Potential opportunities to reduce HVAC energy using lighting sensors in commercial buildings

Report to

LIGHTING ENERGY ALLIANCE

Report by

Jeremy Snyder

Lighting Research Center

Date

June 25, 2019

(Revised Sept. 30, 2019)

Abstract

On behalf of the Lighting Energy Alliance, the Lighting Research Center (LRC) investigated potential opportunities for using lighting controls to reduce HVAC (heating, ventilation, and air conditioning) energy use in commercial buildings.

Background

New or newly renovated large commercial buildings greater than 100,000 ft^2 (9,300 m^2) typically use a building management system (BMS) to control the HVAC equipment. A traditional BMS has four architectural levels: sensor/actuator, field controller, supervisory controller, and server. More details about these levels are shown in Table 1.

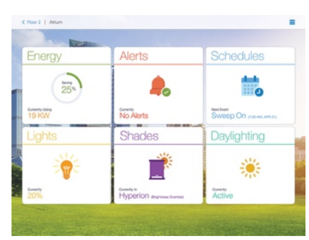
Data transmission and control signaling within and between levels is accomplished with a communication protocol. There are many BMS protocols, but the three that are most widely used are BACnet, LonWorks, and Modbus. All three of these protocols are considered “open protocols” because an international standard exists to define it, at least several manufacturers produce equipment that use it, and equipment using a protocol can communicate with other equipment using the same protocol.

Large commercial buildings typically have multiple automated systems: an HVAC BMS, connected lighting system, security and access control system, fire safety system, audio/visual system, and others. The goal of this investigation was to determine the potential for using occupancy data from lighting systems to reduce HVAC energy use. The occupancy information from lighting sensors can be communicated to the HVAC BMS at any of the four architectural levels, as illustrated in Table 1. The higher the architectural level of the connection between systems, the greater the equipment and labor costs, but also the greater the opportunities for monitoring and control.

Multiple building systems connected to a server is called a building automation system (BAS). A BAS allows the building manager to monitor and control all of the building systems through a single server and database. Monitoring can include current status, trends, alarms and notifications, space utilization, etc. Benefits of a BAS include using sensor information from one system to control other systems and having a central monitoring and control location.

Building systems need to use the same protocol as the BAS server (which is typically also the BMS server) in order to connect with it. Because these protocols originated within the BMS industry, one of the BMS protocols (e.g. BACnet or LonWorks) is typically used to communicate between building systems, even if a proprietary protocol is used internally within a system (e.g. a connected lighting system). The major connected lighting system manufacturers offer at least BACnet communication to a BAS, either natively or through add-on hardware. Some offer LonMark communication as well.

Table 1: Four architectural levels of a building management system, and how a lighting system can be connected at each level. The LRC does not make product recommendations; the products shown are examples of those that are commercially available.

Level		Purpose	Example of HVAC BMS hardware	Example of lighting hardware that can provide occupancy information to HVAC BMS
1	Sensor/Actuator	Sensors make measurements at a single location and include thermocouples, humidity sensors, airflow rate sensors, pressure transducers, etc. Actuators control a single piece of equipment and include actuator motors and relays.	Johnson Controls actuator 	Steinel occupancy sensor with dual outputs for lighting and HVAC 
2	Field Controller	Field controllers take input from sensors, process this information using programmed logic, and send output to actuators.	Honeywell Niagara Edge field controller 	Acuity Distech room field controller lighting extension 
3	Supervisory controller	Supervisory controllers oversee and interact with multiple field controllers. They provide graphics, scheduling, alarming, and trending, and remote connectivity and alarms. They can provide stand-alone control for small commercial buildings.	Honeywell Tridium Jace 8000 	nLight Bacnet IP Interface Appliance 
4	Server	A server provides the functionality of a supervisory controller plus additional or more sophisticated alarms, monitoring, and reporting; longer-term trends, especially when connected with a database; the ability to support multiple buildings; and the ability to connect other building systems (e.g. lighting, security, etc.). Only large buildings or campuses have BMS servers	Schneider Electric EcoStruxure Building Operation Enterprise Server 	Lutron Quantum Vue 

Energy saving opportunities

The LRC identified six potential opportunities for reducing HVAC energy use from lighting occupancy sensor information:

1. Temperature and ventilation setback during vacancy

The simplest strategy for using lighting occupancy sensor data is to set back the temperature and ventilation rate when a space is unoccupied. For example, during cooling season, the thermostat setpoint can be raised by a few degrees and the ventilation rate can be reduced. This strategy can be accomplished by connecting the lighting and HVAC equipment at any of the four architectural levels discussed above.

It has been widespread practice in large commercial buildings to use stand-alone occupancy sensors to set back the HVAC in individual spaces. The primary advantage of using lighting sensors is that it reduces duplication of hardware. The use of lighting sensors to control HVAC in this way has been practiced in the field, but there were differences of opinion about how widespread this is among the experts with whom the LRC spoke. However, if occupancy sensors have already been in widespread use in controlling HVAC systems, it is possible that the public service/utility commissions may not allow utility efficiency programs to count lighting sensors as providing additional HVAC energy savings.

The LRC identified limited case studies on this practice. The only energy savings data the LRC identified is from a computer simulation, and it shows energy savings of 1.4% to 6.0% of total building energy, depending on the climate zone. A field investigation of energy savings is underway by Slipstream, Pacific Northwest National Laboratory (PNNL), and Cadmus Group, with results expected in 2020.

Additional research is needed to answer the following questions:

- How common is it for stand-alone passive infrared (PIR) sensors or luminaire-level lighting controls (LLLCs) to control HVAC systems?
- What energy savings can be expected from integrating lighting and HVAC systems? (Currently being investigated by Slipstream, PNNL, and Cadmus.)
- What HVAC and ventilation setbacks and timeout periods can be used without negatively impacting occupant comfort?
- What is the optimal control logic for different building scenarios?

2. Variable ventilation

Building code ventilation rate requirements are based on the number of people in a space. If LLLC occupancy data could be used to estimate the number of people in a space, the ventilation could be varied in real time.

This strategy is not in practice, and the experts that the LRC spoke with had varied opinions on how well LLLCs could estimate the number of people in a space compared with the incumbent technology, CO_2 sensors. A study is underway at the University of Oregon to investigate this.

The only energy savings estimates of this opportunity identified by the LRC come from computer simulations, which found energy savings from 5% to 19%, depending on the climate zone.

In addition to the difficulty of estimating the number of occupants, another challenge is that HVAC systems use the same air flow for both ventilation and heating/cooling. In other words, both providing fresh air and the heating/cooling of the space is accomplished by conditioning one air flow that is provided through ducts. A newer type of HVAC system, the dedicated outdoor air system (DOAS), separates the ventilation from the heating/cooling of the space. The fresh air is conditioned for both humidity and temperature and supplied through ducts for ventilation needs, but the temperature of the space is controlled by coolant circulated through devices such as chilled beams. Because of this separation of function, variable ventilation is likely to be more efficient with DOAS than traditional HVAC systems.

Another challenge for this strategy is that ANSI/ASHRAE Standard 62 -2007 does not allow ventilation rates to be completely turned off in unoccupied spaces due to off-gassing from furniture, rugs, and other materials.

To advance this strategy, it would be useful to investigate:

- How closely the fraction of LLLCs that detect occupancy in a space correlates with the number of people in that space. (Currently being studied at the University of Oregon.)
- The performance of advanced sensors that can count the number of occupants in a space.
- The feasibility of using lighting controls to vary ventilation rates in a DOAS installation.

3. Office space consolidation

Commercial building managers can use occupancy sensors to identify offices or other spaces that are vacant or underutilized, relocate workers to achieve a higher person-per-square-foot ratio in occupied areas and consolidate the vacant spaces, and then set back the HVAC of the vacant portion of the building. Most connected lighting systems already have this functionality built in, but facility managers often have the opposite goal in mind, such as helping occupants identify and make use of underutilized conference rooms.

Another challenge is that even if commercial space were to be consolidated, its HVAC zones may overlap with occupied zones, at least in part, so the temperature could not be set back.

A second similar strategy is that building managers can group occupants based on their typical arrival and departure times, so the HVAC system can be more frequently set back in each space.

Research is needed to identify with more certainty:

- The fraction of commercial building floor areas that could be consolidated into unoccupied areas.
- The amount of energy that can be saved by setting back the temperature of unoccupied areas in commercial buildings.

4. Using artificial intelligence and occupancy measurements

There are currently two methods of setting back temperatures in commercial buildings: either occupancy sensors trigger the setback or the temperature is set back on a manually-set schedule. It is possible that artificial intelligence (AI) could be used in the form of a machine learning algorithm to predict occupancy patterns of spaces and set back the temperature more effectively with less impact on occupant comfort.

Several laboratory/test-bed studies have been performed, but the LRC did not identify any deployments of this strategy. However, the estimated energy savings from the simulations were significant, ranging from 7% to 52% depending on the strategy and room type, but these savings estimates typically used scheduled HVAC setpoints as the baseline (rather than occupancy sensors).

One challenge is that this strategy would need to be implemented through proprietary BAS software.

Research is needed to identify how much additional energy could be saved by incorporating AI compared with the other advanced techniques and to identify the machine-learning techniques that can result in the greatest energy savings and performance.

5. Smaller thermal zones

This opportunity increases the energy savings potential of the first opportunity with more granular thermal zones, which can make temperature and ventilation setback more effective. Typical thermal zones are controlled by a single variable air volume (VAV) terminal box and include a suite of private offices or roughly 10 to 15 workstations in an open office.

It can be both capital- and labor-intensive to control individual diffusers with an actuator using a BAS, but at least two companies now offer products intended to do this at a lower cost. Emme Controls LLC offers a pneumatic damper that controls airflow through ducts and Air Fixture offers a diffuser that works with underfloor air distribution plenums. It is technically possible to communicate with these devices through a BAS, but this is not included in the current products offered by these companies, so development work would be needed.

Research is needed to determine:

- How much energy can be saved in different types of commercial spaces, such as open and closed offices.

- How best to communicate between the lighting sensors and the HVAC zone controls.
- The payback/ROI for new construction and remodeling.

6. IoT in smaller commercial buildings

Due to the baseline level of equipment and engineering labor needed to install a BAS, they are typically found in buildings 100,000 ft^2 (9,300 m^2) or larger. Some in the BAS industry see "Internet of Things" or IoT devices as a potential path toward lower-cost BAS, which in turn could allow penetration into smaller commercial buildings. In the U.S., the aggregate floor space of small commercial buildings is twice that of large commercial buildings, so potential energy savings could be significant.

Currently, there is a lack of IoT lighting and HVAC products intended to be installed in commercial buildings and that can be connected through a single web platform in the U.S. (However, there are commercial IoT products available in Europe and residential products in the U.S.) As a result, while the concept has promise, the cost and payback of using IoT products in small commercial buildings is unknown. Another challenge is that traditional electrical installers don't have the training to install IoT devices. Research and education would be needed to address these challenges.

Best practices

Barriers to integrating lighting with HVAC include a lack of cooperation between trades and a lack of component standardization. Efficiency programs can maximize the likelihood of successful projects by requiring that best practices be followed on a project, including:

- Require long-term planning.
- Obtain buy-in from the building owner.
- Specify equipment that works on open protocols.
- Ensure clear communications and coordination between trades.
- Hire a professional system integrator.
- Anticipate equipment failure.
- Involve the information technology (IT) department in the system design.

In addition, contractors should be trained in system integration to reduce barriers between trades, which has led to greater implementation in Europe.

Conclusion

While BAS integration is still in its early days, the trends point the way to a future in which all building equipment is connected together and which the current "silos" of HVAC, lighting, security, A/V, and safety are simply considered parts of one single building system.

Background

Motivation

Lighting energy use has been declining over the past decade as LED light sources and advanced controls penetrate the marketplace. As an illustration, in 2003, lighting accounted for 21% of commercial building energy use,[1] and it declined to 10% in 2012,[2] the most recent year for which data is available. Despite these prior gains, additional energy savings are still available from lighting systems, such as by upgrading to high-efficacy LED products, implementing advanced control systems, and designing lighting systems based on occupant needs.

In addition to these lighting efficiency strategies, another means of using lighting to reduce energy use is to leverage the occupancy information from connected lighting systems to reduce HVAC (heating, ventilation, and air conditioning) energy, which represents 44% of commercial energy use as of 2012.[2]

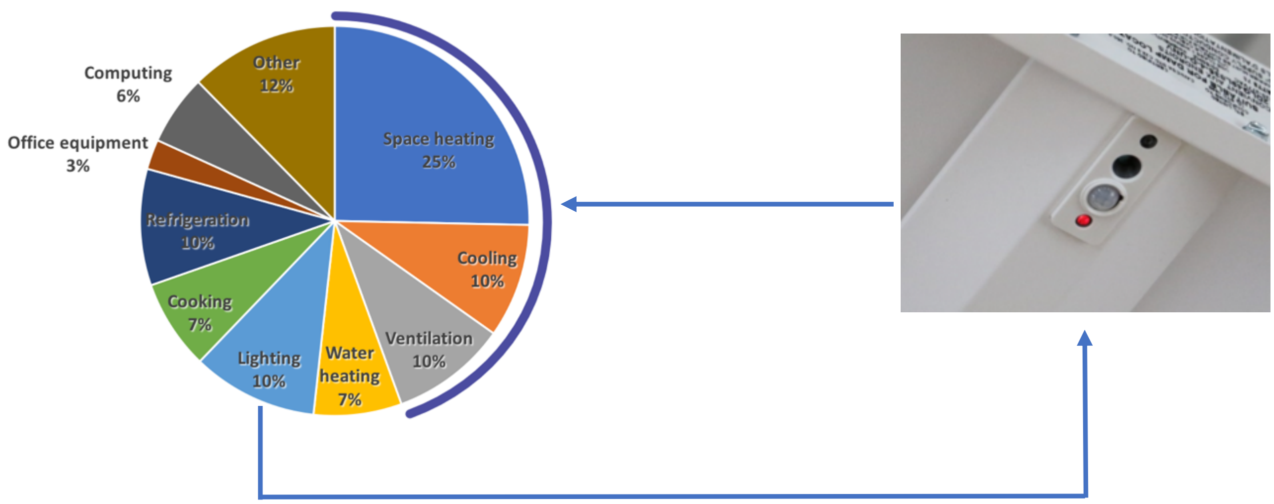


Figure 1: The motivation for this study is to use lighting sensors to reduce HVAC energy use, which is a greater load.

HVAC requirements

As the name indicates, HVAC systems perform three roles in keeping building occupants comfortable and safe: heating, ventilation, and air conditioning.

Heating

According to ASHRAE Standard 55-2013, temperature should be within the "range between approximately 67 and 82°F. A more specific range can be determined from the standard but depends on relative humidity, season, clothing worn, activity levels, and other factors."[3]

Ventilation

ASHRAE Standard 62.1 specifies ventilation rate as cubic feet per minute of fresh air per person occupying the space. The ventilation rate varies by space type, from a low of 5 CFM/person for auditoriums and lobbies to a high of 70 CFM/person for shipping/receiving areas. Office space requires 17 CFM/person.[4]

Air conditioning

Air conditioning reduces the temperature and relative humidity of the air in a building. ASHRAE Standard 55-2013 sets a maximum absolute humidity ratio (the mass of water per mass of dry air) of 0.012. However, this can result in relative humidity “as high as more than 80% at low dry bulb temperatures” while “ASHRAE Standard 62.1-2016 recommends that relative humidity in occupied spaces be controlled to less than 65% to reduce the likelihood of conditions that can lead to microbial growth.”[3] Humidity is reduced by cooling the air below the desired temperature to precipitate out the water, and then allowing the air to heat back to the desired temperature. “The amount of condensate water can range from 3 to 10 gallons per day (11 to 38 liters per day) per 1,000 square feet (93 square meters) of air-conditioned space.”[5]

HVAC systems

There is a range of system designs and equipment for implementing HVAC in commercial buildings, and three examples are discussed below. The first is a typical design for a large commercial building using a central plant, the second is a typical design for a smaller commercial building using roof-top units (RTUs), and the third is the newer, more efficient DOAS.

Central plant

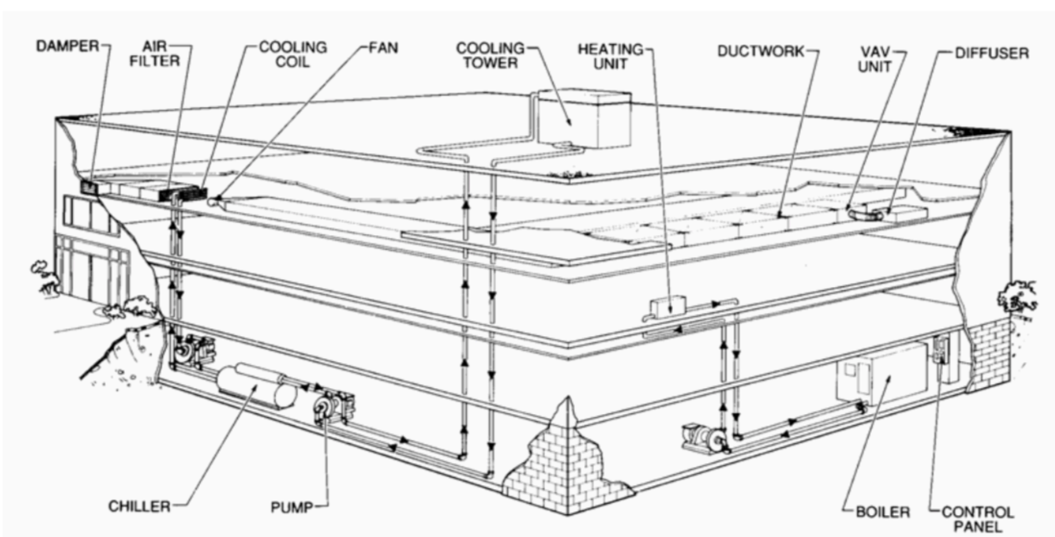


Figure 2: Central plant HVAC system.[6]

Large commercial buildings typically use a central HVAC system consisting of a water boiler for heating, a chiller for air conditioning, and an air handling unit (AHU) for ventilation. Depending on the season, chilled or heated water is piped to the AHU to warm or cool the air passing through it.

The chiller could be water-cooled or air-cooled. If it's water-cooled, the chiller's compressor and condenser will likely be located in the basement, and its cooling tower will be on the roof. If it's air-cooled, it will be located on the roof or on the grounds adjacent to the building.[7]

Most indoor air is recirculated to avoid wasting the energy that was used to condition it, but about 10% of the air is continuously exhausted to the outdoors and replaced with fresh outdoor air to meet ventilation requirements. The AHU controls the exhaust, outdoor air, mixing, and any energy transfer between the streams. The AHU's fan is driven by a variable speed drive (VSD, also known as a variable frequency drive, or VFD), which saves energy compared with a constant speed drive.

The conditioned air is distributed throughout the building through ducts. The building is divided into thermal zones, with one thermostat and one VAV terminal box controlling the air flow into each zone. There is a wide range of thermal zone sizes. According to one source, "the cost/comfort balance typically results in zones of 500 ft^2 to 1,200 ft^2 (47 m^2 to 111 m^2), encompassing five to 10 workstations per zone."[8] Thermal zones in the U.S. Department of Energy (DOE) prototype commercial building range from 2174 ft^2 (202 m^2) for a suite of private offices to 27,256 ft^2 (2532 m^2) for a single open office.[9] The VAV terminal has a damper to control the amount of air flowing from the air duct into the thermal zone, and it may have heating and cooling elements too.

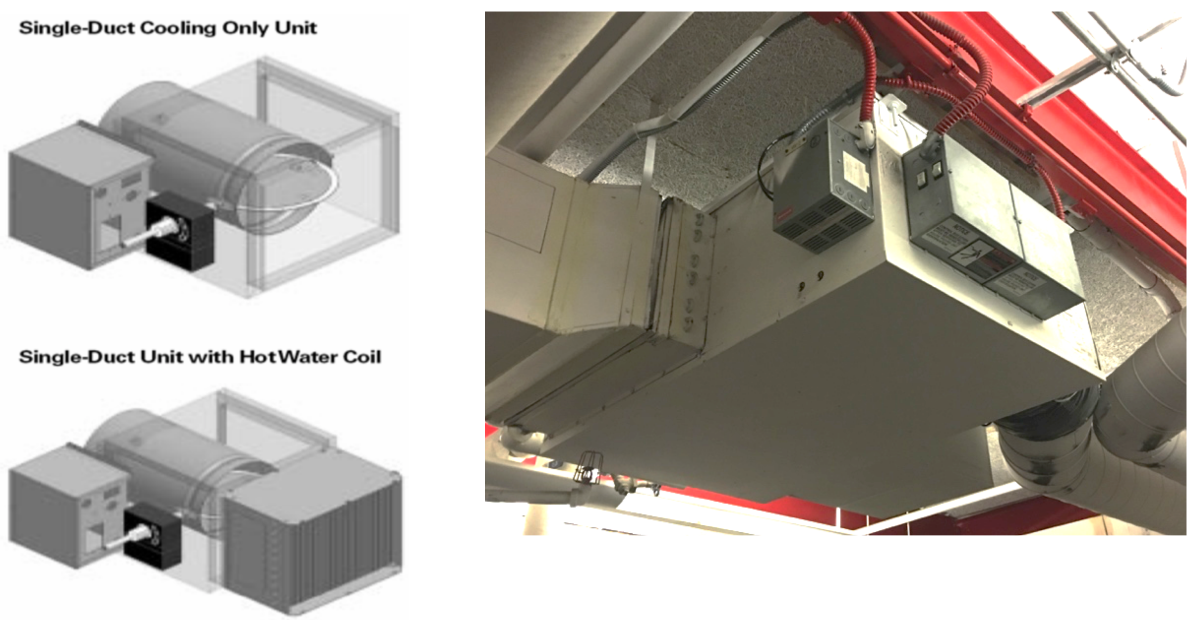


Figure 3: Left: VAV terminal illustrations, with and without heating coils.[6] Right: Photo of VAV terminal with heating coils visible on left side.

Air is supplied from the VAV terminal into the space through diffusers. Room air is removed through return ducts back to the AHU.

Roof-top units

Smaller commercial buildings may use roof-top units, or RTUs, instead of central plants. RTUs package together an AHU and air conditioner into a weather-tight unit on the roof. Water is heated in a boiler and is piped to the RTU to heat the air when needed. In some buildings, there is one RTU per thermal zone, but others add VAV terminals to further split the space into additional zones.

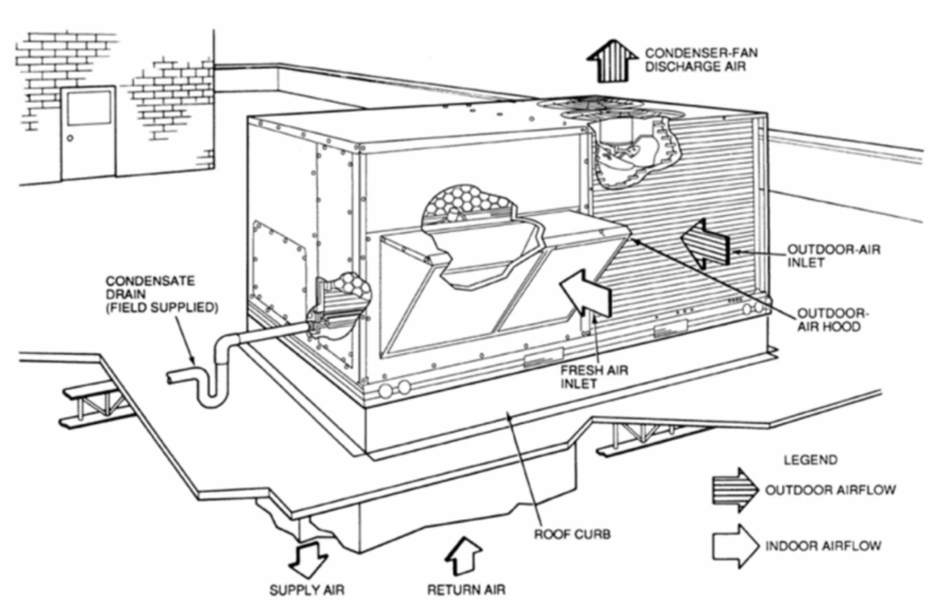


Figure 4: Roof-top unit.[6]

Dedicated outdoor air systems

DOAS is a split system where the outdoor air ventilation structure is separate from the heating and cooling of the building.

According to Roth et al., "It is common practice in commercial building air conditioning to combine ventilation make up air with return air from the building, condition (cool or heat) this air as needed, and distribute the conditioned air to the interior space, with or without zoned temperature control."[10] In contrast, DOAS separates out the latent load (dehumidification) from the sensible (temperature) heating and cooling. This is done by dehumidifying just the amount of air needed for ventilation. Separately, heated or chilled water is piped through devices such as chilled beams throughout the building for temperature control.

This results in energy savings for three primary reasons: "optimal use of the ventilation air provided (allowing compliance with ASHRAE 62 with the minimum quantity of outdoor air), ready use of enthalpy recovery to precool the outdoor air, and allowing the interior load to be handled at higher refrigerant temperature and coefficient of performance…. In space cooling mode, energy savings include the benefit of higher chilled water temperature for the sensible part of the load and reduced ventilation flows to be cooled. In space heating mode, energy is saved as a result of the reduced ventilation air flow allowed by the inherent precision of the DOAS in delivering required ventilation flows in the aggregate and in the individual zones in the building."[10]

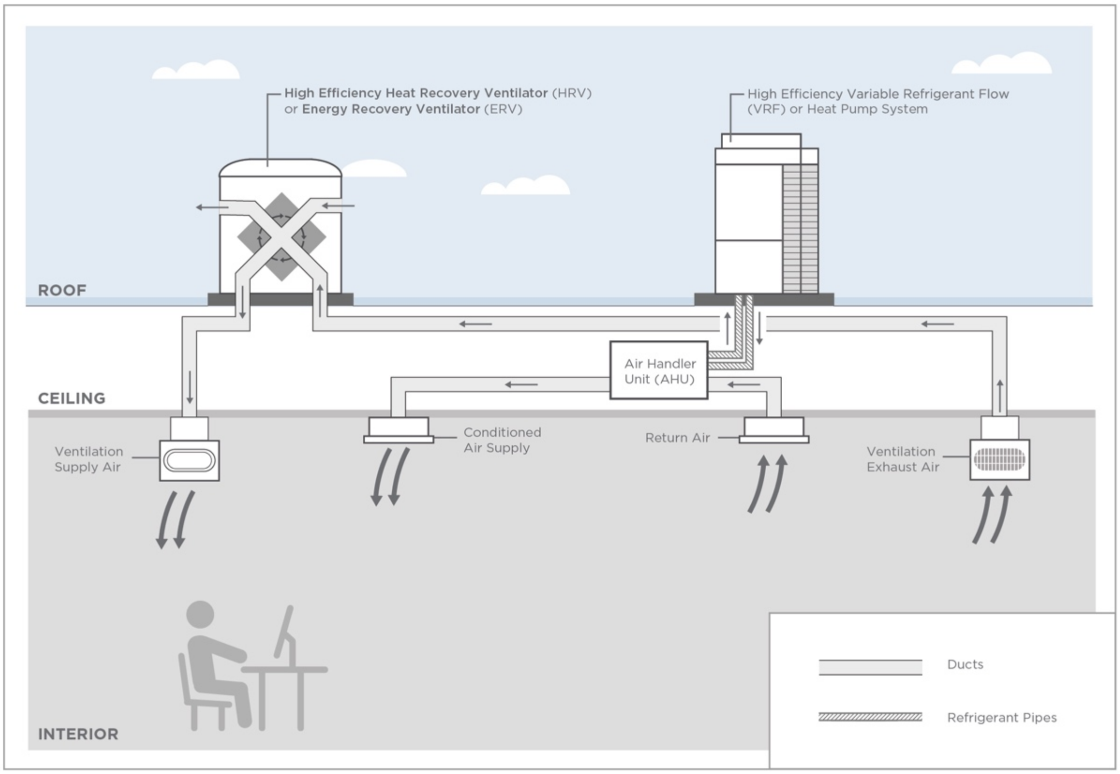


Figure 5: Dedicated Outdoor Air System.[11]

Building automation systems

There can be ambiguity in the terms "building automation system (BAS)" and "building management system (BMS)." Some people in the industry use them interchangeably to mean any computer-controlled system within a building including HVAC, lighting, security, access control, signage, audio/visual, fire, industrial/process control, etc. Others use BMS to refer to HVAC automation, while BAS implies two or more of these systems integrated together. In this report, the second set of meanings will be used in the interest of clarity.

A rule of thumb is that buildings 100,000 ft^2 (9,300 m^2) or greater are candidates for BAS.[12] However, Randy Mead of Cadmus sees a trend toward smaller buildings. "If a building is over 30,000 ft^2 (2800 m^2) and built after 1995 or retrofitted in the last 10 years, it has a BAS."[13]

Building management systems

BMS traditionally refer to HVAC control systems, and can be divided into four functional or organizational levels.[14] This is not related to the degree to which the HVAC can be controlled, but rather describes the architectural levels of a BMS that work together (somewhat analogous to the foundation, walls, and roof of a house).

Level 1: Sensor/Actuator

Sensors include thermocouples, humidity sensors, airflow rate sensors, pressure transducers, etc.

Control devices at this BMS level include actuators and relays. Actuators are electromechanical devices and can be used to control devices such as valves or dampers. For example, an actuator controls the damper position of the VAV terminal, regulating the airflow rate into a space. A relay, which is an electrically-controlled switch, can be used to control electric loads, such as non-dimming fluorescent lighting.

Level 2: Field Controller

Controllers take input from sensors, process this information using programmed logic, and send output to actuators and relays. Some are designed to be freely programmed and others are application-specific (and are customized with menu-driven settings).

Level 3: Supervisory controller

Supervisory controllers oversee and interact with multiple field controllers. According to Phil Zito, a BAS system integrator, "A supervisory device is usually a full-blown computing device that provides graphics, scheduling, alarming, and trending. The supervisory device can also provide remote connectivity and remote alarming. Typically, a supervisory device will contain a traditional operating system like Linux or Windows. Supervisory devices are capable of providing stand-alone control for smaller systems. It's quite common to see a single supervisory device controlling a small office building or school."[14]

Level 4: Server

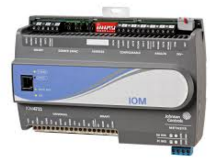
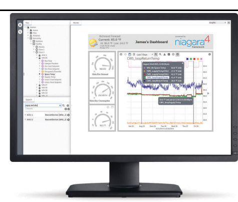
Servers and supervisory controllers have overlapping functions, such as supervising field controllers (logic and scheduling), alarms, and providing access to graphics and trends (when a computer is connected to a supervisory controller). Servers provide additional functionality such as:

- Additional or more sophisticated alarms, monitoring, and reporting.
- Longer-term trends, especially when connected with a database.
- Ability to support multiple buildings.

The server may be physically located onsite or may be hosted at a "cloud" server. Typically, only large buildings or campuses have BMS servers.[14]

Table 2 shows examples of products from each of these four levels of control from three large BMS equipment manufacturers. The LRC does not endorse products or companies.

Table 2: Example products to illustrate building management system components from three leading manufacturers. The LRC is not endorsing these products or companies.

Control level	Honeywell	Johnson Controls	Schneider Electric
1. Sensor/actuator	 LY power relay	 M9124 actuator	 Foxboro thermocouple
2. Field controller	 Niagara Edge	 Metasys FEC	 Modicon M171
3. Supervisory controller	 Tridium Jace 8000	 Facility Explorer FX80	 Andover Continuum b4920
4. Server	 Niagara Supervisor	 Metasys ADS/ADX	 EcoStruxure Building Operation Enterprise Server

Communication protocols

A protocol is the method that the various devices within an HVAC BMS use to communicate with one another. The protocol defines the method of communication and the structure of data that is transmitted, so two devices need to use the same communication protocol in order to transmit data or commands to one another.

There are many BMS protocols in use, but the three that are most widely used are BACnet, LonWorks, and Modbus. All three of these protocols are considered “open protocols” because an international standard exists to define it, at least several manufacturers produce equipment that use it, and pieces of equipment using the same protocol can communicate with one another. The most widely used BMS product lines (such as the ones shown in Table 2) can communicate with one or more of these three protocols. Some devices are built specifically to use one communication protocol. Other devices, such as field controllers and supervisory controllers, may allow for protocol-specific plug-in modules, allowing them to communicate over multiple protocols.

Historically, communication protocols were developed within the area of HVAC BMS, and then were adapted for communications between BAS subsystems (e.g. between a connected lighting system and an HVAC BMS).

BACnet

The BACnet standard was first released in 1995 and is currently defined by ANSI/ASHRAE 135-2016 and ISO 16484-5.[15] The LRC observed that BACnet is likely the most common protocol among BMS equipment, based on the equipment on offer at the AHR Expo trade show (Atlanta Georgia, January 14-16, 2019). The BACnet Testing Laboratory currently lists 943 products as adhering to the BACnet standard.[16]

There are two BACnet network types. One is internet protocol, or BACnet/IP, which uses IP addresses to target devices over CAT5 or CAT6 cable. The other type is Master-Slave Token-Passing, or BACnet MS/TP, which uses 3- or 4-wire cable to connect devices (predominantly field controllers).

LonWorks

LonWorks started as a proprietary protocol from Echelon, but became an open protocol in 1999.[17] It is described in ANSI CEA 709.1 and EN-14908. LonMark International lists 471 certified LonWorks products.[18]

Modbus
Modbus is most commonly used at the sensor/actuator level of the BMS system, especially in the areas of industrial devices and energy metering.[14]

Connected lighting systems

Connected lighting refers to lighting systems that can be monitored and controlled from a central computer (also called a "server"). These systems incorporate sensors and controls and sometimes allow interaction with smartphones or other devices. The communication between the server and the rest of the lighting components goes through a gateway. The gateway either communicates with sensors or fixture adapters, depending on the architecture used by a particular brand.

Connected lighting systems generally fall into two categories: wired or wireless. Wired controls can either use separate signal and power lines or can use Power over Ethernet (PoE), which uses the same wire for both power and signal. Wireless communication protocols include Zigbee, Z-wave, Bluetooth, and Enocean.

IoT is a new trend in connected lighting, in which lighting products connect to the internet directly with WiFi or through a local gateway. This allows monitoring and control through the internet. Some products provide the feature of "self-discovery" by which these products automatically connect to the internet, which can save labor compared with having to manually configure (and possibly wire) the product setup.

Most commercial lighting manufacturers offer connected lighting systems including Daintree/Current by GE, Digital Lumens, Enlighted/Siemens, Hubbell, Acuity, Eaton, Signify (Philips), Cree, and Lutron.

Lighting-HVAC system integration

Lighting and HVAC can be tied together at any of the four BMS levels described in the section "Building management systems" above. The higher the level of integration, the greater the opportunity for more sophisticated control, but also the more expertise that is needed to install the system. For example, integration at the sensor/actuator level can be accomplished by an electrical contractor, while integration at the server level requires a BAS integrator and will involve the building's IT department.

Sensor/actuator level
At the sensor level, some occupancy/vacancy detectors feature dual outputs, so they can be used to control both a lighting circuit and an HVAC relay contact at the same time. An example

of such a sensor is the Steinel DT CM COM2-24 Dual Technology Presence Detector, which provides a 24VDC signal to a lighting power pack and a separate dry contact output for HVAC relays.[19] An advantage is that this level of control can be installed by electricians with no training in control systems. A disadvantage is that no additional logic is included.

Figure 6: Steinel DT CM COM2-24 Dual Technology Presence Detector. Source: https://www.crestron.com/en-US/Products/Lighting-Environment/Steinel-Products/Occupancy-Presence-Detectors/GLA-DT-CM-COM2-24

Field controller level

As discussed in the section "Level 2: Field Controller" above, field controllers can either be freely programmed or application-specific. Freely programmed field controllers can be programmed to control HVAC equipment (such as the temperature setpoints) based on the state of the lighting system or its controls. (In contrast, application-specific field controllers are often menu-driven and less suitable for connecting lighting sensors.)

One example of this is Acuity Distech's "Smart Room Control Solution."[20] Distech suggests that the benefits to integration at this level are reduced labor costs because the equipment comes pre-programmed and avoids building-wide wiring and increased reliability because if the control equipment in one room fails, the remaining rooms will continue to operate normally.[21]

Figure 7: Acuity Distech ECB-PTU series field controller (left) and ECx-Light Expansion Module (right), part of the company's "Smart Room Control Solution." Source: https://www.distech-controls.com/en/products/family/room-control-solution

Supervisory controller level

Multiple field controllers can be connected to a single supervisory controller. At this level of integration, logic can be used to integrate the BMS and lighting systems. For example, if a space is determined to be unoccupied based on the lighting controls, then the temperature setpoint can be changed (set back) from the level needed for occupant comfort and/or the VAV fan speed can be reduced. Additionally, the setback can differ based on the time of day (e.g. at night, a greater temperature setback can be used). Integration at this level requires mapping the lighting zones onto the HVAC zones.

An interface device may be needed between the supervisory device and a proprietary connected lighting control system. For example, the nLight Bacnet IP Interface Appliance connects a BACnet BMS and an nLight control system.[22]

Figure 8: nLight Bacnet IP Interface Appliance, used to connect an nLight control system and a BACnet supervisory device. Source: https://www.acuitybrands.com/en/products/detail/410426/nlight/nbacnet/nlight-bacnet-ip-interface-appliance

Server level

This level of integration is what is most typically referred to as BAS integration. BMS and lighting systems can be installed on their own networks (called "subnets") and have their own servers. This may be the case if (1) the systems were installed at separate times and are just now being integrated, (2) separate vendors are supplying the HVAC BMS and the lighting systems and each builds out their own systems, or (3) using a specialized (i.e. proprietary) lighting server is desired because it provides a greater level of control over the lighting system.

Examples of connected lighting servers that can interface with the BACnet BAS are the Lutron Quantum and Vive systems,[23] Cree SmartCast,[24] nLight SensorView,[25] and Osram Encelium Extend Manager with BACnet Interface Module.[26]

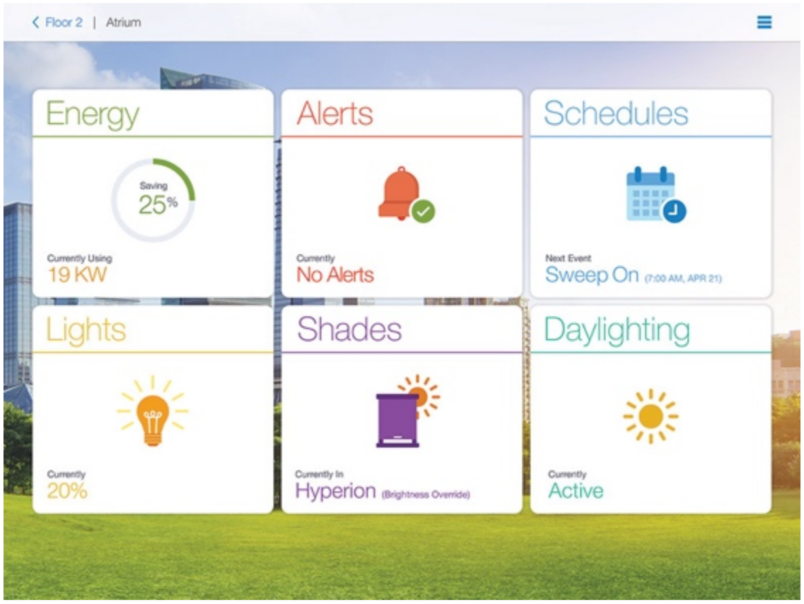


Figure 9: Lutron Quantum Vue interface. Source: http://www.lutron.com/en-US/Products/Pages/WholeBuildingSystems/Quantum/Features.aspx

A router is needed to connect the servers together. If each server does not natively communicate with the same protocol, such as BACnet, then an interface module is used to allow communications.

Lighting-HVAC energy savings opportunities

Six opportunities for reducing HVAC energy using lighting equipment were identified by the LRC. Of these, only the first, temperature and ventilation setback during vacancy, has been widely deployed. The other five concepts point the way to potential HVAC energy reductions in the future.

Opportunity #1: Temperature and ventilation setback during vacancy

Concept

Motion sensors for lighting systems communicate occupancy status to the BMS. When the space is vacant, the temperature and ventilation rate are set back to unoccupied settings. Here is an example of an HVAC BMS sequence for this purpose, as specified in a current experiment being conducted by Slipstream (formerly Seventhwave), and being supported by PNNL and the Cadmus Group:[27]

1. When the occupancy sensor indicates that the space has been continuously unpopulated for 5 minutes during the Occupied Mode, the active heating setpoint shall be decreased (setback) by 0.5°C (1°F) and the cooling setpoint shall be increased (setback) by 1°F (0.5°C).
2. The maximum temperature setpoint setback is limited to *X* (*X* to be determined in the field, initially can be set at 5°F (2.8°C.)
3. When the sensor indicates that the space has been continuously populated for one minute, the active heating and cooling setpoints shall be restored to their previous values.

In other words, for each 5-minute interval of continuous vacancy during the Occupied Mode the active heating setpoint shall be decreased (setback) by 0.5°C (1°F) and the cooling setpoint shall be increased (setback) by 0.5°C (1°F) up to a maximum setback of X.

Current status

This energy savings opportunity has been deployed in commercial buildings. The LRC was not able to find quantitative information on how frequently this strategy is implemented in the field. BAS experts had a range of opinions on how common it is to integrate lighting and HVAC in large commercial buildings.

- Charles Pelletier of Distech said, “This is fairly common in today's world.”[21]
- John Petze of SkyFoundry said, “About 20% of buildings have the capability, and of those about 60% actually implement it.”[28]
- Jon Sargeant of Integrated Building Solutions said, “Most modern systems can do this integration, but it’s rarely implemented. Less than 10% of buildings do this integration.”[29]
- Randy Mead of the Cadmus Group said, “It’s not widespread,” and he has not personally seen a lighting-HVAC integration in his years of work in the BAS field.[13]

Case studies

One example of using connected lighting vacancy sensors to control HVAC setbacks is an installation at Harvard University’s Fay House, home of the administrative offices for the Radcliffe Institute for Advanced Study. “The lighting controls were integrated with the BAS via BACnet, with the emphasis being on using lighting controls to drive HVAC schedules. The lighting controls report occupancy status to the BAS, which then adjusts the HVAC and other building systems accordingly.” The 2004 case study from Siemens notes that there were challenges in performing the integration. “During the early stages of the project, there were some failures at communicating through BACnet that forced multiple tries at getting communication online. While it was all eventually worked out, it showed the importance of clear specifications early in the process.”[30]

Potential energy savings

Currently, the only energy savings estimates are from computer modeling. In 2013, Zhang et al. at PNNL published the results of a computer simulation that calculated the energy savings from using lighting occupancy sensors to control the HVAC.[9] The authors simulated the same DOE prototype large (500,000 ft^2; 46,000 m^2) office building in each of the 15 climate zones in the U.S. The authors used the DOE EnergyPlus building energy simulation program to calculate annual energy use.

The simulation that used lighting sensors to control HVAC made the following assumptions:

Table 3: Summary of assumptions used in the Zhang et al. study.

	Occupied	Unoccupied
Private office	Ventilation 30% of peak design airflow	Ventilation off
	Cooling setpoint 75°F	
	Heating setpoint 70°F	
Open office	Ventilation 30% of peak design airflow	
	Cooling setpoint 75°F	
	Heating setpoint 70°F	
Conference room	Ventilation 50% of peak design airflow	Ventilation off
	Cooling setpoint 75°F	Cooling setpoint 79°F
	Heating setpoint 75°F	Heating setpoint 79°F

In addition, the lighting in private offices and control rooms was assumed to have a 15-minute delay period, while the lighting in open-plan offices did not have occupancy sensors.

The figures below from the Zhang et al. study show the annual energy savings as a fraction of total building energy use and as monetary savings. According to the authors, using occupancy-based HVAC setpoints can achieve a nationally weighted average energy savings of 5.9% in large commercial buildings.

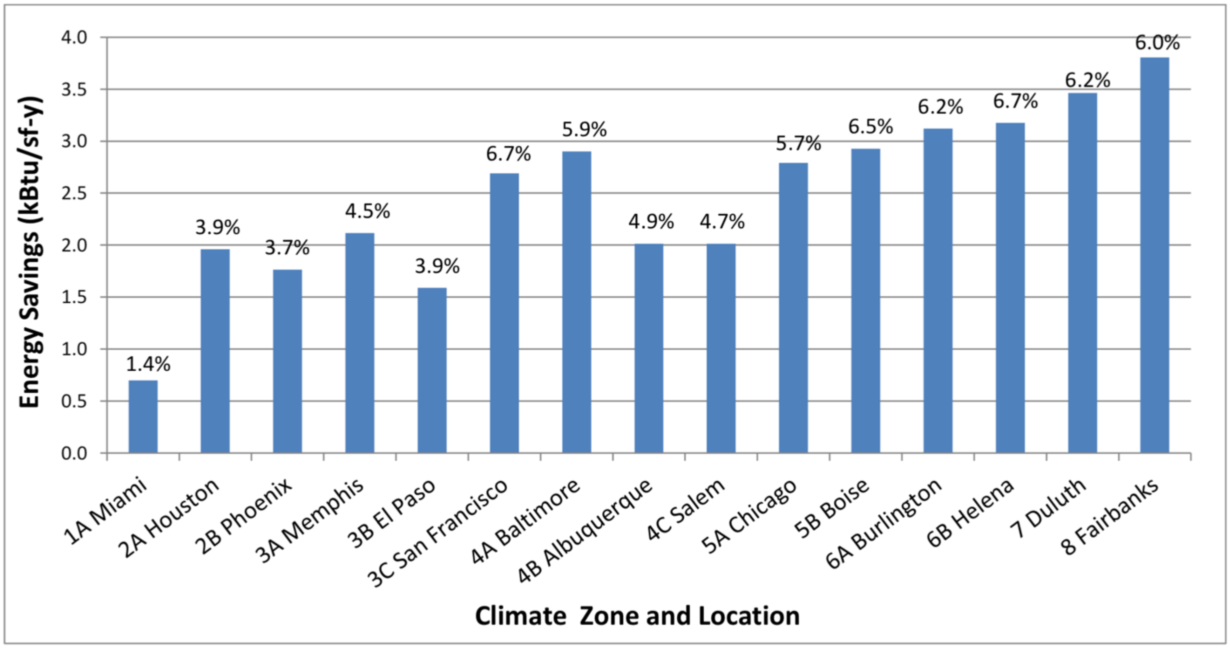


Figure 10: Energy savings from opportunity #1 calculated by Zhang et al.[9]

Randy Mead of Cadmus said that he ran an analysis of potential energy savings that would result from integrating the lighting occupancy sensors and HVAC system that are already installed in a seven-story office building. He assumed that the HVAC would be set back in a VAV zone after the lighting didn't detect occupancy for an hour. He found that the reduction in air flow, cooling, VAV reheat, air handling unit fan energy, and VAV box fan power added up to about 8% energy savings of the total utility bill. Mead said, "They already have LED lighting, and it's the most cost-effective thing they can do in their building right now." Despite this, the client elected not to perform the integration. Mead believes this may be due to a lack of financial incentive or budget allocations on the part of the people who would oversee the implementation. "The client has a facility contractor that runs their facilities, and they already have a budget set for the year."[13]

Capozzoli et al. conducted a field study at a five-story building close to Amsterdam in the Netherlands to determine the energy savings attained by changing from scheduled temperature setpoints to occupancy-based setpoints during the heating season. The base case was a schedule from 6:00 AM to 9:00 PM for the entire building. When they switched to a system in which "the shutdown time of the HVAC system was identified considering the last exit time for a group of occupants belonging to a specific thermal zone. The HVAC stop time was identified for each thermal zone and for each reference period. The reduction in the operational time of the HVAC system … was found to be 27.15 [hours] per week…" which resulted in energy savings of 10%.[31]

As mentioned above, there is currently a project underway by Slipstream to measure energy savings from using lighting sensors to control HVAC. The project includes at least four commercial sites (with a fifth site under negotiation) in the Minneapolis area (Xcel Energy service territory). The spaces under study include offices, a mixed academic use building (classes and office space), a mixed-use fitness center, and an outpatient health center. The buildings include a mix of HVAC systems, with at least one RTU and one central plant, and not all buildings have VAV terminals. In addition to controlling HVAC, the lighting sensors will also be used to control plug loads. All of the sites use the BACnet protocol for the BAS. During this experiment, the temperature setback will increase by 1°F (0.6°C) every five minutes until the maximum setback is reached. (Initially, the maximum setback will be 5°F (2.8°C), but can be changed as needed.) This study will also assess occupant acceptance. The results of the study are expected to be published by April 2020.[27]

Challenges

General challenges of integrating lighting controls with HVAC are discussed in the "System integration implementation" section below. Two challenges specific to this energy savings opportunity will be mentioned here.

First, the occupancy sensors used in BAS don't necessarily need to be part of the lighting. Many BAS systems include stand-alone occupancy sensors, which can be used by the lighting, HVAC, security, and other systems. While stand-alone sensors may work just as well from a technical/energy-saving perspective, they may not allow utilities to count lighting energy savings from an accounting perspective.

- Brian Stacy of Arup said that they are seeing many fewer installations with multiple occupancy sensors in each room. The occupancy sensor may or may not be part of the lighting system, and it depends on how the system integration is configured.[32]
- Kevin Van Den Wymelenberg of the University of Oregon said that the use of stand-alone occupancy sensors for HVAC varies by building type. He said that many schools have them, but office buildings typically don't because many offices are all part of one HVAC zone.[33]
- Randy Mead of Cadmus also said that the use of PIR occupancy sensors is dependent on the space type. They are most frequently found in computer labs and K-12 schools.[13]
- Eugene Gutkin, President and CEO of Integrated Building Solutions (IBS), said that his company prefers to use wireless stand-alone sensors. IBS has found that they are more sensitive for their needs and can be moved as needed. They use sensors built into lighting only as needed for retrofit projects.[34]
- Scott Cochrane, President of Cochrane Supply, estimates that fewer than 10% of commercial buildings have stand-alone occupancy sensors for HVAC. They're in big buildings and built into the thermostat.[35]

A case study that used one set of occupancy sensors to control both the HVAC and the lighting was a project completed by CannonDesign at the North American headquarters of an unspecified company. Different control strategies were used for different areas of the building. The HVAC for the open office space and scientific laboratories was based on schedules, not occupancy sensors. "The inboard offices, conference spaces, and breakout rooms aligned at the core are all provided with integrated occupancy controls that control the lighting, HVAC, and switched receptacles in the room. The base-building HVAC for these spaces is a traditional VAV air system. When rooms are vacant, the lighting and receptacles shut off and the HVAC systems reset temperature and air-flow setpoints. The occupancy/vacancy signal from the lighting controls system communicate to the HVAC controls through a BACNet interface."[36]

Barry Coflan, Chief Technology Officer at Schneider Electric, said that another challenge to setting back HVAC in commercial buildings is thermal inertia.[12] In other words, once occupants return to a space, it will take time to bring the temperature back to the occupied setpoint, and occupants may be uncomfortable in the meantime.

A third challenge may be reduced performance of HVAC systems, which were not designed for frequent cycling. Assistant Professor Gang Wang of the University of Miami College of Engineering recently was awarded a U.S. DOE Building Technologies Office Building Energy Efficiency Frontiers and Innovation Technologies (BENEFIT) Award to study this issue. A press release about the award says, "Occupancy signals greatly increase the dynamics of HVAC systems and introduce inconsistent behaviors, which reduce the efficiency of the HVAC operating units and can be damaging to the HVAC systems in the long run. The elevated dynamics generate challenges for reliable HVAC operations and therefore prevent the implementation of integrated operations for maximum efficiency." The project is intended to validate in real-world buildings an HVAC control algorithm that Prof. Wang developed in the laboratory. He is working in collaboration with Siemens and the University of Oklahoma on the project.[37]

Research needs

Utilities with incentive programs should consider investigating the following queries.

- How common is it for stand-alone PIR sensors or LLLCs to control HVAC systems? This would help determine additionality.
- What energy savings can be expected from integrating lighting and HVAC systems? The Slipstream project discussed above is intended to answer this.
- What HVAC and ventilation setbacks and timeout periods can be used without negatively impacting occupant comfort? For example, Michael Myer of PNNL notes that you may need a longer delay for HVAC than for lighting.[38]
- What is the optimal control logic for different building scenarios? Charles Pelletier of Distech suggests that more sophisticated control strategies would be preferable to just an occupied setpoint when a room is occupied and a single setback when the room is vacant. For example, different setbacks could be used depending on the season of the year, whether it is during business hours or not, or whether occupants are detected in nearby areas. He also suggests that in conference rooms, occupants should be allowed to set their desired temperature manually, but when the room is vacant, the temperature should be returned to a standard setpoint.[21]

Opportunity #2: Variable ventilation

Concept

As discussed in the section "HVAC " above, ventilation requirements are defined by ASHRAE standards in terms of a particular CFM of outdoor air per occupant, with the rate dependent on the space type. The outdoor air is mixed with recirculated air in order to comfortably maintain the temperature of the space while minimizing the conditioning of the fresh outdoor air. Conditioning of the outdoor air and moving the total air volume both require energy, so the less ventilation that is provided while still meeting codes and requirements for occupant comfort, the less energy is used. John Petze of SkyFoundry notes that "the energy used by a fan for ventilation varies with the cube of the volume of air. If you cut the flow in half, you cut the fan energy by 8."[28]

Currently carbon dioxide detectors, which measure the built-up CO_2 from occupant exhalation, are sometimes used to control ventilation rates. But according to Kevin Van Den Wymelenberg, the calibration of these sensors often drift over time and their resolution is not high enough to adequately control variable ventilation.[33] If information from lighting sensors could be used to detect the number of occupants in a space (e.g. the fraction of LLLC sensors in a space that report occupancy), then both energy savings and increased occupant comfort could potentially be achieved.

The DOAS HVAC system described in the section "Dedicated outdoor air systems" above is ideally suited to variable ventilation because with this system the ventilation rate is independent of the sensible load.

Current status

The LRC did not identify any buildings using lighting controls to detect the number of people in an occupied space for the purpose of controlling ventilation.

There is one experiment that is being planned to investigate this concept. Kevin Van Den Wymelenberg, who is an Associate Professor at the University of Oregon, will conduct the study, which is funded by the Northwest Energy Efficiency Alliance (NEEA). The pilot experiment will be conducted on a floor of an office building, including open offices, private offices, and conference rooms, using connected lighting equipment from Siemens/Enlighted. The experiment will test how well LLLCs can be used to estimate the number of occupants in a space (for both accuracy and confidence levels) and use the data to improve on an algorithm that the research team previously developed. The LLLC predictions will be compared against the signals from CO_2 detectors.[33]

Potential energy savings

The Zhang et al. study discussed above also calculated the energy savings using sensors that can count the number of people in a room and adjust the ventilation flow rate accordingly. The authors used the same assumptions shown in Table 3 except:

- The lighting in private offices and conference rooms had a 5-second delay.
- The ventilation in private and open-plan offices varied between 0% and 30% of peak airflow, depending on the number of occupants, and the ventilation in conference rooms varied between 0% and 50%.
- Cooling and heating setbacks were used in private offices.

The energy savings results are shown in the charts below. According to the authors, the nationally weighted average energy savings is 17.9% of total building energy for large commercial buildings. They note that this is "an increase of more than 200% in national-average energy savings" compared with the 5.9% savings calculated for the simpler occupancy/vacancy controls discussed in the section "Opportunity #1: Temperature and ventilation setback during vacancy" above. Unfortunately, the report does not provide information on how much of the energy savings can be attributed to the variable ventilation rather than the more aggressive lighting delay time and private office temperature setbacks.

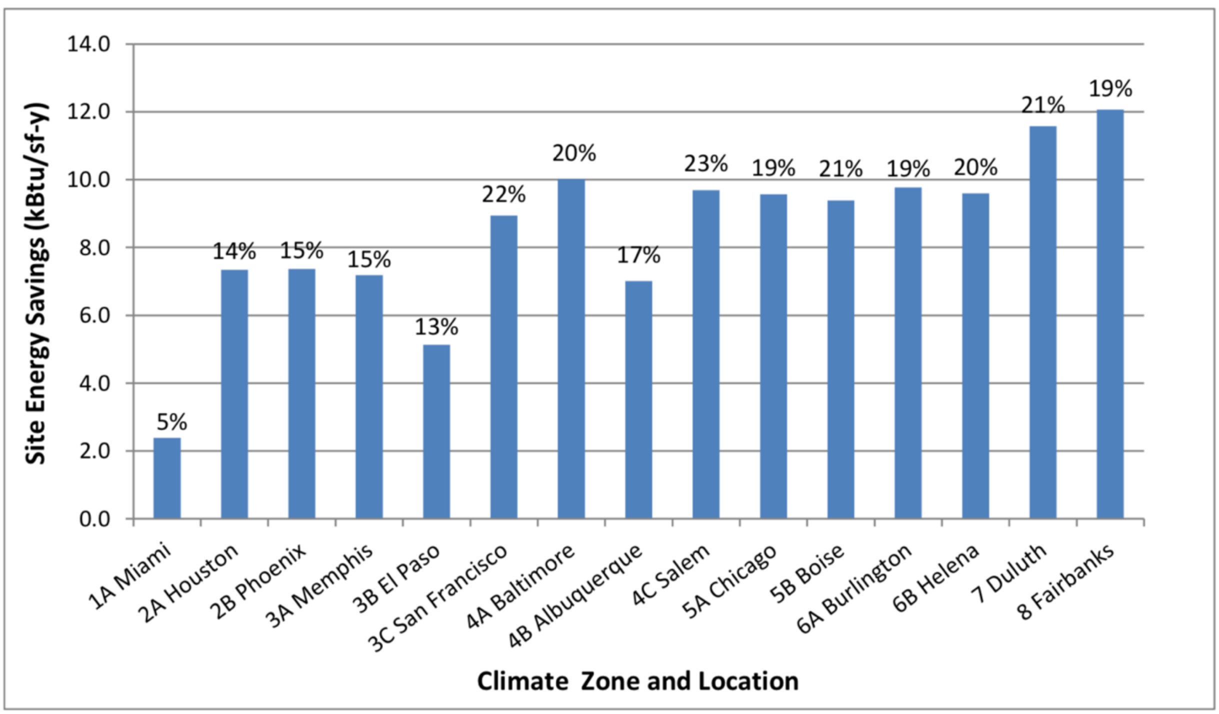


Figure 11: Energy savings from opportunity #2 calculated by Zhang et al.[9]

Challenges

The greatest challenge to implementing this strategy is the lack of commercially available solutions to counting the number of people in a commercial space. The ability of LLLCs to count people is currently unknown, but is being explored by Van Den Wymelenberg, as mentioned above. Some technologies are being developed for a single sensor to count the number of occupants in a space, such as imaging sensors that were developed at the National Renewable Energy Laboratory and licensed to Known Quantity Sensors, Inc.[39]

A second challenge for this strategy is that ANSI/ASHRAE Standard 62 -2007 does not allow ventilation rates to be completely turned off in unoccupied spaces due to off-gassing from furniture, rugs, and other materials. Zhang et al. argue that this standard should be reexamined "because any non-occupant-originating indoor pollutants that build up while the ventilation is off in conference rooms and private offices (the only spaces for which occupancy-based control (OBC) for terminal boxes is considered in [their] study) will decrease relatively quickly as soon as an occupant enters and the terminal box begins to provide air flow for ventilation. Ventilation standards committees may decide to reconsider this constraint on ventilation control for some spaces if the potential energy savings are significant and the risk of exposure to unhealthy pollutant concentrations can be shown to be low."

A third challenge is that traditional HVAC systems are not well-suited for variable ventilation. As Zhang et al. note, "At low occupancies and low loads, design minimum ventilation rates may exceed the supply air-flow rate required to maintain a comfortable room temperature, potentially causing the room to be overcooled, especially for interior conference rooms served by terminal boxes without reheat." This challenge could be addressed in new construction by using DOAS HVAC, as described above.

Research needs

According to Zhang et al., variable ventilation rates (in conjunction with more aggressive setback and delay period sequences) have the potential to save about 3 times as much energy as HVAC setbacks alone. Research that could advance this strategy are:

- Determining how closely the fraction of LLLCs that detect occupancy in a space correlates with the number of people in that space. This is currently being investigated by Van Den Wymelenberg.
- Identifying and testing the performance of advanced sensors that can count the number of occupants in a space.
- Using lighting controls to vary ventilation rates in a DOAS installation.

Opportunity #3: Office space consolidation

Concept

Commercial building managers can use occupancy sensors to identify offices or other spaces that are vacant or underutilized, relocate work spaces to achieve a higher person per square foot ratio in occupied areas and consolidate the vacant spaces, and then set back the HVAC of the unoccupied portion of the building.

Current status

Connected lighting systems already offer this feature. For example, Acuity offers the Atrius Spaces web app for BAS[40] and the Space Utilization Edge app,[41] Osram offers the Lightelligence platform,[42] Enlighted offers the Space application,[43] Signify offers Interact Office,[44] and Lutron offers Quantum Space Utilization Reports software.[45] However, it is not known how frequently building managers use the information to consolidate workers for the purpose of energy savings. Typically, the software is used to find under-utilized space in order to utilize it, which spreads occupants out rather than consolidating them.

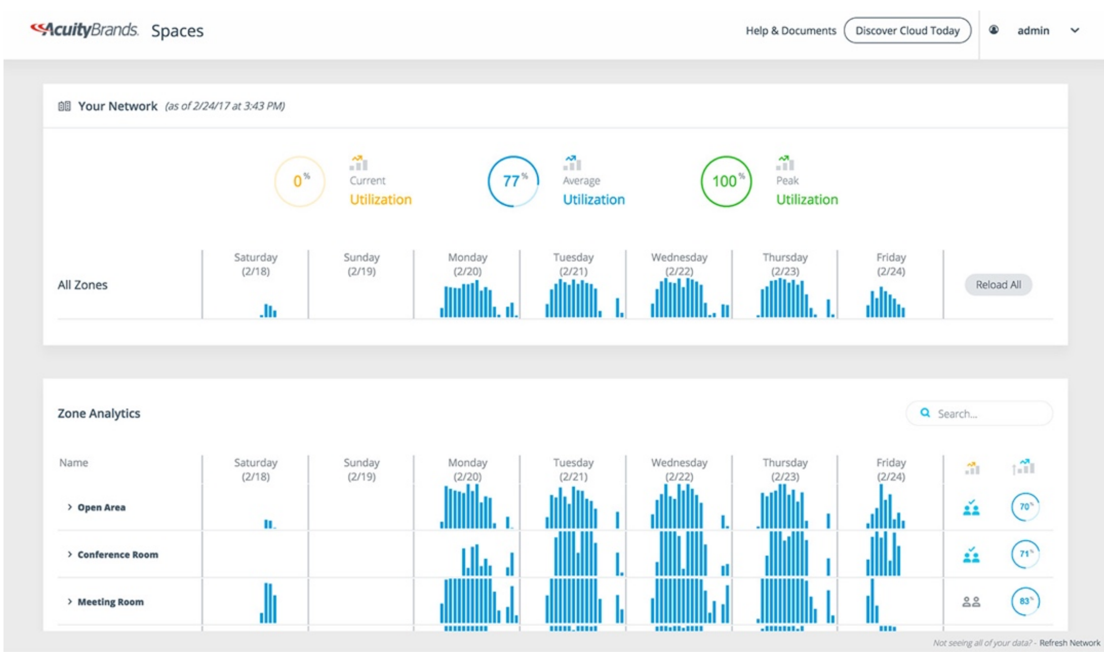


Figure 12: Acuity Space Utilization application. Source: https://www.acuitybrands.com/products/detail/677545/acuity-brands/svsu-application/space-utilization-application

Potential energy savings

Knapp et al. studied the real estate utilization of nine corporate office buildings and found “companies who have an effective occupancy planning program achieved an average of 35 percent reduction in their portfolios.”[46] One study found that for “each degree increase in thermostat setting above 70°F (21°C) in summer can save 0.4-0.7% of total electricity consumption" and "each degree lowering thermostat less than 70°F (21°C) in winter can save 1.4-3.5% of total natural gas consumption."[47] According to the U.S. Energy Information Administration, 116 trillion Btu per year are spent cooling commercial office buildings, and 19 trillion Btu are spent heating them.[48] If 35% of that office space were unoccupied and consolidated and had a setback of 5°F (2.8°C), then 1.1 trillion Btu per year of electricity could be saved and 0.8 trillion Btu per year of natural gas could be saved.

Instead of, or in addition to, spatial consolidation of occupants, building managers can group occupants based on their typical arrival and departure times. This concept was explored by Capozzoli et al. which grouped employees of an office building into thermal zones using machine learning techniques based on when they logged into and out of their computers for the day. Energy savings resulted from controlling HVAC based on occupancy, and the groupings allowed the HVAC system to be more frequently set back. The authors found that "the HVAC schedule occupancy-based post-reconfiguration generated a further reduction of 4.2% (7.3 MWh) at the whole building level for the monitored period during the heating season (from January 2016 to April 2016)," which is additional to the 10% savings achieved by occupancy-based HVAC control prior to the occupant reconfiguration.[31]

Challenges

One challenge with office space consolidation to save energy is that facility managers often have the opposite goal in mind; for example, they would like to help occupants identify and make use of underutilized conference rooms.

A second challenge is that even if 35% of space could be consolidated, its HVAC zones may overlap with occupied zones, at least in part, so the temperature could not be set back.

Research needs

Research is needed to identify with more certainty:

- The fraction of commercial building floor areas that could be consolidated into unoccupied areas.
- The amount of energy that can be saved by setting back the temperature of unoccupied areas in commercial buildings.

Opportunity #4: Artificial intelligence and machine learning

Concept

There are currently two methods of setting back temperatures in commercial buildings: either occupancy sensors trigger the setback or the temperature is set back on a manually-set schedule. It is possible that AI could be used in the form of a machine learning algorithm to predict occupancy patterns of spaces and set back the temperature more effectively with less impact on occupant comfort.

Current status

AI has been commercially deployed to help in the maintenance of HVAC equipment[49] (which can indirectly reduce HVAC energy use by keeping equipment at optimal performance), but the LRC has not identified the commercial use of AI to reduce HVAC energy use through occupancy prediction. However, several laboratory/test-bed studies have been performed, discussed below.

Potential energy savings

Peng et al. conducted a study on demand-driven cooling control (DCC) with learning capabilities, in which the authors used machine learning to control the temperature in an office building in Zurich. The experimental area included "2 multi-person offices, 8 single person offices, and a meeting room. Each room is regarded as a single thermal zone…. [S]ensible cooling is delivered by passive chilled beams (PCBs), and room air temperatures are controlled by regulating the chilled water flow rate of PCBs with motorized balancing valves." Motion sensors and temperature control interfaces were installed in each room. The DCC system "automatically responds to occupants' energy-related behavior for reducing energy consumption and maintains room temperature for occupants with similar performances as a static cooling. In this control strategy, two types of machine learning methods — unsupervised and supervised learning — are applied to learn occupants' behavior in two learning processes. The occupancy-related information learned by the algorithms is used by a set of specified rules to infer real-time room setpoints for controlling the office's space cooling system." The results showed that energy use was reduced by 7% in open offices, 21% in private offices, and 52% in meeting rooms compared to a static-schedule baseline (with occupancy scheduled from 7:00 AM to 6:00 PM on weekdays).[50] No comparison was made with vacancy-based setbacks, so the study did not determine the effect of machine learning versus simply using vacancy sensors (Opportunity #1).

Schneider Electric has partnered with Microsoft to examine the use of AI to control the HVAC in conference rooms.[12] Typically, the Schneider Electric equipment uses PID (proportional integral derivative) controllers with CO_2 and temperature inputs. In preliminary research, they found that AI saved the same amount of energy, through pre-heating and pre-cooling, as PID. However, when occupancy detection data was also fed into the AI, energy savings increased by 20%, which Schneider Electric feels is significant. Therefore, occupancy detection from LLLCs, coupled with AI predictive algorithms, offers the potential for significant energy savings.

Vishwanath et al. conducted a study using "grey box" machine learning to pre-cool a commercial building in Townsville, Australia that houses about 250 people. The grey box model was used to determine how far ahead of occupancy to cool the building and what setpoints to use. Results showed that "optimal pre-cooling reduces peak power by over 50%, energy consumption by up to 30% and energy bills by up to 37%."[51]

Wang et al. used an iBeacon-enabled indoor positioning system (IPS) to track occupant locations. The authors then used these position measurements with machine learning techniques to control the VAV terminals in six thermal zones to match the cooling load to occupancy in a thermal simulation of the office space. This is a more sophisticated technique than simply setting back the HVAC when a thermal zone is unoccupied by using motion or CO_2 sensors. The method proposed by Wang et al. is able to provide "fine-grained occupancy patches to guide the HVAC operation so that the conditioned temperature distribution can match the distribution of occupants. As a result, the problem of space overcooling and over-heating can be effectively addressed." The simulation results found that the proposed method achieved a 20% reduction in energy, compared with a conventional control system using a PID controller monitoring the return air temperature.[52]

Challenges

One challenge to implementing AI-based strategies to control HVAC is that the algorithms need to be incorporated into the BAS server. Unlike other energy saving strategies, building owners and managers cannot implement this on their own, but rather would rely on the BAS software developer to incorporate this as a feature.

A second challenge is that some of the AI algorithms require "training" using the data from a particular space. This would be challenging in a real-world environment, and software developers would likely need to limit their options to self-learning techniques. However, according to LRC Scientist Andrew Bierman, it takes time for self-learning systems to gather enough data to arrive at a good solution, and energy savings, occupant comfort, or both will suffer during this period.[53]

Research needs

The academic studies identified by the LRC compared AI-based energy savings against traditional baselines, such as scheduled temperature setpoints. Research is needed to identify how much additional energy could be saved by incorporating AI compared with the other advanced techniques.

There are a number of different AI techniques available. In the studies referenced here, the authors pre-selected one technique to use. Research is needed to identify the machine-learning techniques that can result in the greatest energy savings and performance.

Opportunity #5: Smaller thermal zones

Concept

This opportunity increases the energy savings potential of "Opportunity #1: Temperature and ventilation setback during vacancy" by decreasing the size of thermal zones. It is analogous to reducing lighting energy use by switching from zone controls to LLLCs. The more granular the thermal zones, the more opportunity to set back the temperature and ventilation, thereby increasing HVAC energy savings.

In a typical commercial building, thermal zones are defined by the area serviced by each VAV terminal. As noted in the “HVAC ” section above, a thermal zone can be up to 27,000 ft^2 (2,500 m^2), though many are smaller than that and typically include a suite of private offices or roughly 10 to 15 workstations in an open office. Randy Mead of Cadmus believes it will be difficult to save significant amounts of energy by using lighting sensors to control HVAC simply because of the large size of typical HVAC zones.[13]

As noted in the “Opportunity #1: Temperature and ventilation setback during vacancy” section above, one challenge is that a BAS can use one set of occupancy sensors to control both the lighting and the HVAC BMS, so the lighting system is not being used to reduce HVAC energy. There is little incentive to make use of the highly granular occupancy data from LLLCs because the HVAC thermal zones are as large as traditional lighting zones. If smaller thermal zones were implemented in a building, then there would be a greater incentive to make use of granular LLLC occupancy data, so lighting may have a greater role to play.

It is possible to implement this opportunity by installing actuators at air registers or dampers upstream of diffusers and controlling them with thermostats installed at every vent or diffuser. However, this is rarely done in practice due to the cost of the added equipment and the additional labor it would take to wire and program the extra thermostats and actuators into the BAS. John Petze of SkyFoundry notes that creating more thermal zones requires additional equipment, so there might not be a cost advantage.[28]

The LRC identified two companies that offer commercially-available products that control the flow of air through individual ducts. The manufacturers claim that these products can be installed for less cost than traditional vent actuators and controls.

One company that offers such a duct-control product is Emme Control, based in Bristol, CT, which offers a system that places inflatable dampers upstream of every vent, a central air supply for inflating the dampers, and a wireless control system that inflates and deflates dampers individually. According to their website, “a rugged, pneumatic damper is placed in every duct run. The Pneumatic Damper is connected by plenum-rated tubing to a Master Unit that causes the Pneumatic Damper to either inflate or fully deflate. When inflated, the Pneumatic Damper completely shuts off the flow of air to the register. When deflated, the Pneumatic Damper allows conditioned air to flow.”[54] This product is suitable for new construction or can be retrofitted into existing ducts.

Figure 13: Emme pneumatic dampers for different duct types. Source: https://www.getemme.com/how-it-works/

Another company that offers a duct-control product is Air Fixture of Kansas City, KS. They offer a number of products for underfloor air distribution (UFAD) systems. Rather than using ducts, UFAD supplies conditioned air to a below-floor plenum, and one diffuser is installed at the floor at each work station. Occupants can manually adjust the diffuser to allow more or less conditioned air into their work area or office. The Air Fixture company recently introduced the Prestige Wireless Variable Air Volume Diffuser.[55] This product adjusts the airflow through the diffuser based on the temperature of the space. It is battery operated (rated for 10 years) and controlled wirelessly, so no wiring is needed during installation. Up to 32 diffusers are controlled with one Zigbee “signal concentrator.”

Figure 14: Air Fixture's Prestige Wireless Diffuser works with below-floor air plenums. Source: https://airfixture.com/product-line/prestige-wireless-diffuser.

Current status

Currently, the two products discussed above are controlled by thermostats, but it would be technically feasible to use the signals from LLLCs to control them based on occupancy as well.

Potential energy savings

The LRC was not able to identify documentation of the potential energy savings from using smaller HVAC zones with occupancy control. This is likely because the technology needed to implement this system is relatively new and isn't widely deployed. A presentation from Emme indicates that energy is reduced by "up to 5% per room" due to reducing the conditioning in unoccupied rooms, but details are not provided on how that figure was established.

Despite the lack of research available on this topic, this concept may hold promise for HVAC energy savings. In a similar way to LLLCs offering significantly greater lighting energy savings compared with zone controls, smaller HVAC zones hold promise by increasing the granularity of the controlled area. This will be especially effective for multiple private offices supplied by one VAV terminal. Research will be needed for energy savings in open offices due to air mixing.

Challenges

One challenge to reducing HVAC zone size is the added labor and expense needed to add the requisite equipment.

A second challenge is that while it is technically possible to connect occupancy information from LLLCs or BAS to HVAC zone control equipment, this would require custom programming.

A third concern was voiced by Randy Mead of Cadmus, who said "If you close off one vent, you're going to start driving more air into another zone. I'm concerned about air noise in zones that remain open."[13]

A fourth challenge is that air-mixing may prevent smaller HVAC thermal zones from being effective in open offices and other large spaces.

Research needs

As discussed above, using LLLC occupancy information to control small HVAC zones has not been practiced commercially to the LRC's knowledge. Research is needed to determine:

- How much energy can be saved in different types of commercial spaces, such as open and closed offices.
- How best to communicate between the lighting sensors and the HVAC zone controls.
- The payback/ROI for new construction and remodeling.

Opportunity #6: IoT in small commercial buildings

Concept

As discussed in the section "Building management systems" above, a BAS requires many components to be specified, purchased, installed, and programmed. The resulting labor and capital expenses are large enough that such BAS are economically feasible only for large commercial buildings. As noted in the section "Building automation systems" above, BAS are typically installed in only large commercial buildings. A certain amount of engineering and planning is required no matter how small the building, so the total cost is not directly proportional to the area of the building.

Some in the BAS industry see "Internet of Things" or IoT devices as a potential path toward lower-cost BAS. Some define IoT devices as those which connect to the internet directly, but others include devices that require a gateway in the definition of IoT. (In contrast, traditional BAS have a primary server, sometimes called the "head end." While both Bacnet and LonMark have or are developing protocols to communicate with devices via the internet, they currently require communicating through a server.) From a web-based interface, each device can be mapped, monitored, and controlled by BAS logic. This may reduce BAS labor costs due to potentially lower planning/engineering costs, commissioning, and installation costs. It may also reduce equipment costs by avoiding the need for field controllers and supervisory devices, which are expensive. Scott Cochrane, of Cochrane Supply notes, "Traditional BAS cost $2 to $3 per square foot. This is cost prohibitive for small commercial building owners. In contrast, a web-based thermostat only costs $100 to $300, and installation costs $100. Costs have been high because of hardware, and now it's turning into a software issue which will bring costs down. With IoT, we're now seeing hair salons and bank branches getting BAS."[35]

The lighting controls company Synapse Wireless offers an example of reduced labor needed to install an IoT networked control system. According to the company, manufacturers embed the controllers in each luminaire. (The embedded hardware costs about $70 per luminaire.) No engineering is needed because each luminaire gets the same chipset. Electricians install several gateway devices in addition to installing the luminaires. (Synapase helps installers determine how many gateways are needed and where they should be located.) Each luminaire has a QR code that the installer can scan to assist in mapping the fixtures within the building. As soon as the luminaires and gateways are powered up, they automatically form a mesh network and connect to the internet. From any remote location, Synapse or the building manager maps the luminaires onto the layout of the building and then sets up schedules and/or control logic. The lighting system can be tied into a BAS through BACnet.[56]

If IoT fulfills the potential for designing, specifying, installing, and commissioning BAS with significantly lower labor and equipment costs, then this creates the opportunity for economically using BAS in smaller commercial buildings, which in turn opens up a significantly larger market and energy savings opportunity.

Current status

While the BAS industry is still in the early stages of incorporating IoT, there are several companies operating in this space. In the lighting industry, Synapse Wireless (mentioned above) Enlighted, and Daintree (now part of Current by GE) are a few examples of early players in the commercial market. In the HVAC BMS industry, IoT deployment companies include SkyFoundry and Small Box Energy.

Using IoT lighting equipment to control IoT HVAC equipment is a nascent field. Tracy Marckie of SmallBox Energy, a company that uses IoT devices to monitor and control small commercial building systems such as restaurants, has, “seen lighting used to control HVAC with IoT a few times. However, these were done with custom-written web applications. There isn’t a general web application that allows this yet.”

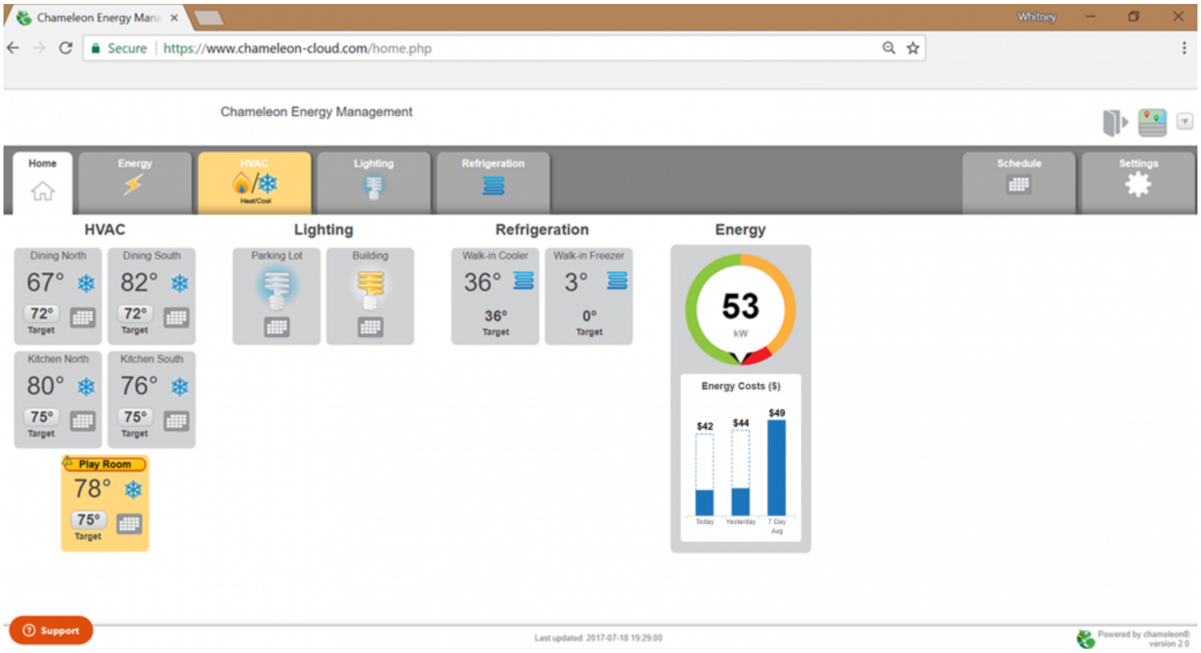


Figure 15: SmallBox Energy customer dashboard example. Source: http://www.smallboxenergy.com/lot_platform/#row1

Two companies have positioned themselves to provide the backend for IoT through their cloud services: Amazon Web Services and Microsoft Azure. Almost all BAS IoT equipment manufacturers use one of these two services to collect and process the data from hardware. These services provide analytics, data visualization, machine learning, incorporation of additional information such as weather forecasts, and device management.

Potential energy savings

As discussed in the five energy savings opportunities described above, using lighting sensors to control HVAC is likely to offer significant energy savings opportunities. However, these opportunities are limited to large commercial buildings due to the economics of BAS. In the U.S., commercial buildings greater than 100,000 ft^2 (9,300 m^2) have a combined floorspace of 30.2 billion ft^2 (2.81 billion m^2), while commercial buildings less than 100,000 ft^2 (9,300 m^2) have a combined floor space of 56.9 billion ft^2 (5.29 billion m^2).[57] Assuming that HVAC energy savings opportunities are proportional to floor space, penetrating the small commercial building market would result in energy savings almost three times greater than the current market.

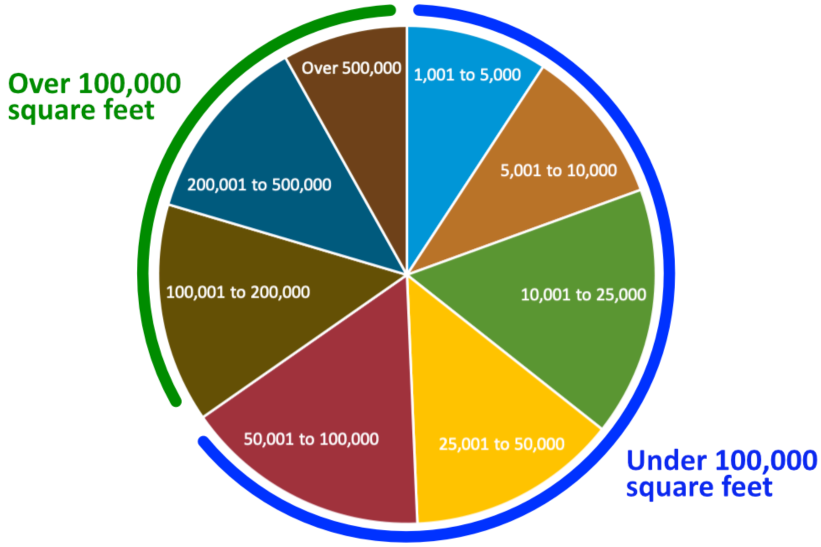


Figure 16: U.S. Commercial buildings by floor area.[57]

Challenges

There are three primary challenges to using connected lighting systems to control HVAC in small commercial buildings.

First, there is a lack of available IoT lighting and HVAC products intended to be installed in commercial buildings and that can be connected through a single web platform. In fact, Scott Cochrane, President of Cochrane Supply & Engineering, a building controls supplier in Michigan, said that U.S. small commercial buildings are using IoT products intended for the residential market, such as those sold at big box home improvement stores, but there is commercial availability of IoT products in Europe.[35] Brian Stacy of Arup also notes that there is much more widespread availability of commercial IoT products in Europe.[32]

Second, the cost and payback of using IoT products in small commercial buildings is unknown. In other words, will the anticipated reduced costs be realized, and are they sufficiently low to provide an attractive payback period?

Third, traditional electrical installers don't have the training to install IoT devices. According to Barry Coflan of Schneider Electric, "It's not trivial to install. You don't need an electrician, you need a 'tech-trician' with computer science knowledge. Some electricians can figure this out, but it's not what they typically do, which is to pull wires. We're starting to see some small hybrid companies in this space, but it's still elusive. Currently, no one is doing IoT for small box retailers like Starbucks or convenience stores. It's not the technology, it's a labor issue. I believe there is a business opportunity for a company to supply the product, provide training over the internet, and execute deals with clients. They would then contract with authorized vendors to do the installation."[12]

Research needs

Research is needed to address the challenges discussed above. First, IoT equipment and services must be identified and proven to work in small commercial buildings. Second, the economics of IoT in small commercial buildings must be documented.

Lighting-HVAC non-energy benefits

While the focus of this report is on energy savings, some of the experts interviewed by the LRC noted that integrating lighting and HVAC controls can result in non-energy benefits as well. For example, Charles Pelletier of Distech said that identifying the exact location of each occupant can improve comfort because the HVAC system can prepare for the heat or cooling load proactively.[21]

Both Scott Cochrane of Cochrane Supply and Kevin Van Den Wymelenberg of the University of Oregon said that using lighting occupancy sensors can do a better job of determining the number of occupants in a room than traditional CO_2 sensors, which will allow variable ventilation systems to better match ventilation rates with occupancy levels. Van Den Wymelenberg believes “Comfort and quality should be #1 period.”[33,35] Other experts felt that current PIR sensor technology is not sufficiently accurate to be used to control ventilation rates, which would negatively impact occupant comfort, and more advanced “people counter” sensors would be needed for this application.[21,29]

System integration implementation

Barriers

Although BAS currently integrate HVAC BMS and other systems including lighting, there are still a number of challenges. Some challenges are specific to each energy savings opportunity, and are discussed in the appropriate sections above. The challenges below are more general and apply to many integration projects.

Lack of cooperation between trades

Several experts the LRC spoke with noted that system integration requires greater cooperation between trades, and therefore subcontractors, than non-integrated building systems require.

Paul Kondrat of CannonDesign puts it this way: “Another challenge between HVAC and lighting controls integration is identifying who connects what wire to a device. When construction managers buy out projects, the divisions of labor are frequently drawn between low-voltage control wiring (i.e. less than 120 V) and 120 V or higher voltage power wiring. It can become more difficult to integrate systems when this type of division happens. For example, one contractor is running the 120 V power for lights or integrated receptacles, but the controlling devices that switches them are 24 V. This results in two electricians, frequently from two companies, working in the same space on the same system. Having one electrical contractor that has experience working with the mechanical and selected controls contractors can go a long way toward achieving success and avoiding the pitfalls of typical division-of-labor issues."[36]

Brian Stacy of Arup notes that integrating multiple systems through a BAS can present a challenge to the traditional division of labor in the building trades. Integrating systems gets contractors concerned about their scope of work for two reasons. First, the line between trades can be blurred (e.g. is low voltage signal wiring part of electrical or IT), which can create gaps. Second, it takes more time to get the interfaces working. Traditionally, one contractor would finish their own work and their job would be done. With system integration, it can be less clear to the contractor when their job is complete and they can get paid.

Barry Coflan of Schneider Electric said that traditionally, in a closed office, there is often an occupancy sensor for HVAC and another one for lighting. Two companies can come in at separate times during construction, and each can get sign-offs when their work is complete. Coflan notes that using one sensor for both lighting and HVAC causes complications. "If the second guy doesn't show up or won't share data, then the first guy can't finish his work and get paid."[12]

Lack of component standardization

Paul Kondrat of CannonDesign says, "An additional hurdle to cross regarding coordinating the controls between lighting, HVAC, and beyond is a fear of commitment and being tied to a single vendor. Even though today's controls operate on a more open protocol, we find ourselves placing faith in one provider to integrate systems and programming. Controls systems in this industry have yet to reach the level of standardization that information technologies have progressed. The level of commoditized standardization hasn't evolved to a point that allows seamless integration."[36]

Best practices

Long-term planning

According to Paul Kondrat of CannonDesign, "Successful integration projects need commitment from design and installation teams to follow the original vision through to a final, reliable solution."[36]

Brian Stacy of Arup says that because BAS integration projects often take several years to be completed, successful projects require long-term commitment from both building owners and agencies providing incentive funding. Common problems include changes in project staffing and changes in standards. For example, a change in IT protocol due to security concerns can eliminate interoperability of building systems. To overcome this, a long-term technology strategy is needed for each building. This needs to be created by a professional who can develop a technology master plan for the business, but there are not many people with this capability, according to Stacy.

Buy-in from the building owner

John Petze of SkyFoundry observes, “The lighting and HVAC [specifiers and installers] never talk to each other, and both are trying to get to lowest first cost. More progressive building owners have heard of integrating HVAC and lighting, and ask for it, but they need to direct the controls people to do it.”[28]

Specify equipment that works on open protocols

Communication protocols allow BAS equipment to communicate. There are many protocols in use, but selecting an open protocol provides the greatest chance that equipment will be able to successfully communicate today and will remain useful in the future.

Phil Zito, a professional BAS integrator, provides his personal requirements of what constitutes an open protocol:[14]

1. Is the protocol a National or International Standard?
2. Is the protocol interoperable? [i.e. Can any equipment communicate with any other equipment if they conform to the standard?] And, is there an organization that ensures that the protocol fulfills the National Standard and that all manufacturers work with them?
3. Are there a minimum of 5 BAS or equipment manufacturers who work with the protocol?

The most common open protocol today is BACnet, followed by LonWorks.

Other open protocols are less likely to be used for BAS. Modbus and OPC are more likely to be used for industrial devices and power meters. Zigbee and EnOcean are specific to wireless devices.

Clear communications and coordination

Larry Stangel of Siemens spoke about lessons-learned from the Harvard case study discussed in the section “Opportunity #1: Temperature and ventilation setback during vacancy” above. “Anytime we do system integration, upfront design and communication between us, the customer and the other vendor, that’s always the most important thing,” he says. “Know what you’re going to do, how you’re going to achieve it, then be on the same page with the vendor.”[30]

Hire a professional system integrator

The Construction Specifications Institute (CSI) publishes MasterFormat®, “a master list of numbers and titles classified by work results” for the building trades.[58] Building construction bidding and specifications are divided based on this numbering system. For example, plumbing is division 22, HVAC is division 23, electrical (including lighting) is Division 26. In the 2004 edition of MasterFormat, division 25, Integrated Automation, was added, but it has not been widely used in practice.[59] Brian Stacy of Arup suggests that including a division 25 integration contractor is “a good start” for specifying and integrating automated building systems.[32]

Bary Coflan of Schneider Electric says that currently, division 25 services can be included in the work of other trades, such as HVAC or lighting, if those companies have the necessary experience. Independent IT integrators performing division 25 services are currently typically found only in large projects. Coflan is currently working with NEMA and major architectural and engineering firms to develop a position paper for a division 25 specification. He says, “It would be good for utilities to be on board with the division 25 process and to provide rebates on that.”[12]

According to Phil Zito, a professional system integrator himself, these professionals are well-practiced at following the steps needed to integrate multiple systems at the server level:[14]

1. Creating a systems integration use case. The use case defines the relationships between the occupants and the systems, the actions taken by the occupants and systems, and the directions in which information and commands flow between systems for the integrated system.
2. Identifying and diagramming the existing systems. Identify the architecture, components, and operation of the existing systems.
3. Using a gap analysis to detail out the new systems. Identify the differences between the capabilities of the existing systems and the integrated systems.
4. Determining the methods to close your gaps. Identify how to bridge the gaps with software, hardware and operational (e.g. personnel and contractors) solutions.
5. Detailing out the physical and logical integration points. Identify physical connections (e.g. the physical network that data will be transmitted over), communication/data flow, and logical connections (e.g. levels of priority for commands from different systems).
6. Creating an integration map. Create a diagram showing the physical and logical integration determined in step 5.
7. Detailing out the data model and system requirements. Identify the data that will be shared between the systems.
8. Developing a sequence of operations. These are the steps that the integrated system will take in response to inputs to the system.

Anticipate equipment failure

Paul Kondrat of CannonDesign says, “Make sure that default programming of controllers is set up so that if a power bump or other failure causes the controller to reset, those default values are what you need to properly operate the systems connected to it.”[36]

Charles Pelletier also said that when designing an integrated BAS control system, the hardware and software need to be implemented in such a way that if there's a failure, such as if a gateway fails, the lighting and HVAC systems will continue operating.[21]

Involve the information technology staff from the start

Paul Kondrat of CannonDesign says, "Involve the client's information technology personnel early and continuously throughout the design process to help determine if control systems can operate on the building data network, or if they need to be separated. A common network is needed to facilitate integrated control system communication."[36]

Train contractors in system integration

Brian Stacy of Arup notes that American builders can look to Europe as a model for how to integrate systems. He says that there, the trades cross over much more frequently than in the U.S. For example, their electrical contractors do IT work, while it is a separate contract in the U.S. He notes that the U.S. division 25 integrator's role is often part of electrical or mechanical contractor's scope in Europe. However, he believes that crossing roles has been resisted by labor unions in the U.S., which prefer more demarcated roles.

Cyber Security

While not specific to integrating lighting and HVAC systems, cyber security must be addressed for any project involving automated building systems. Integrating multiple systems may further increase risk by exposing more points of entry to criminals and providing more information if access is gained. The U.S. Department of Energy Federal Energy Management Program classifies cyber-attacks on connected lighting systems as:[60]

- Vectoring. Gaining entry via one network and then accessing other systems.
- Distributed Denial of Service (DDoS). Making the system or hardware unavailable by overwhelming it with traffic.
- Sniffing. Accessing and possibly modifying signals sent within the system.
- Invasion of Privacy. Obtaining information about occupants or businesses practices from sensor information.

Standards-setting organizations are addressing cyber security. One example is ANSI UL 2900-1: Standard for Software Cybersecurity for Network-Connectable Products. Another is the development of the BACnet Secure Connect (BACnet/SC) protocol.[61]

Conclusions

The LRC identified energy saving opportunities from using occupancy sensors in connected lighting systems to reduce HVAC energy use. The primary finding is that there are no technical barriers to doing this, and in fact, this has been practiced in BAS for a number of years. Energy savings are achieved by using a temperature and ventilation setback when a room is unoccupied. The integration between the lighting sensors and the HVAC system is achieved at one of four system levels: the sensor/actuator level, field controller level, supervisory controller level, or server level. All four of these are practiced in commercial installations.

The challenges for utilities and efficiency programs to implement this as part of their incentive programs are:

- BAS have already been using occupancy sensors to control HVAC. Typically, these are PIR sensors that are included in the HVAC BMS. Sometimes, occupancy information from security systems is used instead. In other words, the benefit of tying in occupancy information from the lighting system would either be to avoid having duplicate sensor hardware in a space (but the additional labor cost for integrating the systems may outweigh the cost of the hardware) or that there is a greater granularity of occupancy information from LLLC data (but HVAC thermal zones are too large to take advantage of this granular data).
- The energy and cost savings using this approach has been estimated with computer simulations but not yet verified in the field. A project by Slipstream, PNNL, and Cadmus Group is currently measuring energy savings and is expected to publish results around April 2020.
- Due to cost and complexity, typically only buildings 100,000 ft^2 (9,300 m^2) and greater are considered candidates for BAS.
- Thermal inertia may reduce occupant comfort when they initially return to a space, before the temperature can be brought back to the occupied setpoint.
- Another challenge may be reduced performance of HVAC systems, which were not designed for frequent cycling.

In addition to Opportunity #1: the energy savings method of using setbacks for unoccupied spaces, the LRC identified an additional five potential HVAC energy savings opportunities from using connected lighting systems. The other potential opportunities are:

2. Variable ventilation.
3. Office space consolidation.
4. Using AI and occupancy measurements.
5. Smaller thermal zones.
6. IoT in smaller commercial buildings.

However, none of these additional opportunities are in commercial practice. Opportunities 2, 3, and 4 have been studied academically, primarily using computer modeling, to estimate energy savings. No energy savings estimates were identified for opportunities 5 or 6.

If an incentive program were to be developed for integrating lighting in BAS, the following best-practices should be included:

- Plan for the long term.
- Obtain buy-in from the building owner.
- Specify equipment that works on open protocols.
- Make clear communication and coordination a priority.
- Hire a professional system integrator.
- Anticipate equipment failure.
- Involve the IT department from the start.
- Train contractors in system integration.

There are three primary motivations for utilities to consider lighting-HVAC integration in their efficiency programs. First, due to the increased penetration of highly efficacious LED light sources, the fraction of building energy used for lighting continues to decrease. Second, HVAC systems have not made the efficiency gains that lighting has. Third, the increased digitization of all building systems makes it more practical than ever to connect these systems together and control them, either onsite or from the cloud. Therefore, research and pilot programs to identify the most energy and cost-effective BAS integration methods would be fruitful.

While BAS integration is still in its early days, the trends point the way to a future in which all building equipment is connected together and which the current “silos” of HVAC, lighting, security, A/V, and safety are simply considered parts of one single building system.

Acknowledgements

This work was improved by the contributions of many people.

The author thanks the sponsors of the Lighting Energy Alliance for their support and guidance:

- Edward Bartholomew, National Grid
- Sam Fankhauser, Eversource and Energize CT
- James Fay, ComEd
- Pierre Gallant, Natural Resources Canada
- Steven Labarge, ComEd
- Lauren Morlino, Efficiency Vermont
- Jill O'Connor, Efficiency Vermont
- Jasmine Rivest, Efficiency Vermont
- Rob Singlehurst, Natural Resources Canada

- Chris Wolgamott, Northwest Energy Efficiency Alliance

The author thanks the technical experts who shared their knowledge:

- Avish Bhalani, Distech Controls
- John Brodeur, Emme Controls, LLC
- Scott Cochrane, Cochrane Supply
- Barry Coflan, Schneider Electric
- Eugene Gutkin, Integrated Building Solutions, Inc.
- Joe Hallman, Synapse Wireless
- Randy Mead, Cadmus Group
- Michael Myer, Pacific Northwest National Laboratory
- Charles Pelletier, Distech Controls
- John Petze, SkyFoundry
- Jon Sargeant, Integrated Building Solutions, Inc.
- Brian Stacy, Arup
- Kevin Van Den Wymelenberg, University of Oregon
- Gang Wang, University of Miami

The author thanks the LRC staff who provided their input and review:

- Andrew Bierman
- Rebekah Mullaney

References

1. U.S. Energy Information Agency. Major Fuel Consumption (Btu) by End Use for All Commerical Buildings, 2003. *U.S. Energy Information Agency Major Fuel Consumption (Btu) by End Use for All Buildings, 2003* (2008). Available at: https://www.eia.gov/consumption/commercial/archive/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003html/e01a.html. (Accessed: 31st January 2019)
2. U.S. Energy Information Agency. Major Fuel Consumption (Btu) by End Use for All Commerical Buildings, 2012. *U.S. Energy Information Agency Major Fuel Consumption (Btu) by End Use for All Buildings, 2012* (2016). Available at:

https://www.eia.gov/consumption/commercial/data/2012/c&e/cfm/e1.php. (Accessed: 31st January 2019)

3. ASHRAE. ASHRAE Technical FAQ #92.
4. ASHRAE. ANSI/ASHRAE Addendum p to ANSI/ASHRAE Standard 62.1-2013. (2015).
5. Glawe, D. *San Antonio Condensate Collection and Use Manual for Commercial Buildings*. 118 (San Antonio Water System, 2013).
6. Brandemuehl, M. J. HVAC Systems: Overview.
7. Evans, P. *How Chiller, AHU, RTU work*. (The Engineering Mindset, 2017).
8. Pacific Gas and Electric Company. *Advanced Variable Air Volume System Design Guide*. 326 (2007).
9. Zhang, J., Lutes, R., Liu, G. & Brambley, M. *Energy Savings for Occupancy- Based Control (OBC) of Variable- Air-Volume (VAV) Systems*. 76 (Pacific Northwest National Laboratory, 2013).
10. Roth, K. W., Westphalen, D., Dieckmann, J., Hamilton, S. D. & Goetzler, W. *Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential*. 281 (TIAX LLC, 2002).
11. BetterBricks. Dedicated Outdoor Air System | VHE DOAS. *BetterBricks* (2019). Available at: https://betterbricks.com/solutions/hvac/dedicated-outside-air-system-doas. (Accessed: 30th May 2019)
12. Coflan, B. Personal communication. (2019).
13. Mead, R. Personal communication. (2019).
14. Zito, P. *Building Automation Systems A to Z*. (Building Automation Monthly, 2016).

15. BACnet International. Frequently Asked Questions. Available at: https://www.bacnetinternational.org/page/faq#What%20is%20BACnet. (Accessed: 27th February 2019)
16. BACnet Testing Laboratories | BTL Product Listings. Available at: https://www.bacnetinternational.net/btl/. (Accessed: 27th February 2019)
17. Protocols/CEA-709.1 - The Wireshark Wiki. Available at: https://wiki.wireshark.org/Protocols/CEA-709.1. (Accessed: 27th February 2019)
18. LonMark - Certifications. Available at: http://www.lonmark.org/certifications/device_certification/product_catalog/search?categoryID=-1&deviceClassID=-1&Submit=Search&manID=-1. (Accessed: 27th February 2019)
19. DT_CM_COM2-24. Available at: http://www.steinel.net/DT_COM_COM2-24? (Accessed: 27th February 2019)
20. Smart Room Control Solution by Distech Controls. Available at: https://www.distech-controls.com/en/us/products/smart-room-control-solution/. (Accessed: 27th February 2019)
21. Pelletier, C. Personal communication. (2019).
22. nBACnet - nLight Bacnet IP Interface Appliance. *overview* Available at: https://www.acuitybrands.com/products/detail/410426/nlight/nbacnet/nlight-bacnet-ip-interface-appliance. (Accessed: 5th March 2019)
23. Lutron. *Building Management System Integration for Lutron Lighting Control Systems*.
24. Cree. *Cree SmartCast BACnet*.

25. nBACnet Plug-In - SensorView to BACnet IP Software Plug-In Module. *overview* Available at: https://www.acuitybrands.com/products/detail/410637/nlight/nbacnet-plug-in/sensorview-to-bacnet-ip-software-plug-in-module. (Accessed: 5th March 2019)
26. Osram. BACnet Integration | Digital Systems. Available at: https://www.osram.us/ds/products/light-management-systems/encelium/software/p001_ds_product_detail_104.jsp. (Accessed: 5th March 2019)
27. Myer, M. Lighting + HVAC. (2019).
28. Petze, J. Personal communication. (2019).
29. Sargeant, J. Personal communication. (2019).
30. Siemens. *Integrated Lighting Controls*. 6 (Siemens, 2014).
31. Capozzoli, A., Piscitelli, M. S., Gorrino, A., Ballarini, I. & Corrado, V. Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings. *Sustain. Cities Soc.* **35**, 191–208 (2017).
32. Stacy, B. Personal communication. (2019).
33. Van Den Wymelenberg, K. Personal communication. (2019).
34. Gutkin, E. Personal communication. (2019).
35. Cochrane, S. Personal communication. (2019).
36. Kondrat, Paul. Best practices for HVAC and lighting controls integration. *Consult. Specif. Eng.* **55**, 34–38 (2018).
37. University of Miami. Exploring the Frontiers of Buildings’ Energy Efficiency: Occupancy Sensors and HVAC Systems.

38. Myer, M. Beyond Lighting: Challenges and Success from Integrating Lighting Controls, HVAC, and Plug Loads. (2019).
39. Known Quantity Sensors. Known Quantity Sensors. *knownquantitysensors* Available at: https://www.kqsensors.com. (Accessed: 21st March 2019)
40. Acuity. Acuity Atrius Spaces Web App & API. *overview* Available at: https://www.acuitybrands.com/products/detail/765896/atrius/spaces-platform-service/atrius-spaces-web-app-api. (Accessed: 27th March 2019)
41. Acuity. nLight Space Utilization Edge Application. Available at: https://insights.acuitybrands.com/blog-new-products/space-utilization-edge. (Accessed: 27th March 2019)
42. Osram. Lighteligence. Available at: https://www.osram.com/cb/applications/lightelligence/index.jsp. (Accessed: 27th March 2019)
43. Enlighted. Space application.
44. Signify. Interact Office. *Philips Hue* Available at: https://www.interact-lighting.com/global/what-is-possible/interact-office. (Accessed: 27th March 2019)
45. Lutron. Quantum Space Utilization Reports Software. 2
46. Knapp, C., Vickroy, K., De Bruyn, L. & Kwong, D. Are the myths of space utilization costing you more than you know? *J. Corp. Real Estate* **11**, 237–243 (2009).
47. Gutierrez, L. & Williams, E. Energy savings from thermostat settings for commercial buildings by climate zone. (2015).

48. U.S. Energy Information Administration. Commercial Buildings Energy Consumption Survey 2012: Energy Usage Summary. Available at: https://www.eia.gov/consumption/commercial/reports/2012/energyusage/index.php. (Accessed: 27th March 2019)

49. Joanna R. Turpin. The Impact of Artificial Intelligence on HVACR. (2019). Available at: https://www.achrnews.com/articles/140789-the-impact-of-artificial-intelligence-on-hvacr. (Accessed: 17th April 2019)

50. Peng, Y., Rysanek, A., Nagy, Z. & Schlüter, A. Using machine learning techniques for occupancy-prediction-based cooling control in office buildings. *Appl. Energy* **211**, 1343–1358 (2018).

51. Vishwanath, A., Chandan, V., Mendoza, C. & Blake, C. A Data Driven Pre-cooling Framework for Energy Cost Optimization in Commercial Buildings. in *Proceedings of the Eighth International Conference on Future Energy Systems* 157–167 (ACM, 2017). doi:10.1145/3077839.3077847

52. Wang, W., Chen, J., Huang, G. & Lu, Y. Energy efficient HVAC control for an IPS-enabled large space in commercial buildings through dynamic spatial occupancy distribution. *Appl. Energy* **207**, 305–323 (2017).

53. Bierman, A. Personal communication. (2019).

54. Get Emme :: How It Works. Available at: http://getemme.com/how-it-works/. (Accessed: 30th April 2019)

55. Prestige Wireless Diffuser. *AirFixture*

56. Hallman, J. & Synapse Wireless. Personal communication. (2019).

57. Energy Information Administration (EIA). Commercial Buildings Energy Consumption Survey (CBECS) Data 2012. (2016). Available at: https://www.eia.gov/consumption/commercial/data/2012/#b1-b2. (Accessed: 22nd May 2019)

58. MasterFormat - Construction Specifications Institute. Available at: https://www.csiresources.org/practice/standards/masterformat. (Accessed: 29th May 2019)

59. AutomatedBuildings.com. Designing An Integrated Building System. Available at: http://www.automatedbuildings.com/news/feb11/articles/sinopoli/110127035808sinopoli.html. (Accessed: 29th May 2019)

60. U S Department of Energy Federal Energy Management Program. *Cyber Security for Lighting Systems*. 4 (2018).

61. David Fisher, Bernhard Isler & Michael Osborne. BACnet Secure Connect: A Secure Infrastructure for Building Automation. (2018).