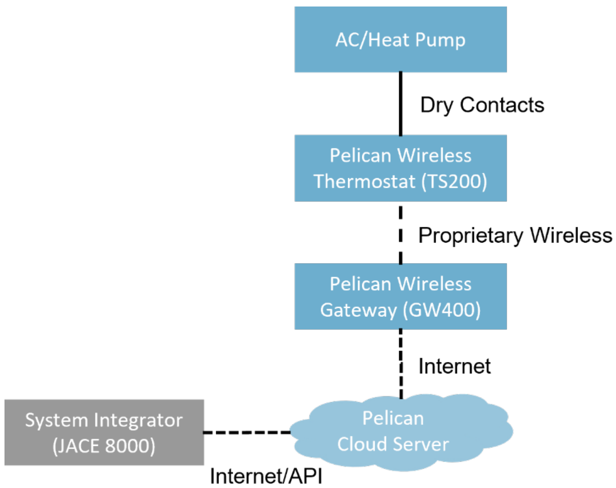


Figure 10. Web-enabled HVAC system architecture.
Source: CLTC

Heat Pump Hot Water Heater

As part of this project, the research team installed a new wifi-enabled heat pump water heater with resistive heating (Figure 12). This unit provides a more energy-efficient heating method. Relative to resistive heating by extracting heat from the surrounding environment. It is also controllable via a web-based API (Figure 12), allowing integration with the BAS for automated operation.

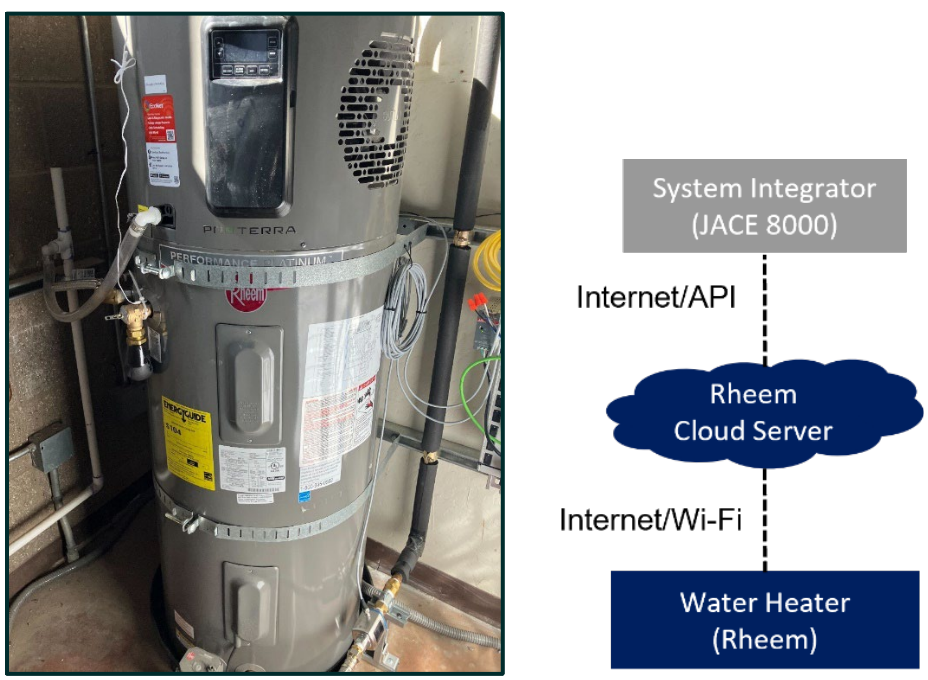


Figure 11. Rheem Wi-Fi -enabled heat pump water heater (left) and unit communication diagram (right).

Plug Load Controller

The research team equipped each office with one Wi-Fi enabled controllable receptacle (Figure 13). The Wi-Fi -enabled controllable receptacles allow for remote control of connected devices and include built-in energy consumption monitoring. These receptacles are accessible via a web-based API, which the BAS controller can poll for real-time data. Devices can be programmed to turn off or adjust during periods of room vacancy, demand response events, or when energy prices are high, helping to conserve energy and reduce operational costs.

Figure 12. Wi-Fii -enabled plug load controller from Yolink (left) and unit communication diagram (right).

Source: CLTC

Environmental Inputs

Real-time environmental data is required to make fully informed building control decisions. The test bed was equipped with two environmental data collection systems. The first system was a locally installed wireless weather station providing outdoor temperature, windspeed and rainfall data (Figure 14).

The second system, a collection of CO_2 sensors installed inside and outside the building, informs ventilation decisions based on carbon dioxide levels. All auxiliary sensors communicate back to the BAS via a BACnet MS/TP or IP network. Use of environmental sensors helps ensure the indoor environment remains healthy and conducive to productivity.

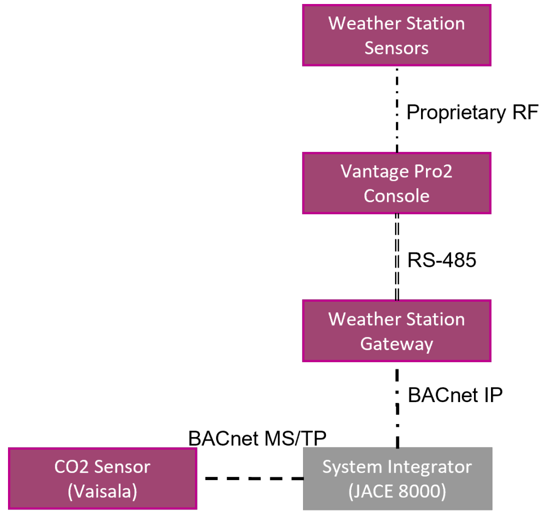


Figure 13. Weather Station Installed on The Barn (left) and BACnet-enabled, auxiliary sensor system diagram (right). Source: CLTC.

Integration/Networking Devices

The Integrated Building Control System architecture requires specific auxiliary integration and networking devices. Ethernet switches manage data traffic and facilitate BACnet IP communication, serving as the backbone for device communication within the building. BACnet bridges are pivotal in converting various building automation protocols into the BACnet standard, allowing devices with differing native communication protocols to interface with the central BAS. At the heart of the system is the BAS itself, which houses the control logic (Figure 18) used to automate subsystem operation.

Figure 14. JACE 8000 system integrator or BAS.

For this implementation of an integrated building control system, a JACE8000 was used as the BAS. It provides a robust development environment with various input/output (I/O) interfaces and the ability to natively support numerous communication protocols including BACnet. Custom control logic, hosted on the JACE8000, dictates the operational behavior of the building's systems by issuing commands to controllable devices based on programmed rulesets, environmental conditions, and device requirements.

Objectives

This project's primary objectives were threefold:

- **Cost-Effectiveness and Incremental Energy Efficiency Analysis:** Assess the cost effectiveness of each integration strategy by comparing energy use of the strategy to the baseline system energy consumption.
- **Demand Flexibility and GHG Reduction**: Evaluate each integration strategy to determine load reduction potential, load flexibility, and impacts on greenhouse gas emissions (GHGs).
- **Evaluate Occupant Comfort and Acceptance**: Gather insights into occupant comfort and acceptance through periodic surveys and ongoing feedback on message boards.

Methodology

The methodology for this project involved testing seven distinct control strategies, each designed to integrate two or more building systems with custom algorithms aimed at optimizing both occupant comfort and energy efficiency. As a reference point, the team established and monitored a baseline control strategy where each building system operated independently, without integration. In this baseline setup, systems like the HVAC used standard controls—such as the Pelican controller for scheduling and implementing "afterhours" and "weekend" setbacks—but did not share data with other systems, such as occupancy data from the lighting system.

The baseline and the seven control strategies were run throughout both the heating and cooling seasons (Figure 19), while metering energy consumption from lighting, HVAC, plug loads, and water heaters, as well as all the metrics detailed in the following M&V section.

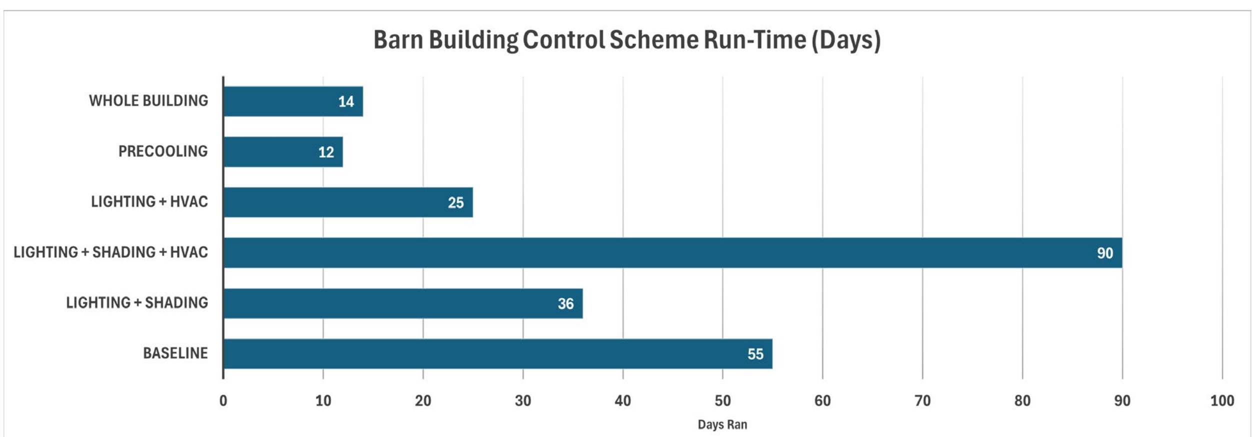


Figure 15. Testing duration for each integration strategy.

The energy consumption of each system was then normalized by the duration of occupancy, as occupancy patterns varied from week to week. Finally, annual energy consumption was projected for each strategy and the baseline, and the energy consumption of each strategy was compared to the baseline.

Control Strategies

Baseline

In the baseline control strategy for this project, each networked building control system operated independently, with no integration or data sharing between systems. The lighting system adjusts automatically to occupancy and daylight conditions using its built-in photosensors and occupancy sensors. The HVAC system follows a preset schedule configured through each thermostat's web interface, without responding to occupancy or input from other systems. Building shades and operable windows are manually controlled by push buttons, and controlled receptacles are operated manually by users, with no automated inputs from the building automation system (BAS) (Figure 20 & Table 2).

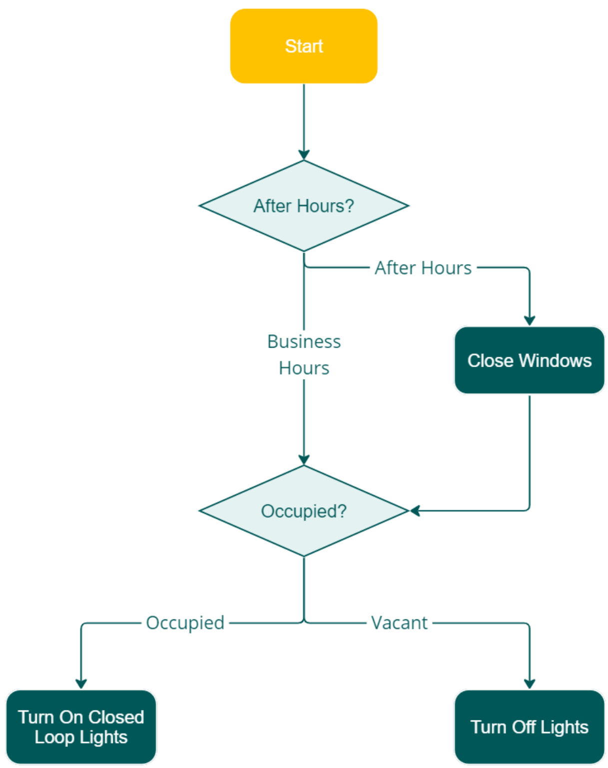


Figure 16. Flow diagram of the baseline control algorithm.
Source: CLTC

The research team ran the baseline control strategy for 55 days, equivalent to 11 weeks. During this period, all systems operated according to the baseline setup to establish a reference point for comparison with the integrated control strategies.

Table 2. Baseline Control Strategy Description

System	Control	Description
Lighting	Manual, Occupancy, Daylight Harvesting	Occupancy based lighting control and manual overrides. daylight harvesting
HVAC	Manual, Programmed Setback Schedule	Heating and cooling setbacks with manual overrides; after hours, weekend and holiday setbacks.
Shading	Manual	Manual control via wall switch.
Operable Windows	Manual	Manual control via wall switch, closed after hours.

Source: CLTC

Strategy 1: Lighting and HVAC

The lighting and HVAC integration strategy is intended to reduce HVAC energy consumption while maintaining a comfortable indoor environment. By leveraging the occupancy sensor from the lighting control system, this strategy enables real-time, occupancy-based, HVAC setback updates to reduce space conditioning loads (Figure 20 & Table 5).

When the rooms within an HVAC zone are occupied, the system first checks whether the thermostat settings have been manually overridden. If so, the HVAC system will operate according to these manual settings. Otherwise, the HVAC system will switch to 'comfort mode' with temperature setpoints of 75°F for cooling and 65°F for heating. These setpoints are the values that had been established by UC Davis' facilities department prior to The Barn's retrofit. When the room is vacant, the HVAC system enters an 'energy-saving mode'. In this mode, the cooling setpoint is raised to 80°F, and the heating setpoint is reduced to 60°F.

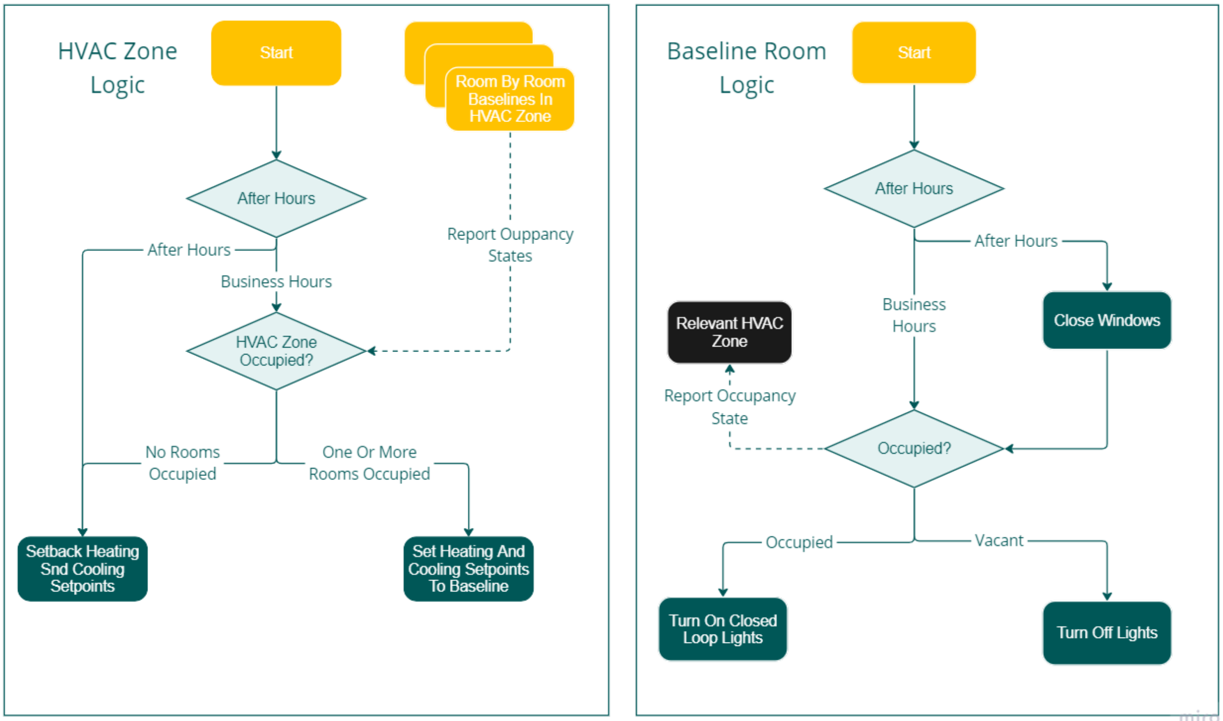


Figure 17. Flow diagram of the integrated lighting and HVAC control algorithm.
Source: CLTC

Table 3. Lighting and HVAC Control Strategy Description

System	Control	Description
Lighting	Manual, Occupancy and Daylight Harvesting	Controlled by occupancy sensors and daylight harvesting. Manual overrides via wall switch.
HVAC	Manual, Programmed Setback Schedule, Occupancy based Setbacks	Heating and cooling setbacks with manual overrides; after hours, weekend and holiday setbacks. Automatic setbacks based on occupancy sensors
Shading	Manual	Manual control via wall switch.
Operable Windows	Manual	Manual control via wall switch, closed after hours.

Source: CLTC

Strategy 2: Lighting and Shading

The lighting and shading strategy optimizes lighting conditions in the space while reducing electric lighting loads and managing solar heat gain. This control strategy operates by automatically opening the shades to take advantage of natural daylight as a substitute for electric lighting when occupants are present. Upon vacancy, the window shades close to minimize solar heat gain during the cooling season. During the heating season, the shades remain open to allow solar heat gain to help warm the space. Additionally, the lighting system is controlled by occupancy and daylight harvesting, with manual overrides available via wall switches for occupant comfort and flexibility.

The HVAC systems are configured with setbacks for heating and cooling, including after-hours, weekend, and holiday schedules, with manual overrides available for specific needs. The shading system is further controlled based on occupancy, the season, and the time of day, with manual control options via wall switches to allow user adjustments as needed. This overall approach aims to reduce energy consumption by minimizing reliance on electric lighting and mechanical space conditioning, responding dynamically to occupancy, available daylight, and seasonal conditions (Figure 22 & Table 4).

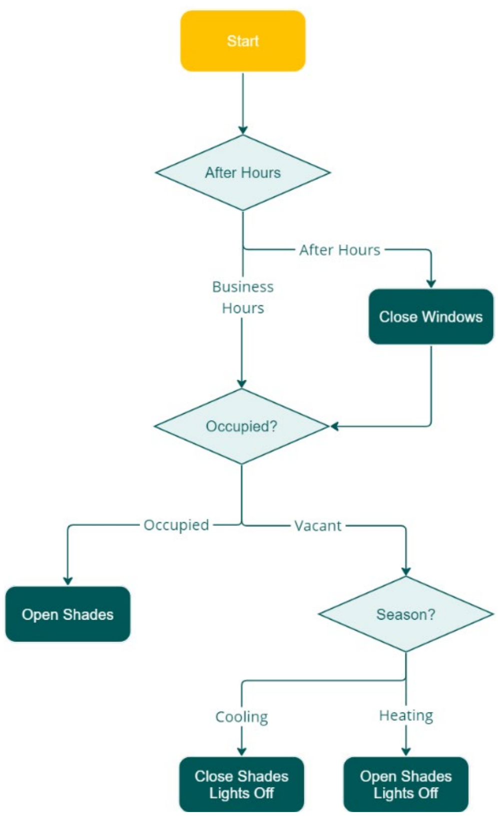


Figure 18. Flow diagram of the lighting and shading control algorithm.
Source: CLTC

Table 4. Lighting and Shading Control Strategy Description

System	Control	Description
Lighting	Manual, Occupancy and Daylight Harvesting	Controlled by occupancy and daylight harvesting. Manual overrides via wall switch.
HVAC	Manual, Setbacks	Heating and cooling setbacks with manual overrides; after hours, weekend and holiday setback schedules.
Shading	Manual, Schedule, Occupancy	Controlled by occupancy, season, and time of day. Manual control via wall switch.

Source: CLTC

Strategy 3: Lighting, Shading and HVAC

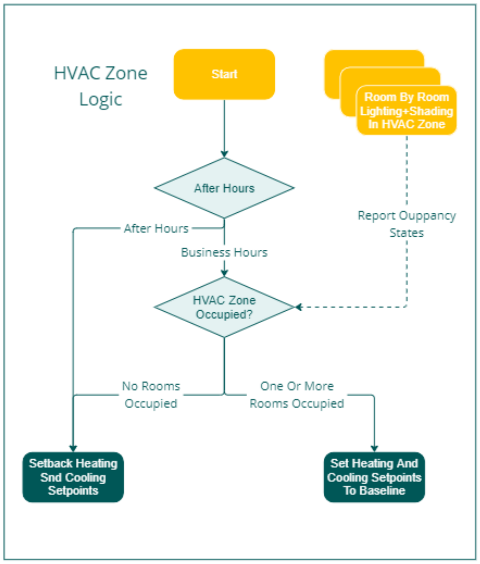
The third strategy coordinates lighting, shading, and HVAC control. The control logic evaluates real-time data related to occupancy, light conditions, and time-of-day parameters. This comprehensive strategy improves building energy efficiency while maintaining a comfortable indoor environment and accommodates user preferences via manual override switches. (Figure 23 & Table 5).

When a room is occupied, the BAS first checks for any manual overrides via the wall switches. If no overrides are detected, the system predicts whether sunlight is incident on the windows using the time of day and year to decide whether to open or close the shades.

During the cooling season, the shades are closed when sunlight is expected to hit the windows, reducing solar heat gain and lowering the cooling load. However, this may result in increased electric lighting use to maintain optimal light levels.

In contrast, during the heating season, the shades are opened when sunlight is present to allow for solar heat gain, helping to warm the space. This also provides natural daylight, reducing the need for electric lighting.

When a room is unoccupied, the BAS activates several energy-saving strategies. The HVAC system switches to an energy-saving mode by adjusting the temperature setpoints to 80°F for cooling and 60°F for heating, enabling the conservation of energy without compromising long-term occupant comfort. The shades are closed during the cooling season to minimize solar heat gain or opened during the heating season to maximize it. Additionally, electric lights are turned off.



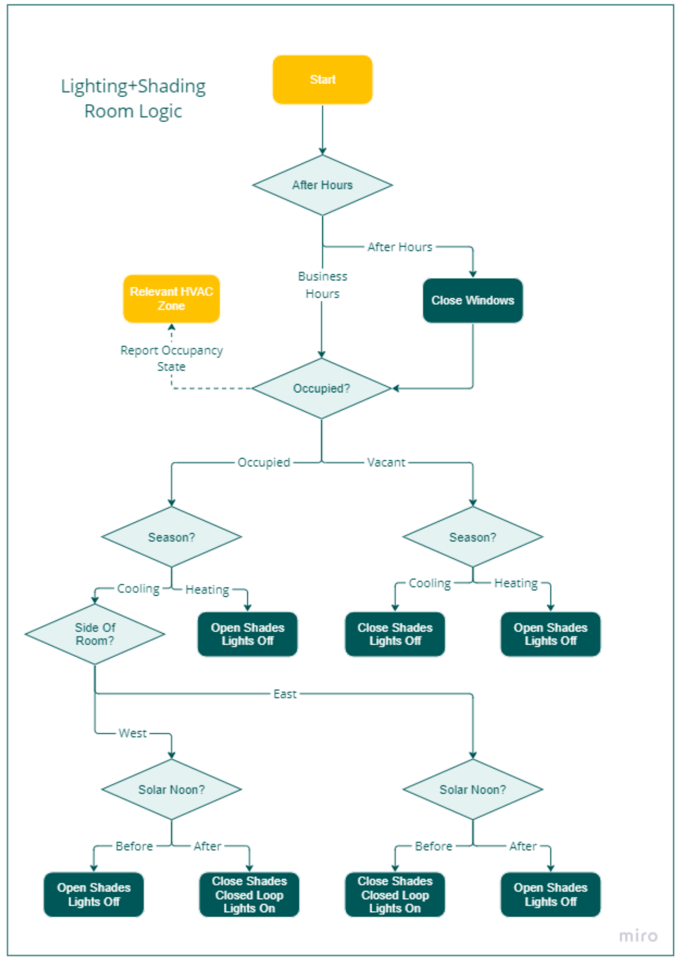


Figure 19. Flow diagram of the lighting, shading and HVAC control algorithm.
Source: CLTC

Table 5. Lighting, Shading and HVAC Control Strategy Description

System	Control	Description
Lighting	Occupancy, Manual, and Daylight Harvesting	Controlled by occupancy. Daylight harvesting. Manual override using a wall switch.
HVAC	Occupancy, Manual, Programmed setbacks	Heating and cooling setbacks with manual overrides; after hours, weekend and holiday setbacks. During business hours, controlled by occupancy signal from the lighting system delivered through the thermostat's API.
Shading	Occupancy, Manual, Programmed Schedule	Shading control via occupancy sensor, season and time of day, Manual control via wall switch

System	Control	Description
Operable Windows	Manual, Programmed Schedule	Manual control via wall switch, after hours closed.

Source: CLTC

Strategy 4: HVAC and Operable Windows (Precooling)

The HVAC and operable windows integration strategy is focused on reducing energy consumption for ventilation and air conditioning by precooling the building via the actuated windows.

In the mornings during the cooling season, the system first checks data from the external weather station, and local weather forecasts to determine the outdoor temperature relative to the cooling setpoint. Additional environmental conditions such as rain and wind are also considered, along with short-term weather forecasts. If the outdoor temperature falls below the cooling setpoint and weather conditions are suitable—no rain, moderate wind, and a favorable forecast—a command is sent to open the windows allowing cool, outdoor air to condition the building.

If the outdoor temperature is above the cooling setpoint, or if adverse weather conditions are detected or forecasted, the system ensures that the windows are closed. This reduces indoor heat gain, prevents rain ingress, and eliminates drafts from open windows, helping to maintain comfortable indoor conditions and reduce energy waste.

Outside of morning hours or during the heating season, the HVAC system operates according to its standard schedule. This involves maintaining the indoor environment based on predefined thermostat setpoints for each hour of the day.

The strategy provides a data-driven approach to managing fenestration and HVAC systems, switching between natural ventilation/precooling and mechanical cooling as environmental conditions allow (Figure 24 & Table 6).

Table 6. HVAC and Operable Windows (Precooling) Control Strategy Description

System	Control	Description
Lighting	Occupancy, Daylight Harvesting	Controlled by occupancy and daylight harvesting with manual overrides.
HVAC	Manual, Programmed Schedule	Heating and cooling setback schedule with manual overrides; business hours, after-hours, weekend, and holiday schedules.
Operable Windows	Manual, Schedule, Weather Station	Automatic control during precooling periods with favorable weather, manual control via wall switch, after-hours closed.

Source: CLTC

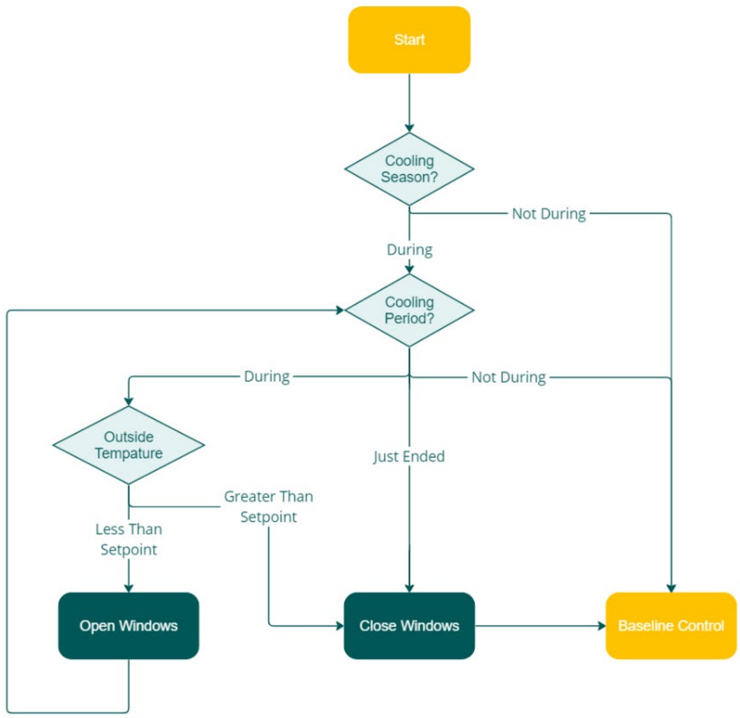


Figure 20. Flow diagram for the HVAC and operable windows control algorithm.
Source: CLTC

Strategy 5: Lighting and Controlled Receptacles

The lighting and controlled receptacles strategy focuses on the efficient management of plug loads by utilizing occupancy data from the lighting control system's occupancy sensors. When the room is occupied, the plug loads operate according to their usual schedule, ensuring that essential equipment and devices are readily available for use. However, when the room is unoccupied, the BAS automatically turns off the controlled receptacle, eliminating unnecessary electrical plug loads (Figure 25 & Table 7). Loads such as monitors, phone chargers and personal desk fans are often connected to controlled receptacles and are chosen by occupants to ensure their workflow is not interrupted, while devices such as computers are powered by uncontrolled receptacles.

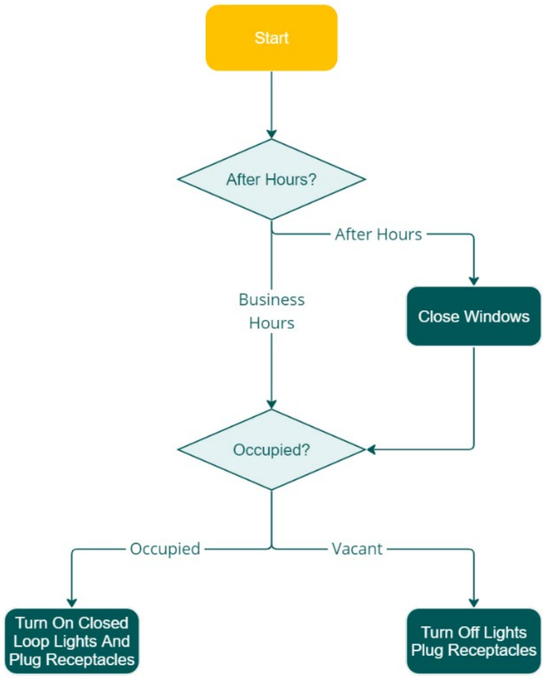


Figure 21. Flow diagram for the lighting and controlled receptacles control algorithm.
Source: CLTC

Table 7. Lighting and Controlled Receptacles Control Strategy Description

System	Control	Description
Lighting	Occupancy, Daylight Harvesting	Occupancy based lighting control with daylight harvesting and manual overrides
Plug Loads	Manual, Occupancy	Automatic control based on occupancy to turn on receptacles when room is occupied and turn off when room is vacant; manual overrides.

Source: CLTC

Strategy 6: Lighting and Heat Pump Hot Water Heater

This control strategy optimizes electric water heating by using an occupant schedule and the water heating rate to ensure the proper water temperature setpoint is achieved and maintained before occupants arrive. The water heater continues to maintain the setpoint if occupancy is detected via lighting system sensors. If no occupancy is detected, the water heater is turned off to conserve energy.

This strategy integrates into the BAS using Wi-Fi and a web-based API, offering an intelligent approach to hot water management by responding to occupancy patterns (Figure 26 & Table 8). By adjusting the water heater's operation based on real-time occupancy, it effectively reduces unnecessary energy consumption.

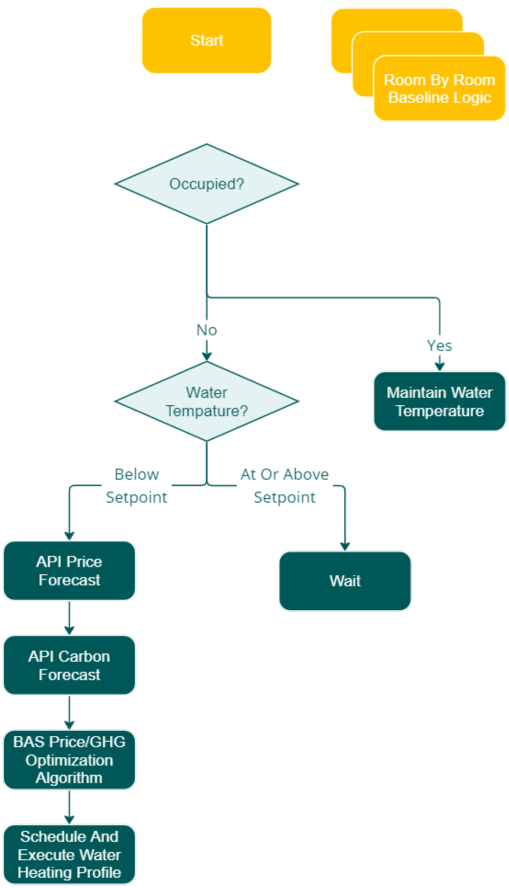


Figure 22. Flow diagram for the water heater integration control algorithm.
Source: CLTC

Table 8. Heat Pump Hot Water Heater Control Strategy Description

System	Control	Description
Lighting	Occupancy and Daylight Harvesting	Controlled by occupancy and daylight harvesting. Manual overrides via wall switch.
Water Heater	Set Point Maintained during Occupancy	Heating setpoints with manual overrides; turned off when building is vacant, after hours, weekend and holiday setback schedules.

Source: CLTC

Strategy 7: Whole Building Integration

The whole-building strategy integrates HVAC, lighting, shading, operable windows, plug loads, and hot water heating to create a fully integrated, energy-efficient building environment. When the building is occupied, the BAS takes the following multi-faceted approach:

HVAC System: The HVAC setpoints are adjusted based on a number of factors, including the outdoor temperature, the time-of-day, and the season, while also accounting for indoor CO_2 levels to optimize ventilation.

Lighting: The building automation system (BAS) uses data on indoor and outdoor illuminance, as well as variables like geographical location, time-of-year, and sun path, to efficiently modulate the electric lighting. The system adjusts electric lighting to maintain target illuminance levels while optimizing for energy efficiency. The BAS considers not only the energy used for electric lighting but also the solar heat gain resulting from the position of the shades, which can be a liability during the cooling season and an asset during the heating season.

Shading: During the cooling season, the shades operate in the closed state until the rooms become occupied, rejecting the solar heat gain automatically without occupant interaction. During the heating season, the shades open to take on solar heat gain, and close when sunlight is not incident, to prevent heat loss via thermal radiation from warmer building mass.

Operable Windows: During the cooling season, and if weather conditions allow, windows are opened in the mornings for precooling to reduce the mechanical cooling load. Throughout the year, the operable windows can offset mechanical ventilation while maintaining the building's required air change outs through natural ventilation. Furthermore, the operable windows are used for demand control ventilation by monitoring CO_2 data from the BAS auxiliary sensors. When CO_2 levels exceed allowable thresholds, the operable windows open, reducing the need for mechanical ventilation.

Controlled Receptacles: The system uses occupancy signals to control plug loads to prevent unnecessary loads when a space is unoccupied.

Electric Water Heater: The system uses occupancy signals to determine when to turn off the water heater.

When the building is unoccupied, the whole-building strategy switches all systems to their most energy-efficient modes. The HVAC system changes to an energy-saving setting with adjusted setpoints for cooling and heating. Lights are turned off, shades are closed (or opened, depending on season), windows are secured, non-essential plug loads are turned off, and the water heating is stopped. For any manual overrides, the system will adjust the affected building systems accordingly. By synchronizing multiple building systems, this strategy is intended to provide an effective method for reducing energy consumption without compromising on the overall user experience or occupant comfort (Figure 27 & Table 9).

Table 9. Whole-building Control Strategy Description

System	Control	Description
Lighting	Occupancy, Daylight Harvesting, Season, Time of day	Occupancy-based lighting control with daylight harvesting and manual overrides. Cooling and Heating Seasonal logic.
HVAC	Manual, Setbacks, Occupancy, Weather Station, CO_2	Heating and cooling setbacks with manual overrides, after hours, weekend and holiday setbacks. Ventilates based on CO_2 and weather
Shading	Manual, Schedule, Occupancy, Daylight, Season	Manual control via wall switch. Controlled based on season and position of sun to provide light and control temperature change in room.
Operable Windows	Manual, CO_2, Schedule, Weather Station	Automatic control during precooling periods, manual control via wall switch, closed after hours. Ventilates based on CO_2 and weather.
Water Heating	Occupancy, Manual	Runs based on water temperature, price of electricity, and GHGs, and occupancy of building.
Plug Loads	Manual, Occ/Vacancy	Turn on during occupancy, turn off during vacancy.

Source: CLTC

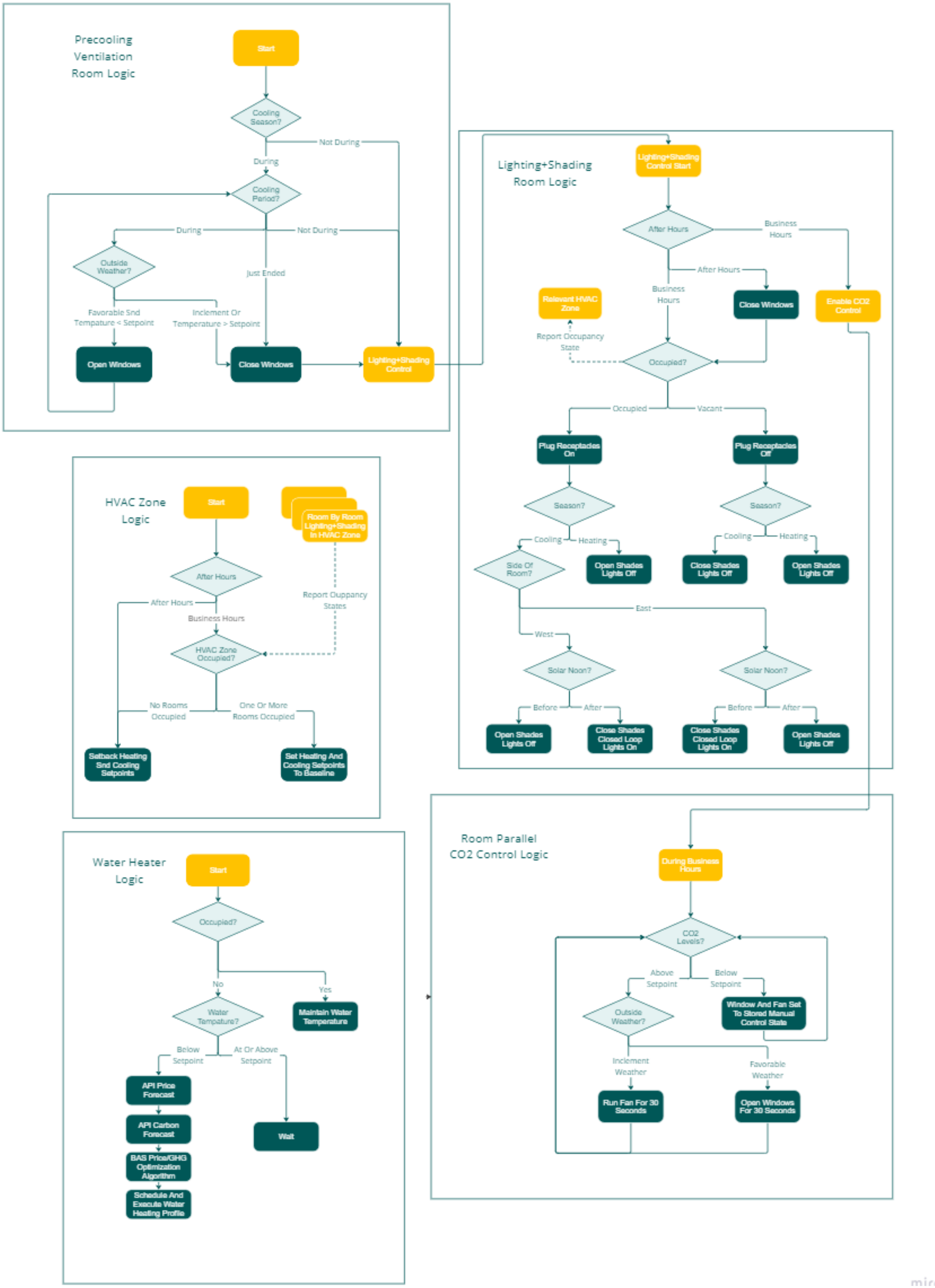


Figure 23. Flow diagrams for the whole-building integration control algorithm.
Source: CLTC

Data Collection – Measurement and Verification System

The research team identified key performance metrics that required independent measurement and verification (M&V) to validate the system's operation and energy savings. The M&V system included sensors for multiple environmental and operational parameters, such as indoor and outdoor illuminance, temperature, relative humidity (RH), carbon dioxide (CO_2) levels, lighting load, HVAC load, window state (open or closed), and weather data, including the current and forecasted rain and wind conditions (Figure 17). Additionally, lighting, HVAC, and water heater electrical energy consumption were metered using current transformers (CTs) and power meters, with this data directly used to calculate each integration strategy's electrical energy usage. Each room was also equipped with multiple Optex brand occupancy sensors to generate an accurate occupancy data stream, a critical metric in energy savings calculations. (Figure 28).

Figure 24. Layout of The Barn, showing locations of M&V sensors.
Source: CLTC

Sensors were distributed in each room of the test area, aligned with the locations of control system sensors or controllable end points, such as luminaires and operable windows (Figure 29). This allows for a direct comparison between the control system data and independent M&V data, enhancing the validity of performance evaluations.

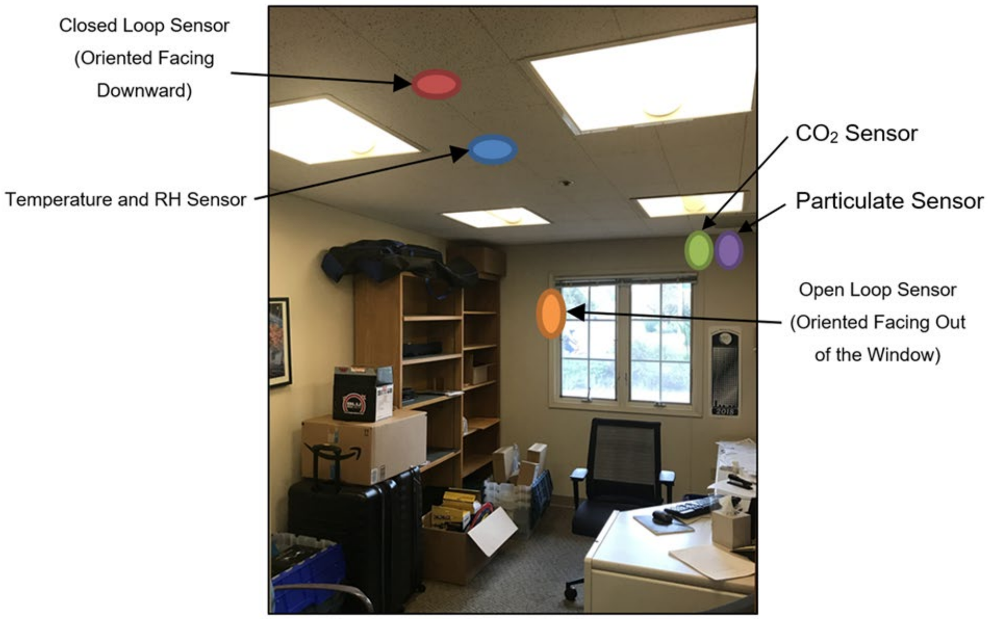


Figure 25. Typical locations of M&V sensors in one office at the test site.
Source: CLTC

Data from the sensors were collected by a network of five Campbell Scientific dataloggers, which have both onboard data storage and remote data uploading capabilities. This configuration enabled robust data management for subsequent performance analysis, separate from the control system's own measurements. The data was collected at intervals ranging from one second to one minute or upon change of value/state for some data types (Table 10).

Table 10. Overview of M&V Sensor Types and Sample Rates

Performance Metric	Sensor	Sample Frequency	Accuracy
Illuminance	Li-Cor LI-210R	1s	±5%
Temperature	EE181 Temp/RH Probe	1m	±0.2°C
RH	EE181 Temp/RH Probe	1m	±1.3 + 0.003*RH
Energy	WattNode RWNB-3Y-208-P	Pulse	±0.5%
CO_2	GMW95	1m	±30 ppm + 2% Reading

Performance Metric	Sensor	Sample Frequency	Accuracy
Window State	Kele SM-35 Contact Sensor	State Change	N/A
Occupancy	RCTD-20U Wireless Occupancy Sensor	State Change	N/A

Source: CLTC

Data Processing

The critical data points used to calculate annual energy savings included lighting electrical energy consumption, HVAC electrical energy consumption, water heater electrical energy consumption, and occupancy data. A full year of previous occupancy and weather data was available to serve as a reference for projecting annual energy usage across each integration strategy and the baseline.

For each strategy, including the baseline, the lighting energy consumption was normalized by the time each room was occupied. This provided a metric of lighting energy used per minute of occupancy. The total number of minutes occupied from the previous year's dataset was then used to estimate the annual energy consumption of the lighting system under each strategy.

Similarly, for HVAC energy consumption, the electrical energy used per Cooling Degree Day (CDD) was calculated for each strategy. This normalized metric accounted for the varying thermal demand on the HVAC system based on outdoor temperatures. The HVAC energy usage for the full year was then extrapolated using the previous year's CDD data to estimate annual consumption for each strategy.

By applying these normalization methods to the M&V data, projections of total energy consumption for lighting, HVAC, and water heating were made for each integration strategy and compared with the baseline, allowing for a comprehensive assessment of the energy savings achieved through system integration.

Lighting Energy Consumption

For each strategy, lighting energy consumption was calculated per minute of occupancy for each room. The measurement and verification (M&V) system utilized infrared (IR) sensors to detect occupancy, which had a retrigger period of 10 seconds, much shorter than the 15-minute interval used by the lighting control system's sensors. A data processing algorithm was applied to the M&V sensor data to calculate the total time a room was occupied. The algorithm assumed that if an occupancy event occurred within 15 minutes of the previous one, the time between the two events was considered occupied. This method aligned with the control system's logic, where the lights remain on for 15 minutes after the last detected occupancy.

Lighting energy consumption was measured directly using current transformers (CTs) and power meters installed in the lighting circuits. The daily lighting load in the test bed, measured in kilowatt-hours (kWh), was then compared to the room occupancy time, recorded in minutes. To normalize the data, the total lighting energy consumption was divided by the room occupancy time, resulting in a metric of kWh per minute of occupancy for each room.

The lighting energy consumption rate is calculated using the following formula:

Equation 1. Normalized Lighting Energy Consumption per Minute Occupancy

$$Energy\ Consumption\ Rate_{Lighting} = \frac{\sum_{n=Liting\ Circut}^{Lighting\ Circuits} kWh_n}{\sum_{n=Room}^{Rooms} Occupied\ Time_n} = \frac{kWh}{min}$$

This normalized metric of kWh per occupied minute was used to project annual lighting energy consumption based on the recorded occupancy data from the previous year. This approach ensured that the results were not skewed by variations in building utilization during the study period.

HVAC Energy Consumption

Cooling degree days (CDD) and heating degree days (HDD) were both used as the normalizing metrics for HVAC energy consumption. Degree days represent the thermal load that the HVAC system needs to dissipate each day, and this approach is widely accepted in commercial energy analysis. A degree day is calculated as the difference between the day's maximum and minimum temperatures, divided by two, with 65°F typically used as the reference temperature for HVAC operation. The formulas for cooling degree days and heating degree days is shown in Equation 2.

Equation 2. Cooling Degree Days Calculation

$$CDD = \frac{T_H - T_L}{2} - 65°F$$
$$HDD = -(CDD)$$

For the east zone HVAC unit, heating and cooling loads were directly measured by metering the heat pump unit with current transformers and power meters. On the west side, the compressor and fan were similarly metered, but gas flow for the furnace was not measured. Instead, the research team estimated the furnace's energy consumption by converting its BTU output to kilowatt-hours (kWh), as if it were an electric heater, and used the runtime provided by the Pelican Thermostat system. The runtime was estimated using the M&V data from the duct temperature probes and metered fan energy consumption on the west side. These estimates were then confirmed by the Pelican system's self-reported runtime, which is part of the control system. Energy usage for HVAC was analyzed daily during occupied business hours which were typically 8 AM to 5 PM but sometimes extended from 6 AM to 7 PM. The energy consumption rate of HVAC systems for each strategy was calculated according to Equation 3. Water heater consumption was also measured and converted to kWh using the same method as applied to other electrical components within the HVAC system.

Equation 3. Normalized HVAC Consumption per CDD

$$Energy\ Consumption\ Rate_{HVAC} = \frac{\left(\sum_{n=circuit}^{HVAC\ circuts} kWh_n\right)}{\sum_{n=day}^{days} |CDD|_{day}} = \frac{kWh}{CDD}$$

Annual Energy Consumption Projection

To project the annual energy consumption for each control strategy, the research team utilized occupancy data and cooling degree day (CDD) data from the previous year (2023-2024). During this period, no control strategies were running, and the water heater and plug load controllers were not yet installed. However, this dataset provided valuable information on occupancy patterns, showing when and how often the building was occupied throughout the year. Due to project time constraints, this occupancy data and weather data were used to project the annual consumption for each strategy, normalizing the energy use based on the observed occupancy and weather patterns from the previous year.

For the lighting system, energy consumption was metered using current transformers and power meters for the duration of each strategy. This measured consumption was then normalized by the amount of time the rooms were occupied while the respective strategy was employed. Using the previous year's occupancy data, the lighting energy consumption was projected for the entire year by applying the measured energy use per occupied minute to the total expected annual occupancy time for each strategy. This method ensured that the lighting projections were aligned with actual usage patterns, capturing variations in occupancy across different days and seasons.

Equation 4. Estimated Lighting Energy Use

$$Lighting\ Energy\ Use = Energy\ Consumption\ Rate_{Lighting} * Total\ time\ Occupied$$

For each strategy, HVAC energy consumption was metered (or estimated as previously discussed), and cooling degree days (CDD) were recorded. An energy consumption per CDD metric was calculated for each strategy. This metric was then used to project annual HVAC energy consumption by applying it to the CDD data from the previous year. In a similar manner, heating degree days (HDD) were used to assess and project annual heating energy consumption for each strategy.

Equation 5. Estimated HVAC Energy Use

$$HVAC\ Energy\ Use = Energy\ Consumption\ Rate_{HVAC} * Total\ CDD$$

By using this method of normalizing energy consumption based on occupancy and degree days, the projected annual energy use for both lighting and HVAC systems reflected realistic operational conditions. This approach ensured that the energy projections for each strategy accounted for both the occupancy-driven lighting demand and the climate-driven HVAC loads over the course of a full year.

Results

Baseline

The baseline strategy was operational for 55 workdays, equivalent to 11 work weeks. During this period, the M&V system recorded power consumption for the lighting, HVAC and water heating[1] systems. The collected data was then projected over an entire calendar year using Equations 4 and 5, resulting in an estimated total energy usage of 7,498 kWh (Figure 30). This consumption at an estimate energy rate of $0.30/kWh[2] in California, would result in $2249.48 in energy costs, assuming all energy used in heating was electric. The greenhouse gas emissions associated with this consumption is approximately 3.22 tons. of CO_2[3].

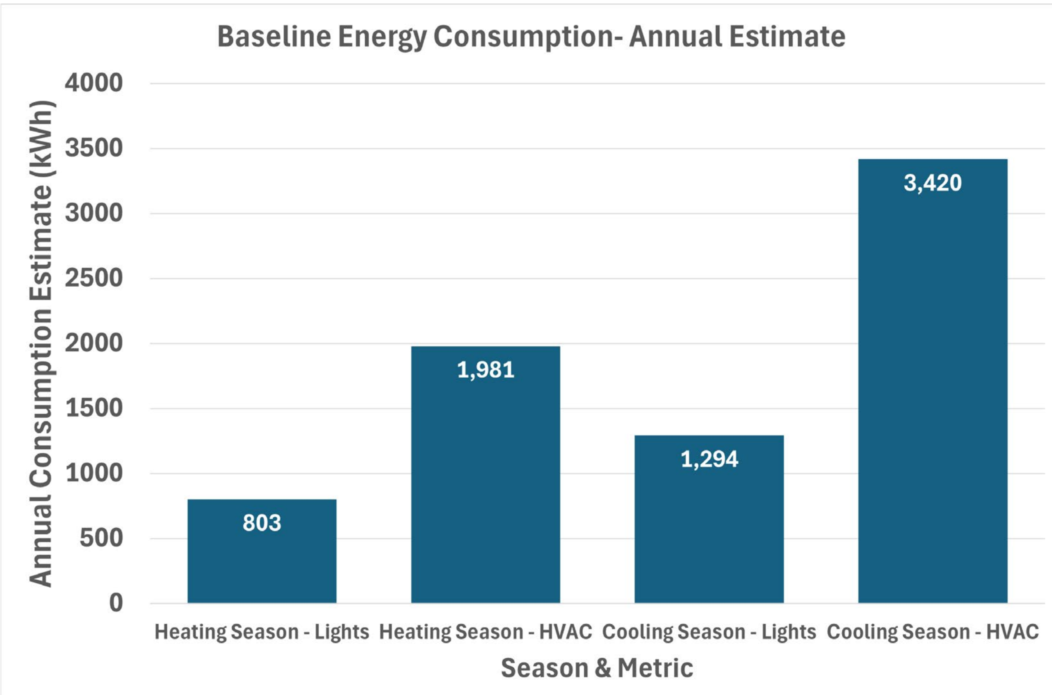


Figure 26. The estimated annual energy consumption for the baseline strategy.

Strategy 1: Lighting and HVAC

The lghting and HVAC strategy was operational for 25 workdays, equivalent to five work weeks, spread throughout the heating and cooling seasons. During this period, the M&V system recorded power consumption for the lighting and HVAC systems. The collected data was projected over an entire calendar year, using an established CDD and HDD regression, fit to energy consumption to past year degree day data from NOAA historical data, and established lighting load per day fit to accumulated occupancy, applied to past year occupancy data. This resulted in an estimated total energy usage of 6,309.75 kWh (Figure 31), which is 1,188.53 kWh less than the baseline conditions, yielding an estimated 15.85 percent annual savings across HVAC and lighting loads.

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1 Water Heating load was insignificant for this building compared to lighting and HVAC load

2 https://www.pge.com/tariffs/en.html#ELECTRIC%20RATE%20SCHEDULES

3 https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results

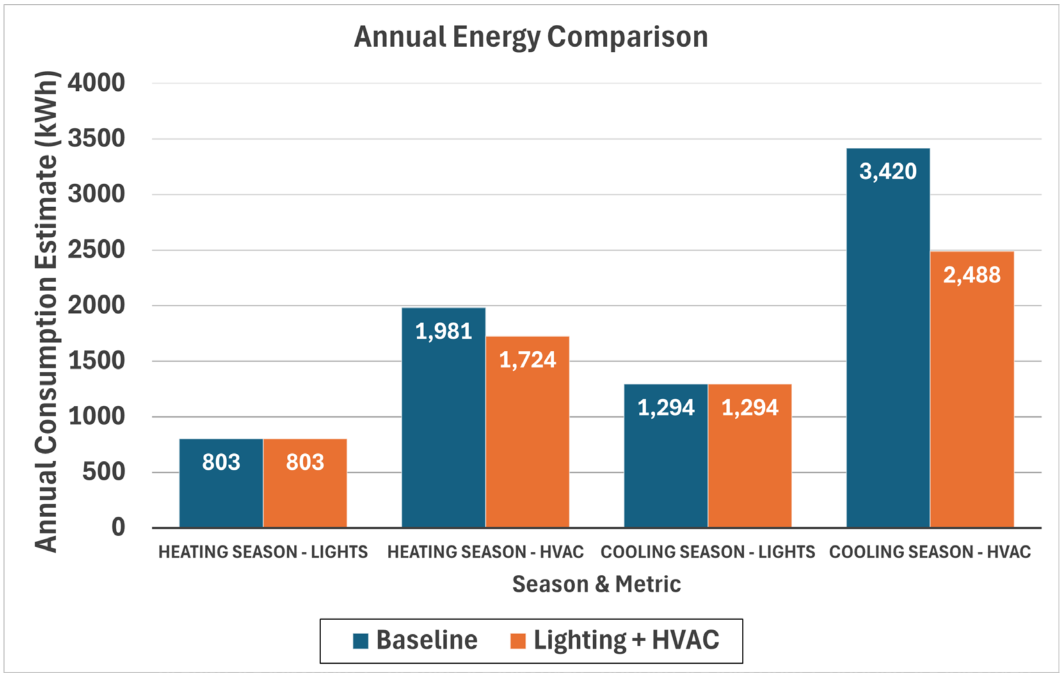

Figure 27. Annual energy consumption for the lighting and HVAC integration strategy.

Based on a local commercial energy cost of $0.30 per kWh, this strategy would save approximately $356.56 per year compared with baseline operation. The estimated greenhouse gas emissions for this strategy are 2.71 tons of CO_2, which is 0.51 tons less than baseline emissions.

The majority of savings in this strategy resulted from the significant variability in The Barn's occupancy schedule. This strategy would set the HVAC back to its prior temperature when all of the rooms in that zone were unoccupied. For The Barn, which houses traveling environmental scientists with flexible work schedules, this happened regularly. Additionally, as work-from-home practices become more prevalent and occupancy patterns become less predictable, similar energy savings could be realized in other buildings over the long term.

It is important to note that the lighting load in this strategy was the same as the baseline, as no specific measures were taken to reduce lighting energy use. The only control point utilized was the occupancy data from the existing lighting system, which allowed for real-time HVAC adjustments based on occupancy.

Strategy 2: Lighting and Shading

The lighting and shading integration strategy was run for 36 workdays, equivalent to seven work weeks. The collected energy consumption data was projected over an entire calendar year, resulting in an estimated total energy usage of 7,095.81 kWh, which is 402.46 kWh less than expected for baseline strategy, yielding an estimated 5.37 percent annual savings on energy use across HVAC and lighting loads (Figure 32).

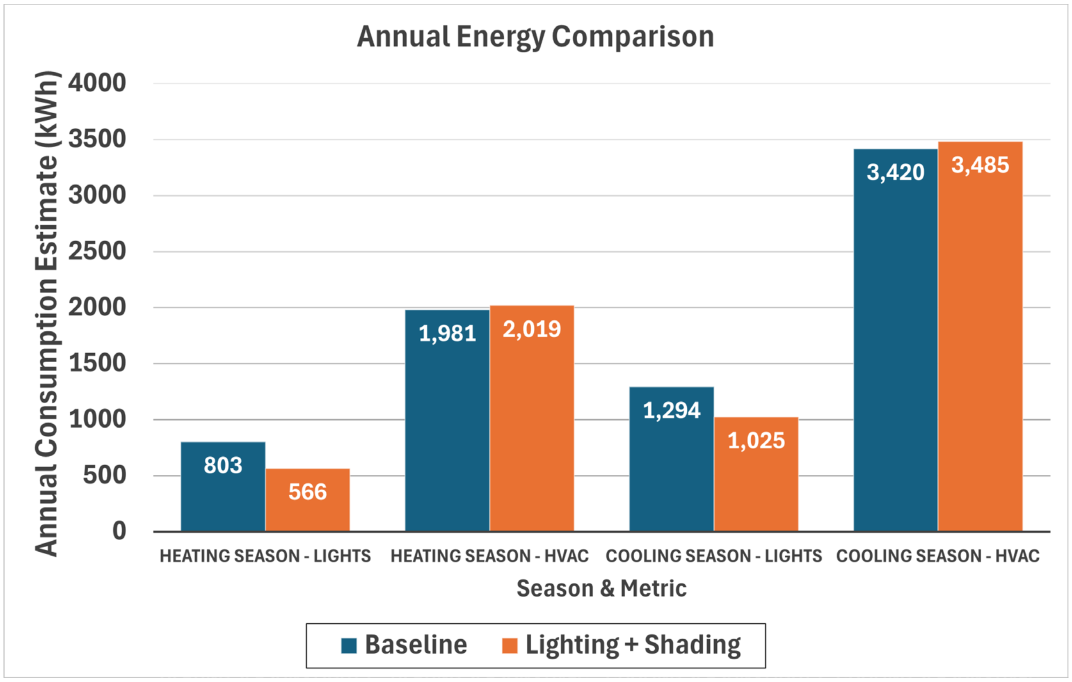

Figure 28. Annual energy consumption for lighting & shading strategy

This strategy is estimated to save approximately $120.74 per year, compared with baseline operation. Estimated greenhouse gas emissions are 3.05 tons of CO_2, which is 0.17 tons less than baseline emissions. This strategy was the least effective energy saving metric that directly aimed to influence HVAC and lighting loads.

This strategy saved energy in lighting but at the expense of additional heating and cooling load, compared with the baseline. However, the lighting savings were substantial enough to more than offset the extra energy used by the HVAC system. This demonstrates the interconnected nature of building systems and confirms the hypothesis that integrating these systems can lead to overall energy savings.

Strategy 3: Lighting, Shading and HVAC

The lighting, shading and HVAC strategy was operational for 90 workdays, equivalent to 18 work weeks. The collected data was projected over an entire calendar year, resulting in an estimated total energy usage of 5745.48 kWh, which is 1752.79 kWh less than expected for baseline conditions, yielding an estimated 23.38 percent annual savings on energy use across HVAC and lighting loads.

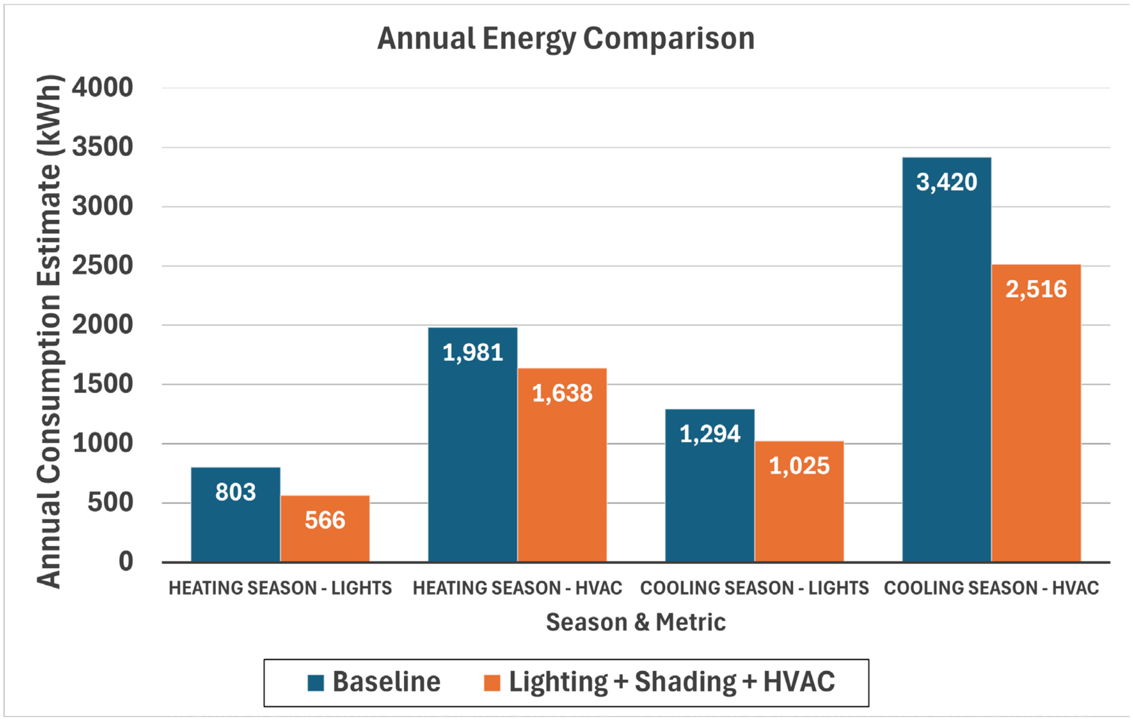

Figure 29. Annual energy consumption for the lighting, shading and HVAC integration strategy.

This strategy was estimated to save approximately $525.84 per year, compared with baseline operation. The estimated greenhouse gas emissions for this strategy are 2.46 lbs. of $CO_2$2, which is 0.76 tons less than baseline emissions. This strategy operated the lights similarly to the lighting and shading strategy. However, the occupant-based HVAC setbacks contributed a significant amount of savings in both cooling and heating due to the occupants' irregular schedules, as previously mentioned. This dynamic HVAC control based on real-time occupancy led to greater energy savings across the board.

Strategy 4: HVAC and Operable Windows (Precooling)

The precooling strategy was run for 12 workdays, equivalent to 2.5 work weeks. During this period, the M&V system recorded power consumption for the lighting and HVAC systems. The collected data was projected over an entire calendar year, resulting in an estimated total energy usage of 6,848 kWh, which is 651 kWh less than expected for baseline conditions (Figure 34). This represents a 19.1 percent savings in HVAC cooling load, but since it didnot affect heating or lighting, it results in an estimated 8.7 percent annual total energy savings. Based on an energy cost of $0.30 per kWh estimate, this strategy was estimated to save approximately $195.19 per year compared to baseline operation. The estimated greenhouse gas emissions for this strategy are 2.94 tons of CO_2, which is 0.28 tons less than baseline emissions.

This strategy was only run on optimal days when external early morning temperatures were below both the internal temperature of The Barn and the setpoints for the test bed. Due to this, there were no expected or reported savings on the lighting circuits, as well as no expected savings during the heating season.

Sacramento Valley weather patterns are particularly suitable for precooling, as summer temperature swings of 35 to 40 degrees are common. This makes the climate ideal for precooling strategies. However, other environmental factors, such as smoke from wildfires during the summer, need to be considered alongside the energy benefits, as they can affect air quality and the feasibility of using outside air for cooling.

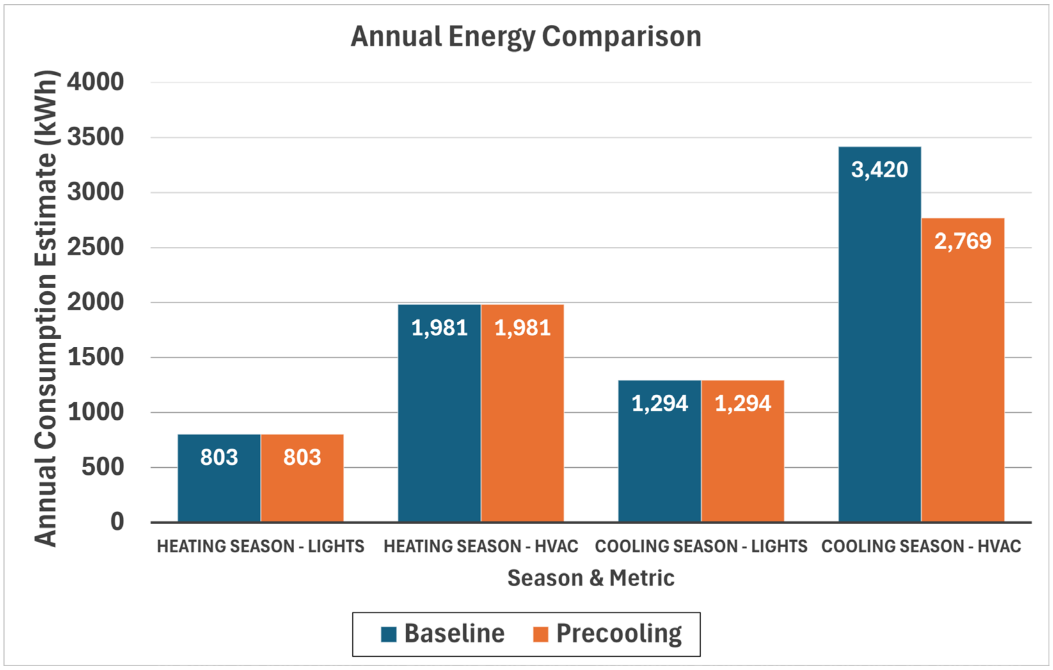

Figure 30. Strategy 4 precooling - annual energy consumption.

Strategy 5: Lighting and Controlled Receptacles

The research team implemented plug load controls within some of the office spaces to validate and confirm integration capabilities with the space. The aim was to identify any potential savings opportunities that could exist with commercial plug load control. When installing these plugs, the research team took inventory of all potential devices that could be controlled via the occupancy signal from the lighting system and concluded that air purifiers and personal heaters would make the most sense to control. The main benefit observed was the reduction of vampiric or redundant loads associated with receptacle use. However, the occupants in The Barn were not using air purifiers or space heaters and instead only elected to allow laptop and camera chargers for plug load control. As a result, the potential for significant energy savings was limited to these lower-load devices (20 to 60W).

The plug load control strategy was run as part of the whole building control strategy, since utilizing occupancy signals to control plug loads did not affect any other building system. Occupants agreed to connect camera and laptop chargers to the plug load controllers. However, as these devices are both used to charge batteries, applying an occupancy-based control strategy to their charging did not reduce the overall energy usage of these devices. The overall energy usage, however, did shift when the energy was consumed to times when the spaces were occupied. As a result, the team was not able to show significant energy savings from the plug load control, but they did validate the functional integration with the lighting system and demonstrated that plug load control could serve as an effective load-shifting strategy.

Strategy 6: Lighting and Heat Pump Hot Water Heater

The integration of the smart water heater strategy was focused on adjusting the heater's operation based on occupancy, aiming to save energy. The water heater in use was a heat pump model, known for its efficiency, compared with traditional resistive element heaters. Before any modifications, the baseline consumption averaged 0.37 kWh per day. After incorporating occupancy-based control, the average daily consumption rose slightly to 0.47 kWh. Although this increase was small, it suggests that the low demand for hot water in the building limited the potential for energy savings. The Barn's hot water usage occurred only at bathroom sinks and one central kitchen sink, indicating that buildings with higher usage would be better candidates for this type of energy-saving strategy.

One key aspect of the strategy was shifting the water heater's electrical use to align with occupied hours. While this strategy achieved its goal, there may have been unintended consequences. The water heater was allowed to cool down completely during unoccupied times, such as overnight. This cooling behavior may have impacted the heater's efficiency when it needed to reheat the water, especially since heat pumps are sensitive to ambient air conditions. The energy required to reheat the cooled water could have offset the savings, explaining the higher post-integration consumption.

This experiment provided useful insights into the factors commercial buildings should consider when deciding whether to retrofit or integrate smart controls with their water heaters. In the case of The Barn, with its limited demand for hot water, the benefits of such integration were minimal. However, for buildings with more consistent or higher hot water needs, such as restaurants, hotels, or gyms, smart control systems could offer more significant energy savings. The occupancy patterns and the type of water heater in use—whether it's a heat pump or a resistive model—should be central considerations in determining whether smart integration is likely to be effective.

Strategy 7: Whole Building Integration

The whole building strategy was conducted over 14 workdays, equivalent to roughly three work weeks. The lighting and HVAC energy data projected over a full year revealed an estimated energy usage of 4,862.76 kWh, which is 2,635.52 kWh less than the baseline, achieving a remarkable 35.15 percent in annual energy savings.

The estimated cost savings were approximately $790.65 annually, compared with the baseline. This strategy also significantly reduces greenhouse gas emissions to 2.23 tons of CO_2, marking a decrease of 0.98 tons from the baseline. This is the most effective strategy of those tested, providing extensive energy and emissions reductions across the board. As expected, the combination of all methods used to save energy resulted in maximal energy savings. The biggest improvement was observed in HVAC savings, particularly during the summer, due to the compounding effects of precooling and occupancy-based HVAC setpoint adjustments. On typically energy-intensive days, this approach allowed for the complete elimination of HVAC cooling operation, contributing to the significant reduction in overall energy use.

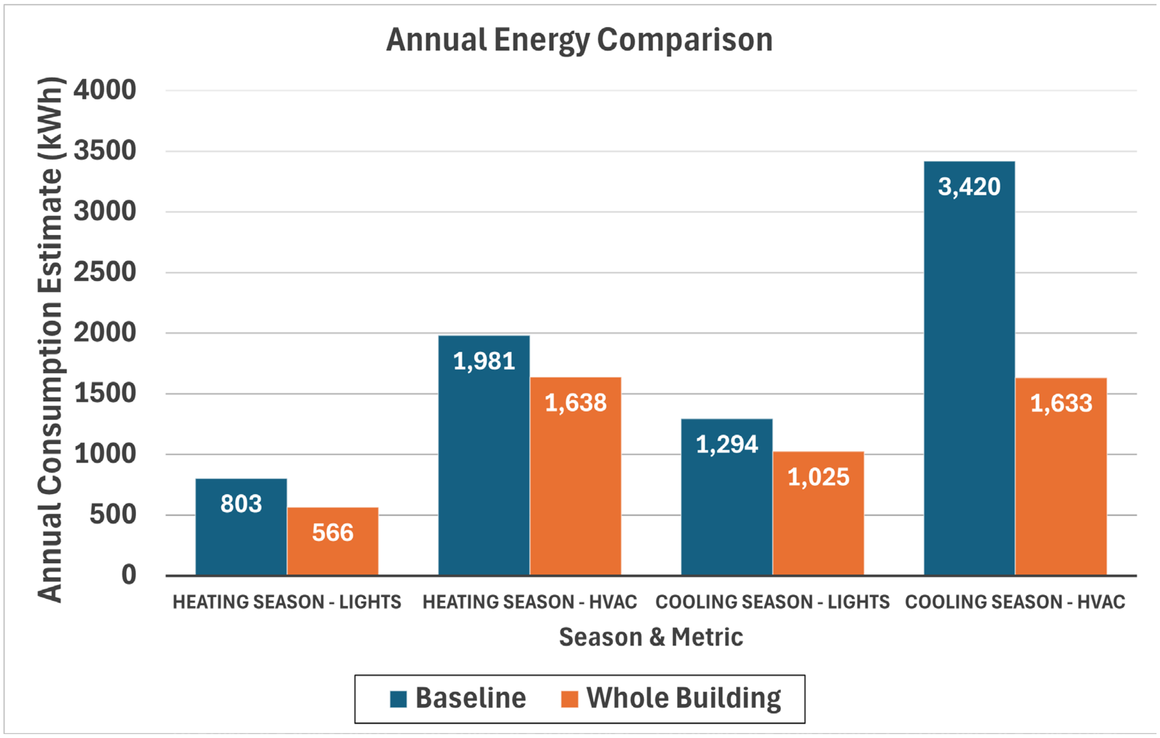

Figure 31. Annual energy consumption for the whole building strategy.

Combined Results

The study evaluated several control strategies across both the heating and cooling seasons, focusing on their impact on lighting and HVAC energy consumption. The baseline operation resulted in an annual energy usage of 7,498 kWh. The lighting and shading strategy achieved a modest 5.4 percent annual savings, primarily by reducing lighting energy use during the cooling season. However, integrating HVAC with the lighting and shading controls significantly increased the savings to 23.4 percent, reflecting more efficient coordination between lighting and HVAC systems (Figure 36).

The precooling strategy, which delayed mechanical cooling by using outdoor air to cool the building before occupancy, was particularly effective during the cooling season, yielding a 19.1 percent savings in HVAC cooling load. Since this strategy did not apply to the heating season and had no impact on lighting, the total annual savings were calculated to be 8.7 percent. The whole-building integration strategy, which coordinated the control of lighting, shading, and HVAC systems, achieved the highest savings, reducing annual energy consumption by 35.1 percent. This fully integrated approach demonstrated the substantial benefits of comprehensive building system integration (Table 11).

In comparison, the integration of lighting and HVAC alone resulted in 15.9 percent annual savings. While integrating HVAC with occupancy-based lighting control proved effective, even greater savings were realized when shading and other systems were incorporated into the control strategy. It should be noted that the plug load control and water heater integration strategies are not included in this section, as neither demonstrated significant energy savings during the study.

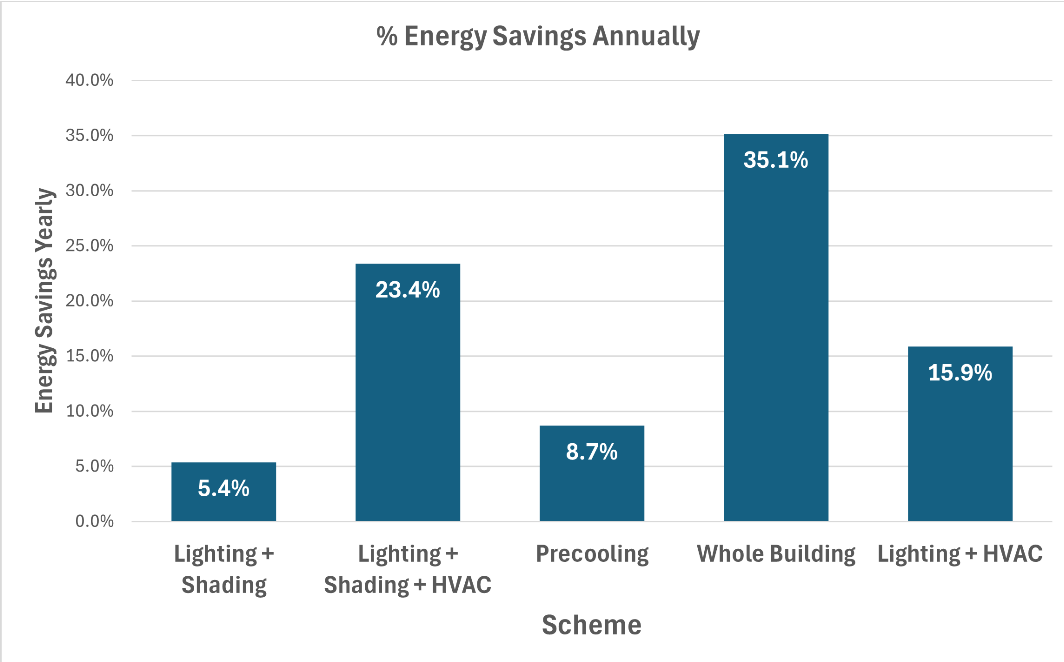

Figure 32. Annual energy savings for each integration strategy.

Table 11. Annual Energy Usage by Strategy in kWh

	Heating Season		Cooling Season		Annual			
	Lighting	HVAC	Lighting	HVAC	Lighting	HVAC	Total Savings	% Annual Savings
baseline	803	1981	1294	3419	2097	5400	7498	N/A
lighting shading	566	2019	1025	3485	1591	5504	7095	5.4%
lighting shading HVAC	566	1638	1025	2515	1591	4154	5745	23.4%
precooling	803	1981	1294	2769	2097	4750	6848	8.7%
whole building	566	1638	1025	1633	1591	3271	4862	35.1%
lighting HVAC	803	1724	1294	2488	2097	4212	6309	15.9%

Greenhouse gas (GHG) emissions in buildings are closely tied to energy use, particularly from HVAC and lighting systems powered by fossil fuel-generated electricity. The data shows that basic control strategies, like the lighting and shading strategy, provide modest reductions of 0.17 tons of CO_2, while more advanced integrations, such as lighting and HVAC, reduce emissions by 0.51 tons of CO_2. The most substantial impact comes from the whole-building integration strategy, which mitigates 0.99 tons of CO_2 annually. This demonstrates that comprehensive system integration is key to achieving significant GHG reductions and energy savings, highlighting the importance of full building system coordination in addressing climate change (Table 12).

Table 12. Calculated GHG Emission and Reduction by Strategy

	Annual mitigated energy use (kWh/ft^2)	Annual CO_2 Emissions (ton CO_2)	Annual Carbon Emissions Reduction (ton CO_2)
Baseline	0	3.22	0
Lighting shading	0.1950	3.05	0.17
Lighting HVAC	0.5758	2.71	0.51
Lighting shading HVAC	0.8492	2.46	0.75
Precooling	0.5419	2.93	0.28
Whole building	1.2769	2.23	0.99

ROI Analysis

When calculating the return on investment for each integration strategy, the research team considered the annual energy savings for each strategy as well as the cost associated with enabling the integration for that strategy. The annual savings for each strategy range from $120.74 to $790.65 (Table 13).

Table 13. Annual Energy Savings by Strategy

Strategy	Annual marginal savings ($\$/ft^2/year$)	Savings for Test bed ($)
Lighting Shading	0.057	$120.74
Lighting HVAC	0.17	$356.56
Lighting Shading HVAC	0.25	$525.84
Precooling	0.09	$195.19
Whole Building	0.33	$790.65

The cost of integration refers to the expenses associated with enabling cross-communication between existing networked building control systems. The research team developed both best-case and worst-case scenarios to establish a range of potential ROI for integrating these systems.

At a minimum, integrating each room requires the digital programming in the BAS of control 'points' for lighting, shading, and actuated windows. For these scenarios, the HVAC system is treated as a fixed cost since it serves multiple rooms but if the building requires a network bridge to enable communication with the BAS, an estimated $500 purchase and installation cost is added. If communication cable wiring is required, the cost is estimated at $100 per point. Additionally, if a

BAS controller or weather station has not already been installed, fixed purchase and installation costs of $6,000 and $2,000, respectively, are factored in. These estimates, combined with the specific installation data from The Barn, provide a detailed breakdown of integration costs per square foot.

In the **best-case scenario**, it is assumed that the building is already equipped with networked systems, all connected to a central building controller—such as one already in place for energy monitoring. In this case, the primary cost of integration involves paying a programmer to configure the BAS, bringing all data points into the BAS, and implementing the control algorithms. This results in minimal hardware costs and a faster, simpler integration process (Table 14).

Table 14. Cost Associated with Integration for Each Strategy, Best Case Scenario

	Device	Cost/QTY	Lighting + Shading	Lighting + HVAC	Lighting + shading + HVAC	Precooling	Whole Building
Fixed Costs	Weather Station	$2000	0	0	0	0	0
	BAS	$6000	0	0	0	0	0
	HVAC Network Bridge	$500	0	0	0	0	0
		Total Fixed Cost $	$0	$0	$0	$0	$0
Per Room Costs	Equipment/Expense	Cost per Room	Lighting + Shading	Lighting + HVAC	Lighting + shading + HVAC	Precooling	Whole Building
	Comm Cable Install	$100	0	0	0	0	0
	Point Configuration	$25	2	1	2	2	3
		Marginal Cost (\$/ft^2)	$0.36	$0.18	$0.36	$0.36	$0.54
		Total Integration Cost	$750	$375	$750	$750	$1,125

In the **worst-case scenario**, the building lacks a BAS, and additional infrastructure is required. An HVAC network bridge must be installed to enable communication, and communication wiring must be run from each system controller back to the BAS. Each control system end point must still be configured in the BAS and the algorithms implemented. This scenario represents a more extensive and costly integration process, involving significant hardware installation and commissioning expenditures (Table 15).

Table 15. Cost Associated with Integration for Each Strategy, Worst Case Scenario

	Device	Cost/QTY	Lighting + Shading	Lighting + HVAC	Lighting + shading + HVAC	Precooling	Whole Building
Fixed Costs	Weather Station	$2000	0	0	0	1	1
	BAS	$6000	1	1	1	1	1
	HVAC Network Bridge	$500	0	1	1	1	1
		Total Fixed Cost $	$6,000	$6,500	$6,500	$8,500	$8,500

	Equipment/Expense	Cost per Room	Lighting + Shading	Lighting + HVAC	Lighting + shading + HVAC	Precooling	Whole Building
Per-Room Costs	Comm Cable Install	$100	2	1	2	2	3
	Point Configuration	$25	2	1	2	2	3
	Marginal Cost ($/ft^2)		$1.79	$0.89	$1.79	$1.79	$2.68
	Total Integration Cost		$9,750	$8,375	$10,250	$12,250	$14,125

With the estimated cost of integration for each strategy and the annual savings, a payback period can be calculated using Equation 6.

Equation 6. Payback Period For each Strategy, Accounting for Building Size

$$Payback\ Period\ years = \frac{Startup\ Cost + Marginal\ Cost * Building\ Size}{Annual\ Marginal\ Savings * Building\ Size}$$

Using this equation and the square footage of The Barn test bed, a range of payback periods for each strategy and each scenario were calculated to be between one and 31 years, depending on the strategy and the preexisting building conditions (Table 16).

Table 16. Payback Period for Each Control Strategy

Strategy	Annual demand reduction (kWh/ft^2)	Annual savings ($/ft^2)	Annual GHG reduction (g CO_2/ft^2)	Minimum payback period (years)
Lighting + Shading	0.19	0.06	76.1	6.2 – 31.1
Lighting + HVAC	0.58	0.17	331	1.1 – 5.3
Lighting + Shading + HVAC	0.85	0.25	211	1.4 – 7.1
Precooling	0.32	0.09	123	3.8 – 19.2
Whole Building	1.28	0.33	225	1.4 – 7.11

These results indicate that the most cost-effective strategy is to integrate the lighting occupancy sensors and the HVAC system. This does not require the integration of many points, yet w provides high energy savings across the building. integrating the whole building will result in the highest energy savings but the cost to integrate is higher than the other strategies. The payback for the whole building strategy, despite the high integrating cost, still maintains a short payback period, even in the worst conditions for integrating building systems. The lighting and shading integration, while being relatively cheap to integrate, results in savings small enough that it by far the least cost-effective integration measured (Figure 37).

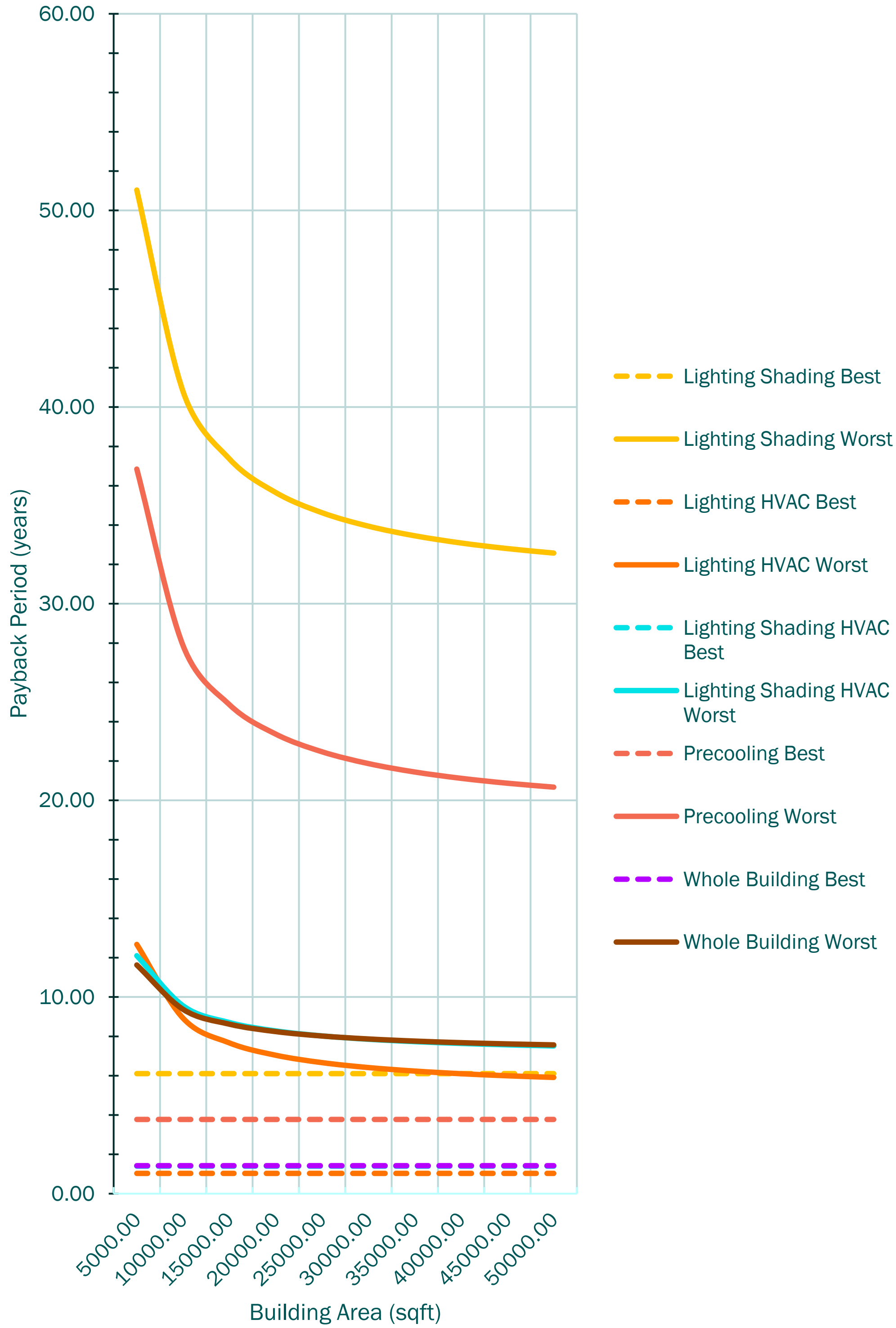

Figure 33. Calculated payback period for each strategy, best- and worst-case scenarios.

Demand Reduction/Load Flexibility

Precooling proved to be the most effective strategy for demand reduction and load flexibility. By using windows to cool the building passively in the early hours, the internal temperature was lowered, allowing the HVAC system to remain inactive for several hours during peak periods. This strategy successfully shifted HVAC loads, reducing active cooling time when outdoor temperatures were highest. Figure 38 compares two days with similar external temperature profiles, illustrating that precooling delayed the west-side HVAC system activation by approximately four hours—until 1:33 PM—providing substantial load flexibility in the morning. However, as external temperatures rose later in the day, the potential for further load shifting decreased (Figure 38).

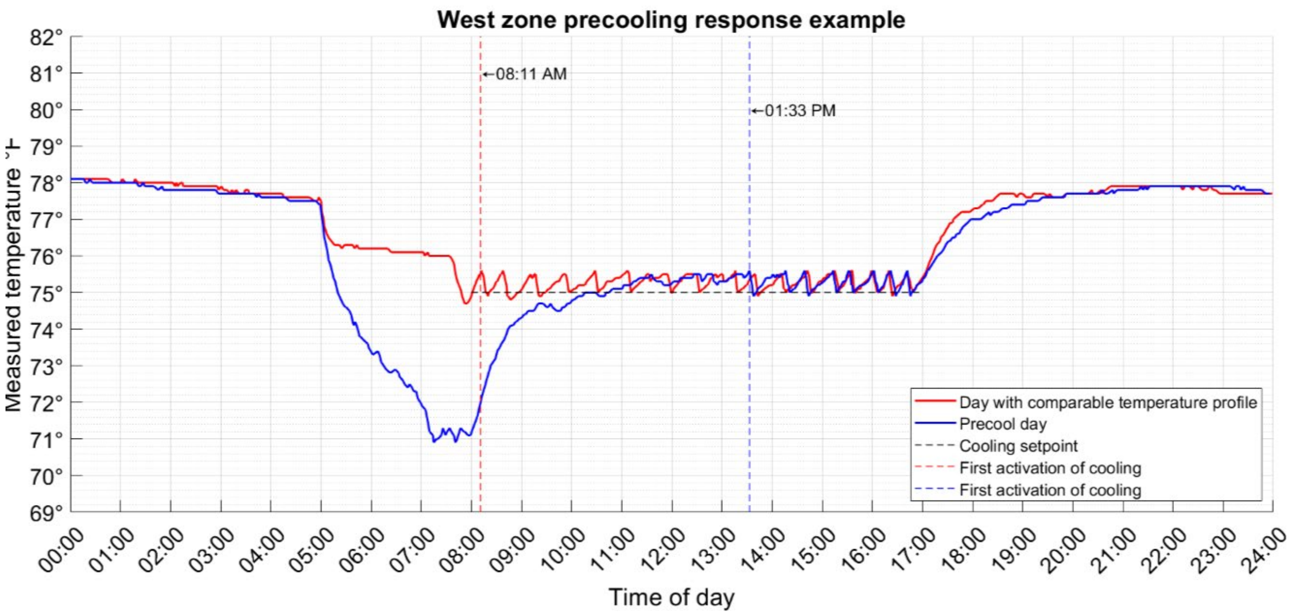

Figure 34. HVAC usage during a day with precooling.

In contrast, the water heater offered less flexibility but still contributed to peak demand reduction. By scheduling the 400-watt water heater to avoid peak operation times and enabling communication for real-time adjustments, some load shifting was achieved. Although this system was relatively small in electrical load, larger water heating demands in other buildings could increase the potential for load flexibility through integrated controls.

Integrating controllable plug loads also holds potential for further demand flexibility, though it was not fully realized at The Barn, due to the nature of the office devices. In other buildings with non-essential equipment, plug load integration could enhance demand reduction. The integration process was streamlined through wireless communication, requiring minimal setup. Connecting key devices to occupancy sensors and building schedules could enable additional shiftable loads depending on the type of equipment used.

While not tested under this project, one promising feature for demand flexibility that is enabled by this integrated control system is dynamic HVAC setpoints. With real-time integration between HVAC, occupancy, and external data sources such as pricing databases, the system can adjust heating and cooling setpoints dynamically in response to grid conditions, time-of-use pricing, or demand response signals. This would enable buildings to lower energy consumption during grid peak times by preconditioning spaces when electricity is cheaper and reducing HVAC operation when demand is high, offering a valuable load-shifting strategy. For example, HVAC setpoints could be raised or lowered by a few degrees during peak periods without compromising occupant comfort, especially in buildings with thermal mass that can store cooling or heating for short periods.

Occupant survey

A survey was issued to the occupants of The Barn in the fall of 2024, requesting feedback on the performance of the building systems over the last year. Additionally, QR codes linking to the survey were handed out, with occupants encouraged to complete it. For those not present when the survey was distributed, the QR code and instructions were posted on their office doors.

The survey highlighted both appreciated features and challenges with the integrated control system. Occupants generally valued the automatic window opening in the morning for precooling, noting that it effectively cooled their offices and improved comfort. The automated shades that opened to allow daylight and closed to prevent heating and glare were also well-received, contributing positively to both thermal and visual comfort.

However, some occupants experienced issues with the lighting system, reporting that lights were occasionally too dim, did not turn on upon entering the room, or turned off when daylight was insufficient. There were also mixed experiences with temperature comfort, as some occupants found their offices consistently too cold, while others felt they were consistently too warm.

While the integrated features like precooling and automated shading enhanced the working environment for most occupants, the issues raised in the responses highlight the challenges of maintaining an integrated building environment that meets the varying needs of occupants in a controlled space. Occupants also reported swift responses to comfort-related issues when they arose, underscoring the advantage of integrated building controls, which allow building managers to address concerns quickly with all systems aggregated into one platform.

Issues reported to the research team during study

As part of the building control experiment conducted in the test space, several issues were reported by the occupants during the test period. Many of these issues were attributed to the control system's occupancy sensors requiring adjustments in sensitivity or alignment. The issues have been categorized by type, quantified where possible, and summarized in the table below. These issues have been categorized by type, quantified where possible, and summarized in the table below (Table 17).

Table 17. Summary Table of Occupant Feedback about the Integrated Control System

Issue Type	Specific Issue	Number of Occurrences	Affected Rooms
Lighting Issues	Lights turning off while room is occupied	Multiple times	104, 120A

	Lights auto dimming/brightening randomly	Multiple times	119A, 120A
	Lights not turning on automatically upon entering	2 times	102, 118A
	Brightness settings not maintaining user preference	1 time	118A
Window/Shade Issues	Windows not opening/closing via control panel	Multiple times	102, 117, 120A
	Control panels unresponsive	Multiple times	102, 117, 120A
	Shades stuck halfway and unresponsive to control panel	1 time	117
	Windows opening automatically without occupant's initiation	2 times	102
HVAC/Thermostat Issues	Limited access to thermostat controls	1 time	General
Operational Issues	Office doors left open during environmental monitoring work	1 time	General

Conclusion

This study demonstrated the energy-saving potential of integrating various building systems, including lighting, HVAC, shading, and automated ventilation, under a central BAS at "The Barn" . The most effective strategy was whole-building integration, achieving a 35.1 percent reduction in annual energy consumption, illustrating the substantial efficiency gains made possible through comprehensive system coordination.

While this strategy incurred higher upfront costs due to the need for additional control points and system components, the energy savings suggest a favorable payback period of between 1.4 and 7.1 years depending on existing building conditions. Based on the 35.1 percent reduction in energy use and the current electricity rates, the initial investment could be recouped within a reasonable timeframe, especially when considering rising energy costs. Integrating fewer systems, such as lighting and HVAC, still yielded significant energy savings of 15.9 percent, which would provide a quicker payback due to lower upfront costs, though with slightly less total energy reduction.

The results also highlight the need to carefully balance system integration. For instance, integrating lighting and shading resulted in increased HVAC loads, though overall energy savings were still achieved. These findings emphasize the importance of holistic system coordination to avoid unintended energy trade-offs.

The occupant survey revealed mixed feedback regarding the comfort and usability of the integrated controls. While respondents reported discomfort with automatic lighting and shading adjustments, they provided positive feedback on the precooling strategy, which proved particularly effective in climates like the Sacramento Valley, where large diurnal temperature swings make it viable. This supports the inclusion of occupant feedback in future system designs to improve user experience alongside energy savings.

Plug load control and smart water heater integration showed minimal energy savings in this context, but these systems could offer greater potential in buildings with higher demand for hot water or plug loads, such as gyms or hotels.

In summary, this project provides a blueprint for optimizing energy consumption in commercial buildings through smart, integrated control systems. The whole-building integration strategy offers the greatest energy savings, and with regard to payback periods and occupant comfort, these strategies represent a cost-effective approach to reducing energy consumption in the long term.